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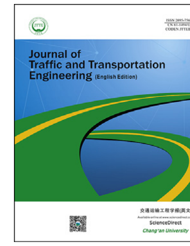

Review Article

New innovations in pavement materials and engineering: A review on pavement engineering research 2021

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HIGHLIGHTS

- Define "safe, durable, sustainable and intelligent" pavement infrastructure.
- Summarize the latest research achievements in the field of pavement engineering.
- Forecast the future research trend of pavement engineering.

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ABSTRACT

Sustainable and resilient pavement infrastructure is critical for current economic and environmental challenges. In the past 10 years, the pavement infrastructure strongly supports the rapid development of the global social economy. New theories, new methods, new technologies and new materials related to pavement engineering are emerging. Deterioration of pavement infrastructure is a typical multi-physics problem. Because of actual coupled behaviors of traffic and environmental conditions, predictions of pavement service life become more and more complicated and require a deep knowledge of pavement material analysis. In order to summarize the current and determine the future research of pavement engineering, *Journal of Traffic and Transportation Engineering (English Edition)* has launched a review paper on the topic of "New innovations in pavement materials and engineering: A review on pavement engineering research 2021". Based on the joint-effort of 43 scholars from 24 well-known universities in highway engineering, this review paper systematically analyzes the research status and future development direction of 5 major fields of pavement engineering in the world. The content includes asphalt binder performance and modeling, mixture performance and modeling of pavement materials, multi-scale mechanics, green and sustainable pavement, and intelligent pavement. Overall, this review paper is able to provide references and insights for researchers and engineers in the field of pavement engineering.

1. Introduction

It is evident that highway transportation is significant to the world economic development and the corresponding investment in highway engineering is undoubtedly great. Pavement engineering is not only an important part of highway engineering, but also an important factor affecting the service capacity of the road. In the past 20 years, the highway engineering has been facing the following two major changes:

(1) With the society development pavement engineering facing unprecedented opportunities and challenges

As well-known, in the 1960s and 1970s, the modern science and technology was just beginning with a relative slower development of the society and economy, and the vehicle axle loading was not heavier with the lower traffic volume. Although there were no high-performance computers or advanced experimental testing methods, the developed countries in Europe and America established the comprehensive road networks for their economic take-offs, and blazed a trail for the modern highway engineering with the standards or specifications which provides valuable experience for road construction of the other countries in the world. In the 21st century, the world economy has been rapidly developing with the human society transforming from the process-oriented electrification into the digitization and intelligentization. Till now, the European and American specifications or standards are popularly used in highway engineering, but the large-scale road infrastructure construction takes place in developing countries such as China and India. Obviously, in the era of digital intelligence, road construction in developing countries, including China and India, has unprecedented opportunities and challenges. On one hand, great changes took place in computer technologies, numerical methods, digital technologies, testing methods, construction technologies and so on, providing unprecedented opportunities for pavement engineering; on the other hand, road service and construction conditions are becoming more and more complex, and road engineering is facing unprecedented new challenges, such as dramatic changes of the climatic conditions, more cars with heavier axle loads, more effective travel demands, lack of green and safe road construction materials, and higher requirements of low carbon and resistant road construction.

(2) With the modern education development pavement engineering facing unprecedented accumulation of scientific manpower and literature

In the 21st century, the higher education in the world is constantly being improved and a plenty of high-quality talents with master's or doctor's degrees has been cultivated in highway engineering. As a result, the number of scientific papers has been rapid increasing. In the research databases of Ei Compendex and the China National Knowledge Infrastructure (CNKI), taking "pavement" as the key word, more than 4000 scientific papers were published in the 127 years from 1863 to 1990, with an average of 34 papers per year. However, from 2001 to 2021, nearly 20,000 scientific papers were published, with an average of 1000 per year. Obviously, the rapid increase of papers, on one hand, brings a lot of scientific and technological innovation information, on the other hand, brings difficulties for scientific and technological achievements selection.

Facing the above two changes, it is necessary to summarize, categorize, and classify the scientific and technological literature for extracting the key research points and developing the highway engineering of the new era. In order to make full use of the coming opportunities for embracing the future challenges of this era, Journal of Traffic and Transportation Engineering (English Edition) organized this review paper. A joint-effort of 43 scholars from 24 well-known universities in highway engineering was made to write this article. The editorial board member, professor Dawei Wang from Harbin Institute of Technology, was invited to lead and organize the writing and editing work of this long review paper. The structure of the paper is shown in the Fig. 1.

2. Asphalt binder performance and modeling

2.1. *Binder damage, healing and aging behaviors*

The experimental testing and characterization of asphalt binder is a fundamental element to the performance modeling of asphalt concrete and pavement. Since the strategic highway research program (SHRP) study in the 1990s, a significant research effort has been done to capture and distinguish the damage resistance of asphalt binder in high, intermediate and low temperature range by means of rheological and other approaches. Besides, the binder healing and aging behavior that happen in field pavement also simultaneously impact the damage evolution of the asphalt binder. Thus, a scientific binder damage understanding and interpretation should be integrated by the damage law with the consideration of healing and aging effects. This section starts with the healing and aging studies followed by a critical review on damage characterization of asphalt binder.

2.1.1. *Binder healing characterization and performance*

The damage evaluation and resistance are critical for the asphalt binder's long-term performance during the pavement service stage. Meanwhile, the damage healing potential of asphalt material during the possible rest periods has also been initially proven in the 1960s and widely verified and characterized in the past 30 years. In this section, the current healing characterizing approaches, performance indicators and various influencing factors are critically reviewed to address the recent developments in asphalt binder healing performance and modeling.

2.1.1.1. Characterizing approaches for binder healing behavior. Since the time sweep (TS) that developed in NCHRP 9-10 project is the main testing procedure to evaluate the fatigue resistance of asphalt binder in recent 20 years, it is widely applied to utilize the TS test to further quantify the binder healing ability by modifying the procedure with additional rest periods. Generally, there are two patterns to apply the rest period into the continuous fatigue loading sequence in the TS protocol, which can be summarized as the "TS with one-single rest period" and "TS with multiple rest periods". The testing condition impacts on binder healing performance are usually completed on the TS test with one-single rest period, which is less time consuming, as shown in Table 1. Meanwhile, the TS with multiple rest periods is normally employed to investigate the long-term healing recovery ability under the repeated fatigue-healing-fatigue cycles, as shown in Table 2.

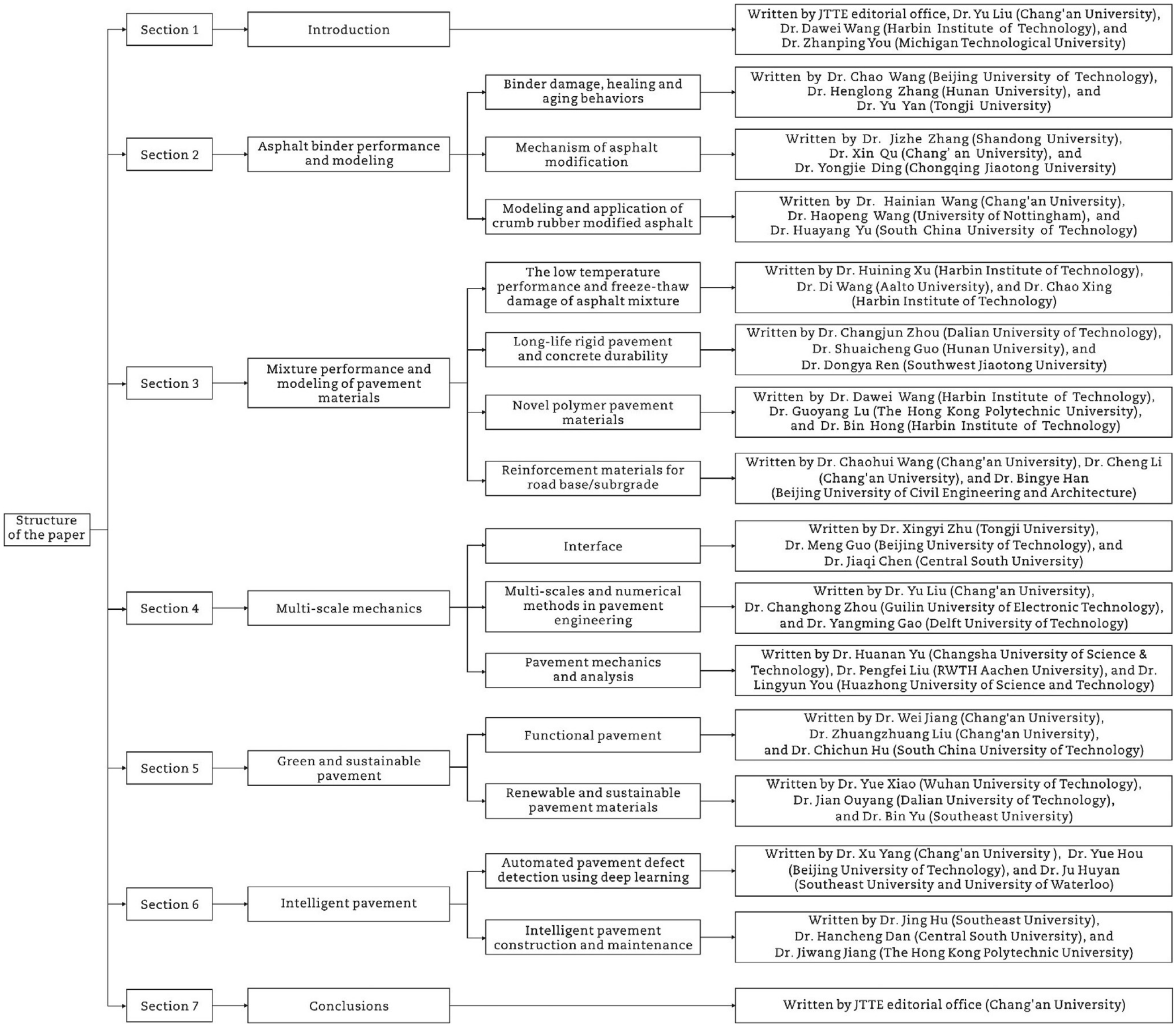


Fig. 1 – Structure of the paper.

Based on the TS procedure with rest period application, various performance indicators have been proposed for the healing evaluation of asphalt binder in recent 10 years. The stiffness or modulus based parameters (or pseudo variables, the area of modulus curve) are easily measured and mostly utilized to define the binder healing recovery by accounting the stiffness/modulus change before and after the rest period (Baglieri et al., 2018; De Oliveira et al., 2021; Qiu et al., 2020a, b; Shan et al., 2011; Sun et al., 2021a). To reveal the characteristic binder healing behavior, the continuum damage mechanics and dissipated energy approaches are also respectively investigated to establish the intrinsic healing model from the constitutive perspective. The healing performance can be accessed either from the damage intensity or dissipated energy variables (Baglieri et al., 2018; Palvadi et al., 2012; Shen et al., 2014; Sun et al., 2021b). Several research efforts have been conducted to combine and compare the traditional stiffness-based indicators and constitutive mechanics-based parameters to achieve a more comprehensive understanding on binder healing characterization (Canestrari et al., 2015; Qiu et al., 2020a, b; Tan et al., 2012). Furthermore, some researchers recently began to employ the fracture mechanics principals to address the mechanisms that lead to asphalt binder fatigue damage growth, in which way the crack initiation and propagation can be clearly observed. Thus, the healing recovery can also be defined based on the crack length property during the TS tests with rest period (Li et al., 2020a; Wang et al., 2021a).

The linear amplitude sweep (LAS) test (AASHTO TP101) has been widely applied and verified to quantify the fatigue damage resistance of asphalt binder in recent 10 years. Cooperating with the viscoelastic continuum damage (VECD) or simplified-VECD (S-VECD) modeling approaches, the traditional TS fatigue performance can be fully simulated from a simple 5-min LAS procedure. Due to the fact that the LAS specification is promising to be implemented in different countries, a LAS-based healing (LASH) procedure was newly

Table 1 – Summary of time sweep test with one-single rest period.

Reference	Proposed healing performance indicator
Shan et al., 2011	The change of modulus-cycle curve before and after rest period
Tan et al., 2012	$HI = 100\frac{G^*_{terminal}}{G^*_{initial}}\frac{N_{after}-N_{before}}{N_{before}}$
Shan et al., 2013	$HI = \frac{A_d}{A_{before}}$
Baglieri et al., 2018	$HI_c = \frac{C_{AR}-C_{BR}}{1-C_{BR}}; HI_s = \frac{S_{BR}-S_{AR}}{S_{AR}}$
Qiu et al., 2020a, b	$HI_1 = 100\frac{\lvert G^*\rvert_{h_0}}{\lvert G^*\rvert_0}; HI_1 = 100\frac{W_{after}}{W_{before}}\frac{N_{after}}{N_{before}}$
Li et al., 2020a	$HI = 100\left\lvert\frac{M_H-M_D}{M_0-M_D}\right\rvert$
Sun et al., 2021b	$HI_1 = \frac{G^*_h}{G^*_i}; HI_2 = \frac{N_h}{N_i}$

Note: HI is the proposed healing performance indicator; $G_{initial}$ and $G_{terminal}$ are the dynamic modulus before and after loading test; N_{before} and N_{after} are the numbers of cycles before and after rest period; A_d is the area between the modulus evolution curves before and after rest; A_{before} is the area below the modulus evolution curve before the rest; C_{BR} and C_{AR} are the pseudo stiffness values at the end of the first loading phase and at the beginning of the second loading phase; S_{BR} and S_{AR} are the damage intensity variable values at the end of the first loading phase and at the beginning of the second loading phase; $|G^*|_0$ and $|G^*|_{h0}$ are the complex shear modulus before and after healing; W_{before} and W_{after} are the initial dissipative energy before and after healing; M_D and M_H are the pseudo stiffness values, dissipated pseudo strain energy and crack length before and after healing; C_0 is the pseudo stiffness value at the initial of test; G_h* and G_i* are the complex shear modulus in first and second loading stage; N_h and N_i are the numbers of cycles in first and second loading stage; G is the dynamic shear modulus; N is the measured number of loading cycle; A is the calculated areas from performance curves; C is the pseudo stiffness; S is the damage intensity; W is the dissipated energy; M could be the pseudo stiffness, dissipated pseudo strain energy and crack length respectively.

proposed to characterize the binder healing behavior with better time efficiency (Fig. 2) (Xie et al., 2017). The percent healing (%HS) parameter is also defined from the damage intensity recovery from the rest period based on S-VECD

Table 2 – Summary of time sweep test with multiple rest periods.

Reference	Proposed healing performance indicator
Palvadi et al., 2012	$HI_i = \frac{S_f-S_i}{S_i}$
Shen et al., 2014	$HI_i = \frac{N_{ri}}{N_0}$
Canestrari et al., 2015	$HI = 100\frac{G^*_{terminal}}{G^*_{initial}}\frac{N_{after}-N_{before}}{N_{before}}$
De Oliveira et al., 2021	The decay curve of modulus evolution

Note: S_f and S_i are damage intensity variables representing state of material before and after introduction of rest period; N_{ri} is the relative fatigue life; N_0 is the fatigue life for the intact material before rest.

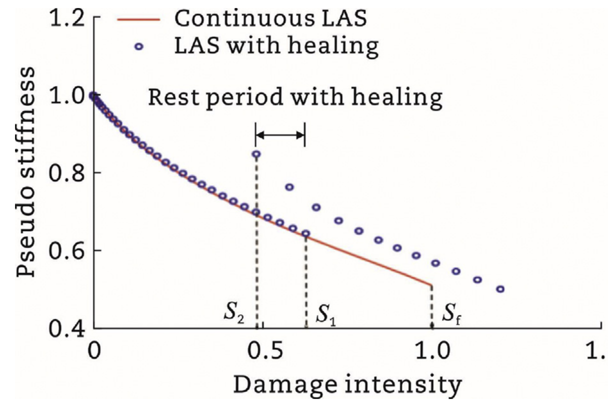


Fig. 2 – Schematic illustration for LASH protocol (Xie et al., 2017).

modeling approach. This LASH protocol and %HS-based healing evaluation method have been successfully verified through a chemo-rheological comparison (Wang et al., 2018g) and specific application to various polymer modified asphalts (PMAs) and warm mix asphalt (WMA) binders (Asadi and Tabatabaee, 2020; Yue et al., 2021).

Despite the application of traditional oscillation shear mode to binder fatigue and healing evaluation, other available loading modes on dynamic shear rheometer (DSR) were also tried to measure the binder self-healing potential after a concerned degree of damage/failure occurrence. Bommavaram et al. (2009) developed a two-piece binder healing test in tension mode on a DSR and quantified the healing ratio by the recovery of dynamic modulus (Fig. 3). Similar procedures can be also found in literature elsewhere (Leegwater et al., 2018; Qiu et al., 2013). Besides, the creep/recovery loading mode on the DSR can also be employed to access the binder healing behavior through a namely creep and step-loading test (Ma et al., 2020c).

It should be noted that all of the above reviews are only focused within the binder cohesive healing framework; however, it is also widely accepted that the cracking with growing damage in asphalt concrete normally initiates and propagates either within the cohesive asphalt binder/mastic phase or from the binder-aggregate adhesive interface. Therefore, both cohesive and adhesive healing together contribute to the macro-scale self-healing behavior of asphalt concrete. The adhesion between the binder and aggregate is usually evaluated from binder bond strength (BBS) test. Lyu et al. (2017b) further successfully apply the BBS procedure to measure the adhesive healing potential of the BBS specimen after the adhesive failure with various binder and aggregate types (as shown in Fig. 4), which is also verified by other case studies in recent years (Hu et al., 2020b; Wang et al., 2021a). It is promising to integrate the cohesive and adhesive binder healing models to enhance the fundamental understanding of the binder role in asphalt concrete healing behaviors during the in-site pavement service.

2.1.1.2. Various factors influencing binder healing performance. As the typical viscoelastic material, the asphalt binder healing behavior is also governed and influenced by various

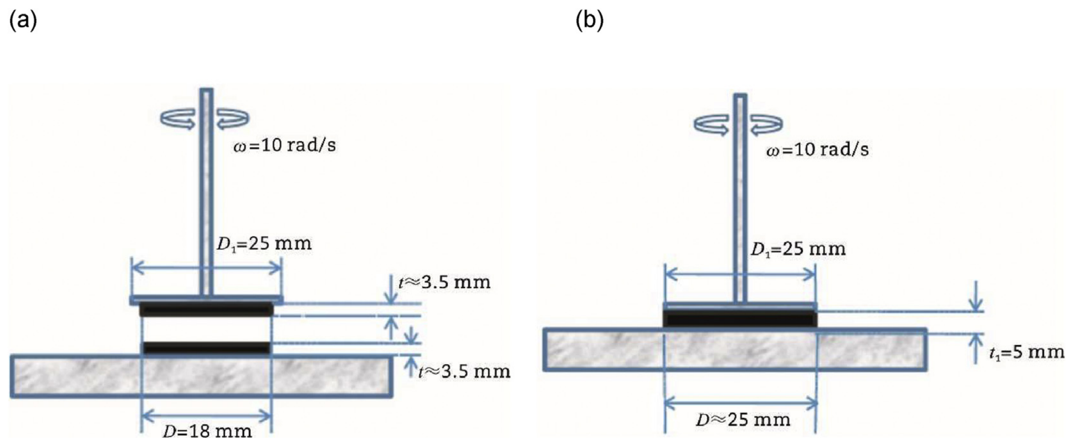


Fig. 3 – Schematic illustration of the two-piece specimen to determine healing function. (a) Before the test. (b) After the test (Bommavaram et al., 2009).

factors as briefly summarized in Fig. 5. In this section, the possible effects from the materials types, modifications, testing conditions and environmental impacts are respectively reviewed to a systematic comparison for evaluating the binder healing performance as summarized in Table 3.

Several studies demonstrated that the softer binders with higher penetration grade always displayed better healing potentials with clear monotonic trend (Wang et al., 2018g, 2020n; Xu et al., 2016b). Meanwhile, the micro-scale chemical composite and molecular structure effects on macro-scale healing is relatively complex and the binder with more oil phases (saturates and aromatics) and lower relative molecular weights generally showed higher healing recovery (Sun et al., 2017; Wang et al., 2018g). Besides, the modification to asphalt binder also exhibited uncertain impacts on healing performance. Some recent studies showed that modification improved the binder healing ability (Li et al., 2020c; Zhang et al., 2021b; Zhu et al., 2020c). However, there are also literatures reported that modification effects are strongly dependent on the material damage levels (Wang et al., 2018g, 2020n, 2020j). Regarding the reclaimed asphalt pavement (RAP) material re-use in asphalt pavement, Mullapudi et al. (2020) and Mullapudi and Sudhakar (2020) verified the negative impacts on binder healing from the RAP additions. Therefore, it is indeed necessary to specifically characterize the healing potentials with various binder types and modifiers.

The filed asphalt pavement experiences rather complex conditions in terms of the temperature range and traffic loading variables. The binder healing ability is proven to be increased with higher temperature (Bhasin et al., 2011b) but decreased when beyond the 40 °C threshold (HasaniNasab et al., 2019; Tang et al., 2016). The binder damage level before the rest period application is also important for the possible healing potential. With the growing damage, the binder healing performance is clearly becoming poor and even impossible to heal when accumulating to a critical damage degree or cohesive failure occurrence (Pang et al., 2012; Shen et al., 2016; Wang et al., 2020n). This is similar to the rest period case that a longer duration normally results in higher healing recovery; however, this positive impact is also relied on the binder damage condition (Pang et al., 2012; Wang et al., 2020n; Yue et al., 2021; Zhang et al., 2021b).

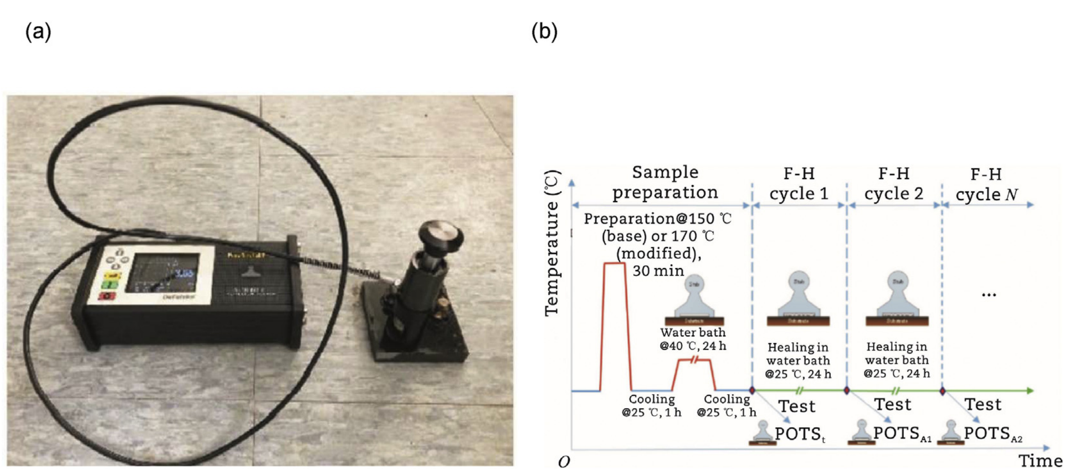


Fig. 4 – The use of the BBS test to binder adhesive healing. (a) The device of BBS test. (b) Schematic view of experimental procedure to quantify healing by BBS test (Lyu et al., 2017b).

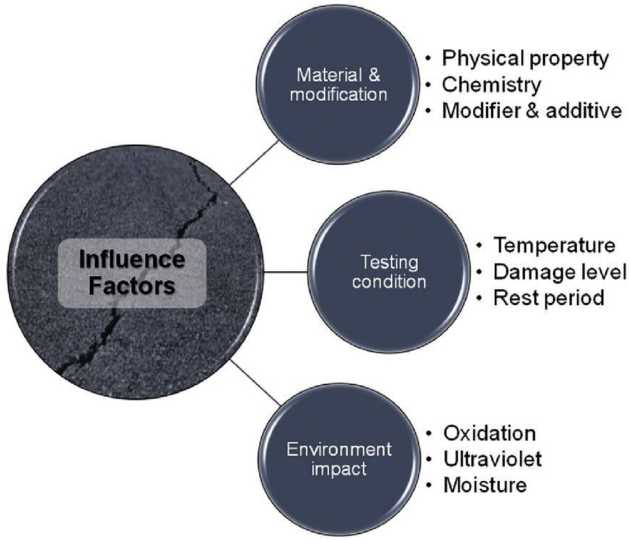


Fig. 5 – Systematic influencing factors on binder healing performance evaluation.

It is well accepted and known that the pavement performance (fatigue resistance and healing potential included) is negatively influenced by the various environmental elements like oxidation and ultraviolet aging as well as the moisture condition. But some recent studies found that the short-termed aged binder sometimes showed better healing ability than its original binder (Bao et al., 2019; Bhasin et al., 2011b; Yue et al., 2021; Zhang et al., 2018). Consequently, special attention should be further addressed for the aging effects on binder healing behavior. Besides, the water presence in the pavement under traffic loading is found to weaken both the cohesive and adhesive binder healing (Bhasin et al., 2011b; Yue et al., 2021). Thus, the environmental effect is a critical consideration to accurately characterize the binder healing contribution to asphalt concrete fatigue resistance. The influence factors on binder healing performance is summarized in Table 3.

2.1.2. *Asphalt aging: mechanism, evaluation and control strategy*

2.1.2.1. Phenomena and mechanisms of asphalt aging. As a critical component of asphalt pavement, asphalt material consists of a mixture of varying-weights molecules, along with their non-metallic oxides, and a few other constituents (Polacco et al., 2015; Ren et al., 2020b; Tauste et al., 2018; Wang et al., 2020i). Its primary function is to bond mineral aggregates into a whole after compaction (Majidifard et al., 2019; Mazzoni et al., 2018). However, exposed to complex

Table 3 – Summary of the influence factors on binder healing performance.

Influence factor		Positive (+) or negative(−) impact	Monotonic influencing trend	Reference
Material type and modification	Lower penetration	+	Yes	Wang et al., 2018g, 2020n
	Chemical composites & molecular structure	/	None	Sun et al., 2017 Wang et al., 2018g
	Modifier general	/	None	Li et al., 2020c Zhu et al., 2020c Zhang et al., 2021b
	RAP additive	–	Yes	Mullapudi et al., 2020 Mullapudi and Sudhakar, 2020
Testing condition parameter	Temperature	+	None	Bhasin et al., 2011b Tang et al., 2016 HasaniNasab et al., 2019
	Damage level	–	Yes	Pang et al., 2012 Shen et al., 2016 Wang et al., 2020n
	Rest period	+	Yes	Pang et al., 2012 Wang et al., 2020n Yue et al., 2021 Zhang et al., 2021b
Environmental impact	Oxidation	–	None	Bhasin et al., 2011b Yue et al., 2021
	Ultraviolet	–	None	Zhang et al., 2018g Bao et al., 2019
	Moisture	–	Yes	Mannan et al., 2017 Sun et al., 2021a

environmental factors such as heat, oxygen, and ultraviolet (UV) radiation during service, asphalt material is susceptible to hardening and embrittling, namely asphalt aging (Chen et al., 2021; Wu et al., 2009; Xu and Wang, 2017). Theoretical and experimental practices have indicated that after experiencing aging processes, the contents of oxygen-containing functional groups (such as carbonyl and sulfoxide) and the weight of most molecules in asphalt considerably increase (Hong et al., 2020b; Wang et al., 2020o). Meanwhile, the contents of saturates and aromatics decrease, while the contents of resins and asphaltenes extend (Mirwald et al., 2020; Qin et al., 2014). In terms of properties indicators changes, penetration and ductility values of asphalt reduce, but the softening point, viscosity, and stiffness increase with its aging process proceeding (Sirin et al., 2018; Zhang et al., 2020b).

Further, Table 4 shows various opinions on the mechanism of asphalt aging. It has been widely accepted that the loss of light components and oxidation reaction are the main reasons for asphalt aging (Petersen, 2000; Petersen and Glaser, 2011). According to some researchers, the former is referred to as the escape of light components (saturates and aromatics) in asphalt binder when the ambient temperature is higher than a threshold value (Filippi et al., 2018; Petersen and Glaser, 2011). Generally, the asphalt aging induced by the volatilization process mainly occurs in the phase of mixing, hauling, and paving of asphalt mixtures. Moreover, some previous researches found that the volatilization rate of light components would increase with the heating temperatures elevating (Tauste, et al., 2018; Ye et al., 2019; Zeng et al., 2015). Additionally, researchers have observed that the oxidation reaction of asphalt mainly involves hydrocarbons in asphalt reacting with oxygen when asphalt material is exposed to weathering environments during service (Petersen and Glaser, 2011). Besides, the processes of polymerization (the formation of large molecules by small molecules), thixotropy (steric hardening), syneresis (the exudation of oily components), and separation (the fractions separation of asphalt binder due to the absorption of aggregates), to some extent, will contribute to asphalt aging according to Hamzah et al. (2015) and Tauste et al. (2018). Also, the presence of moisture will influence the aging rate of asphalt. Huang et al. (2012) found the UV-induced aging rate of asphalt could be retarded in humid environments, while an opposite finding that moisture accelerated asphalt aging and hardened asphalt was shown in the study of Noguera et al. (2014). The reason for the controversy may be the differences in experimental materials, especially for the binder types, because gel-type asphalt that has higher polar components is more sensitive to water than sol-type asphalt.

However, even though various aging mechanisms of asphalt have been established, it is still unknown that the relative contributions from different factors or processes to asphalt aging. Furthermore, since most of the studies only focused on the aging of asphalt binders in the laboratory, it is necessary to clarify the effect of aggregates on asphalt aging during the aging process of asphalt mixture. In addition, with the development of characterization techniques, more newly-developed or advanced techniques are expected to reveal more details about asphalt aging.

2.1.2.2. Simulation methods of asphalt aging. As mentioned above, asphalt material is subjected to two different aging phases, known as short-term and long-term aging processes respectively. To reveal the aging behavior of asphalt and predict its road performances, asphalt aging processes are simulated with various laboratory techniques (Pradhan and Sahoo, 2019; Wang et al., 2020l, o; Zhao et al., 2021). Thin-film oven test (TFOT) and rolling thin-film oven (RTFO) test are commonly conducted to simulate the short-term aging process of asphalt according to ASTM D1754 and ASTM D2827 (or AASHTO T240) respectively. As for the long-term aging process, short-term aged samples are processed with a pressure aging vessel (PAV) in accordance with ASTM D6521 (or AASHTO R28).

However, with the exposure to heat, air (oxygen), and UV radiation for asphalt material in service, the long-term aging conditions created only by PAV are insufficient (Jin et al., 2018; Sun et al., 2020b; Zhang et al., 2012c). Therefore, numerous researchers have employed self-designed ultraviolet (UV) aging vessels to understand the effects of UV radiation on asphalt aging. Table 5 presents configurations of long-term

Table 4 – Various opinions on the mechanism of asphalt aging.

Reference	Main opinion on the importance ranking of factor/process inducing asphalt aging
Traxler, 1961	(1) Oxidation; (2) volatilization; (3) physical hardening; (4) polymerization induced by actinic light; (5) condensation polymerization.
Petersen, 1998, 2000, 2009; Petersen et al., 1974; Petersen and Glaser, 2011	(1) Loss of oily components; (2) oxidation; (3) thixotropic effects (steric hardening).
Bell 1989	(1) Loss of volatile components; (2) progressive oxidation of the in-place material field.
Hamzah et al., 2015	(1) Oxidation; (2) volatilization; (3) polymerization; (4) thixotropy; (5) syneresis; (6) separation.
Tauste et al., 2018	(1) Physical (steric) hardening; (2) loss of volatile components; (3) asphalt oxidation.
Ma et al., 2021	The presence of moisture can influence the oxidation process of asphalt.

Table 5 – Configuration of long-term photo-oxidative aging simulation.

Reference	Film thickness (mm)	Temperature (°C)	Radiation intensity (W/m^2)	Duration
Zhang et al., 2015d	3.0	60	8	12 d
Wang et al., 2019j	1.5	45	129	3–12 d
Xie et al., 2020a	3.2	35	370	10 d
Zeng, et al., 2015	1.2	30, 50, 70	5	20 d
Yu et al., 2019a	2.0	25	50, 100, 150, 200	40, 80, 120, and 160 h
Yu et al., 2009	2.0	80	Not reported	0–18 d

UV-oxidative aging simulation in some research. It shows that the configurations of the UV aging process vary in different research. Specifically, the film thickness of pre-aged samples ranged from 1.5 to 3.2 mm; the aging temperatures were set with the lowest temperature of 25 °C and the highest of 80 °C; the ranges of UV radiation intensity and duration were 5–370 W/m^2 and 40–432 h respectively. Thus, it is difficult to compare the aging degree or aging resistance of asphalt binders in two different studies. Also, owing to little attention paid to the effect of UV radiation on the aging behavior of mixtures, it is important to disclose the UV-induced aging behavior of asphalt mixture for future research. In addition, developing a universal or configurable parameter UV aging method for asphalt binders or asphalt mixtures is expected.

Although there are two aging methods available for aging asphalt mixtures, the correlation between mixture aging degree obtained by laboratory simulation aging techniques and that of field aging is poor. For this reason, some researchers extended the duration time to better build the relationship between laboratory aging and field aging (Alamdary et al., 2021; Sadek et al., 2020). Unfortunately, the results have been still unsatisfactory with only considering the aging factors of heat and oxygen. With the requirements of aging methods for asphalt mixtures (such as being easy to perform, not too time-consuming, no binder flow during testing), some environmental aging simulation vessels have been developed. Steiner et al. (2016) introduced ozone and nitric oxides into the aging environment of asphalt to provide a higher oxidation rate. Results showed that with the optimized aging procedures (60 °C, 4 d, 1 L/min for gases flow rate), the long-term aging conditions of asphalt mixtures in the field could be successfully simulated. Similarly, a flow of oxygen was adopted to achieve the same effects. Considering the contributions from UV radiation and moisture to asphalt aging, Crucho et al. (2020) set various aging conditions, including temperature, UV radiation, watering/drying cycles along with an immersion period, to simulate asphalt mixture aging. Based on the above analysis, it can be concluded that laboratory aging simulation techniques are developing towards creating aging environments containing multi-factors, namely being closer and closer to in-filed conditions.

Besides, the aging method of directly exposing asphalt samples to natural environments is used to obtain aged asphalt samples with different aging periods. To evaluate the durability of thermochromic microcapsule modified asphalt, Chen et al. (2019a) placed the asphalt samples to an outdoor natural environment and took some of them at intervals of three months. Likewise, in the studies of Qin et al. (2014) and Wang et al. (2016b), some amounts of other asphalt binders or compacted specimens are aged with a certain aging period to evaluate their performances. Obviously, the aging method is well related to a real situation in service, but the process is time-consuming or inefficient. Thus, it is necessary to develop aging devices with configurable aging parameters. Then, based on the historical weather data of target application fields, the performances of asphalt mixtures can be predicted by adjusting parameters (temperature, UV radiation intensity, humidity, drying/wetting frequencies, etc.) of aging environments.

2.1.2.3. *Characterizing approaches for asphalt aging behavior*. Asphalt aging is an inevitable outcome for asphalt pavements in service due to exposure to various adverse factors (Raab et al., 2017; Vo et al., 2020). To characterize the aging behavior of asphalt and assess the effects of polymer(s) or other additives on the aging resistance of asphalt, various indicators have been adopted.

Based on the aging mechanisms of volatilization and oxidation reaction for asphalt binders, the asphalt molecular weight and intermolecular strength increase, consequently altering the characteristics of physical properties, rheological properties, surface morphology, chemical functional groups, molecular weight, etc., of asphalt binders (Hong et al., 2020b; Liu et al., 2020b; Wang et al., 2020o; Zhang et al., 2016e). Therefore, the properties change rate of asphalt with and without an aging process is employed to quantitatively characterize the aging degree of aged asphalt. Eqs. (1)–(3) and Eqs. (4)–(5) have been commonly used for calculating physical and rheological aging indicators and chemical functional groups indicators of asphalt, respectively. For instance, complex modulus and phase angle aging index have been calculated with Eq. (2) and utilized to reflect rheological behavior changes of asphalt during aging processes (Chen et al., 2015a; Zhang et al., 2018d). Further, Zhang et al. (2018b) investigated the feasibility of other rheological indexes, including rutting factor ($G^*/\sin\delta$) aging index, fatigue factor ($G^*\sin\delta$) aging index, zero shear viscosity (ZSV) aging index, non-recoverable compliance (J_{nr}) aging index, and DSR function (DSRFn) aging index, to evaluate aging behavior of base asphalt and two polymer modified asphalt. They found that the indicators not only could reflect aging behavior and aging sensitivity but also were well correlated to each other and could indicate performances of asphalt. Therefore, the aging behavior and road performances of asphalt can be well predicted with the evaluation indicators. Other evaluation methods derived from various property indicators of asphalt are presented in Table 6.

In the case of asphalt aging evaluation, it is necessary to conduct the experimental work from different views as a single evaluation indicator has its shortcomings and may not reflect the actual aging degree of asphalt. Also, building the relationship between macro evaluation indicators and micro ones is crucial to deeply understand the aging mechanisms of asphalt. But before that, the validity of every indicator demands to be justified. A recommended approach is to understand the evolution characteristics of asphalt properties with the aging time proceeding by conducting the aging process of asphalt in natural weathering environments, field aging or laboratory.

$$AI_1 = P_{aged} - P_{unaged} \quad (1)$$

$$AI_2 = \frac{P_{aged}}{P_{unaged}} \quad (2)$$

$$AI_3 = \frac{P_{aged} - P_{unaged}}{P_{unaged}} \quad (3)$$

$$CAI = \frac{A_{C=O}}{\Sigma A} \quad (4)$$

$$SAI = \frac{A_{S=O}}{\Sigma A} \quad (5)$$

where AI_1, AI_2 and AI_3 are aging index of asphalt, while P_{aged} and P_{unaged} are asphalt properties of aged and unaged asphalt, respectively. And CAI and SAI are carbonyl aging index and sulfoxide aging index of asphalt, respectively. $A_{C=O}$ and $A_{S=O}$ are the area of carbonyl band at 1699 cm^{-1} and sulfoxide band at 1030 cm^{-1} respectively, and "ΣA" is the total band area from 2800 to 3000 cm^{-1}.

2.1.2.4. Anti-aging additives used for controlling asphalt aging. Despite the inevitable phenomenon of asphalt aging, the introduction of anti-aging additives into asphalt can effectively delay or hinder the aging rate of asphalt (Chen et al., 2021; Zhang et al., 2018c). As shown in Table 7, various anti-aging additives have been used to cope with one or more detrimentally environmental factors, which mainly cover oxygen, heat, and UV radiation.

Antioxidants and inorganic fillers (such as hydrated lime) are two commonly used methods for improving the thermo-oxidative aging resistance of asphalt (Apeagyei, 2011; Choi et al., 2020a; Sirin et al., 2018; Tauste et al., 2018). Further, the antioxidants can be divided into three categories according to their action mechanism: 1) chain terminator (interrupting free radical reaction during a polymer chain reaction process), 2) peroxide decomposition agent (decomposing hydroperoxide into inactive products), and 3) metal ion passivator (fixing variable valence metal ions in a stable valence state by complexing with metal ions). The initial free radical (R-) is produced by the pyrolysis of hydrocarbon under the action of heat and oxygen and then reacts with oxygen to form peroxide free radicals (ROO-). Furthermore, owing to a chain reaction among the two components, asphalt aging has been aggravated. However, the activation energy required for the reaction between antioxidants and peroxide radical is low, thus terminating the reaction chain between peroxide radical and oxygen. Further, along with the decomposition effect of antioxidants on hydrogen peroxide (ROOH), the aging process

Table 6 – Aging evaluation with various indicators.

Evaluation type	Principle (with the asphalt aging process proceeding)	Evaluation indicator	Reference
Physical property	The increase of hardness and high-temperature stability but the decrease of ductility and mobility for asphalt binders	(1) Penetration residual ratio. (2) Softening point increment. (3) Ductility residual ratio. (4) Viscosity increase ratio.	Zhang et al. 2018c Zhao et al. 2016b Zhu et al. 2019b
Rheological property	The increase of stiffness and the loss of viscous components for asphalt binders	(1) Complex modulus aging index. (2) Phase angle aging index. (3) Zero shear viscosity aging index. (4) Non-recoverable compliance aging index. (5) DSR function aging index.	Zhang et al. 2018b Wang et al. 2020o Huang et al. 2002 Jin et al. 2018 Ren et al. 2020b
Surface morphology (AFM)	The decrease of aromatic fraction (related to bee-like structures)	(1) Surface roughness. (2) Amount and size of bee-like structures (qualitative evaluation).	Hong et al. 2020b Wu et al. 2009
Chemical component	The occurrence of oxidation reaction for asphalt molecular	(1) Carbonyl aging index. (2) Sulfoxides aging index. (3) Butadiene index.	Cong et al. 2014 Liu et al. 2015 Xie et al. 2020a
Molecular weight	The increase of hydrocarbon molecules size and proportion of asphaltenes	The large molecular content ratio.	Hao et al. 2017b

Table 7 – Types and characteristics of anti-aging additives.

Anti-aging additive	Influence factor	Principle	Shortcoming	Reference
Antioxidant	Oxygen	Two approaches to hinder the oxidation reaction	Going failure after full self-oxidation	Apeagyei et al., 2011; Choi et al., 2020a
Inorganic filler (such as hydrated lime)	Oxygen	Physical and chemical interactions	Poor compatibility and limited improvement to UV resistance	Huang et al., 2002; Tauste et al., 2018
Layered silicate	Heat and oxygen	Shielding from oxygen and heat	Poor compatibility with asphalt and limited improvement to UV resistance	Yu et al., 2009; Zhang et al., 2012a
Carbon black	UV radiation	Many surface groups (such as quinones, phenols, etc.)	Poor compatibility with asphalt	Cong et al., 2014; Tauste et al., 2018
UV absorbent	UV radiation	Converting absorbed UV radiation into releasing heat and capturing active free radicals	Going failure after full self-degradation	Xu et al., 2019b; Zhao et al., 2016b
LDH	UV radiation	Multi-level shielding, reflection, and absorption of UV light	Poor compatibility with asphalt and limited improvement to thermo-oxidative aging	Xu et al., 2015d Filippi et al., 2018
Nanoparticle	UV radiation	Reflection and absorption of UV light	Limited improvement to thermo-oxidative aging	Xie et al., 2020a; Filippi et al., 2018
Polymer	Various factors	Absorption of oxygen and UV light	Self-degradation	Cortizo et al., 2004; Hao et al., 2017
Multi-dimensional nanomaterial	Heat, oxygen, and UV radiation	Shielding heat and oxygen and absorbing UV light	The possibly poor homogeneity of modifier components in asphalt	Zhang et al., 2017d; Wang et al., 2020o

of asphalt has been considerably slowed down. Concerning the positive effect of inorganic fillers (such as hydrated lime) on the aging resistance of asphalt, the generation of water-insoluble calcium salts in asphalt delays the asphalt aging by restraining aging-induced hardening kinetics (Filippi et al., 2018; Huang et al., 2002; Tauste et al., 2018). In addition to hindering asphalt aging, calcium hydroxide can significantly improve the resistance of asphalt pavement to moisture damage. However, antioxidants will go failure after their complete oxidation, and many inorganic fillers have poor compatibility with asphalt. And both of them have little improvement effect on the UV resistance of asphalt. Consequently, the above shortcomings have limited their application.

Layered silicates, such as montmorillonite (MMT), rectorite (REC), and expanded vermiculite (EVMT), have platelet-layered structures, which can impart shielding effects to heat and oxygen with its introduction into the asphalt. The studies of Yu et al. (2009), Zhang et al. (2012b), and Zhu et al. (2019b) showed that the addition of layered silicates can slow down the aging rate of asphalt, confirmed with a smaller property change for the modified asphalt. Nonetheless, layered silicates have shown limited positive effects on UV-induced aging resistance of asphalt and poor compatibility with asphalt due to their different nature (Liu et al., 2010b; Yu et al., 2010).

As for the improvement of UV resistance, carbon black, UV absorbents, layered double hydroxides (LDHs), and nanoparticles (several types) are common choices though they act in different ways (Feng et al., 2012; Liu et al., 2015d; Xu et al., 2015d, 2021c; Zhang et al., 2016d, 2021e). Some studies have concluded that the positive effects of carbon black are derived from its numerous surface functional groups (such as quinones, lactones, etc.) (Cong et al., 2014; Tauste et al., 2018). Furthermore, Xu et al. (2019c) and Zhao et al. (2016b) have specified that the introduction of UV absorbents converted the absorbed UV radiation into releasing heat, consequently inhibiting the UV-induced aging process of asphalt. The effectiveness of LDHs and nanoparticles is generated from their reflection and absorption to UV radiation. Additionally, polymer modifiers such as styrene-butadiene-styrene block copolymer (SBS) can improve not only the anti-UV but anti-thermo-oxidative aging properties of asphalt (Cortizo et al., 2004; Hao et al., 2017b). Unfortunately, the polymer modifiers will gradually degrade until fail. Moreover, other modifiers also have different shortcomings (Table 7) despite a positive effect on UV aging resistance of asphalt.

Previous studies have found that the anti-UV aging properties of asphalt can be significantly improved by zero-dimensional nanomaterials such as nano-SiO_2, nano-TiO_2, and nano-ZnO, while the anti-thermo-oxidative aging characteristics of asphalt can be improved by layered silicates (two-dimensional nanomaterials) (Li et al., 2015b; Ray and Okamoto, 2003; Zhang et al., 2012a). For this reason, Zhang et al. (2015c, 2017d) developed multi-dimensional nanomaterials modifiers, composed of zero-dimensional and two-dimensional nanomaterials, to comprehensively improve the anti-thermo-oxidative and anti-UV aging properties of asphalt. Results showed that after thermo-oxidative and UV aging processes, multi-dimensional nanomaterial modified asphalt had a lower aging degree than unmodified asphalt. Moreover, Wang et al. (2020o) also concluded that along with good aging resistance, multi-dimensional nanomaterials could improve the low-temperature and fatigue resistance of asphalt binder and mixtures. Therefore, multi-dimensional nanomaterial modifiers are promising in enhancing the aging resistance and road performances of asphalt. However, the component homogeneity of multi-dimensional nanomaterials in asphalt is worrying, possibly limiting the additive effects of components on asphalt. Nanocomposite technology, an approach to combining two single components, is hopeful to eliminate the adverse effect and further improve properties, including but not limited to aging resistance, of asphalt, as well as impart interesting functions to asphalt pavement.

Actually, the anti-aging additives are required to not only impart sustainably positive effects on the aging resistance of asphalt but maintain or enhance other performances (such as high-temperature stability). Therefore, multi-dimensional nanocomposite modifiers may be a promising candidate.

2.1.3. *Damage in the characterization of binder cracking performance*

Load-induced fatigue cracking (bottom-up and top-down) is one of the primary modes of failure in asphalt pavements (Roque et al., 2002; Shen et al., 2006). Previous study has shown that most crack occurs within asphalt binder and/or at the interface tween asphalt binder and aggregate, and therefore, asphalt binder as a bonding agent plays a critical role in cracking resistance of asphalt mixtures (Soenen et al., 2003). It becomes a general understanding that accurate characterization and proper selection of asphalt binders that are fatigue-resistant could prolong the fatigue life of asphalt pavement. In the Superpave performance grade specification, the fatigue performance of an asphalt binder is evaluated by the parameter $|G^*|\sin\delta$, which is an indicator of total dissipated energy during cyclic loading (Anderson et al., 2001). The effectiveness of this parameter has been widely questioned for several reasons including: 1) the strain applied is too small to introduce sufficient damage into the binder specimen; 2) not all the total dissipated energy is associated with damage; 3) the assumption of linear viscoelastic does not work for polymer-modified binders; and 4) the meaning and appropriateness of linking cracking performance with intermediate temperatures are debatable (Bahia et al., 2001; Yan et al., 2017). To summarize, there is a lack of information about the role of asphalt binder in the damage progress.

2.1.3.1. *Damage characterization based on rheological properties*. Recognizing the inadequacy of the superpave PG binder fatigue parameter ($|G^*|\sin\delta$) in dealing with the polymer-modified asphalt binders, there have been significant efforts to accurately measure and characterize binder fatigue properties by means of damage characterization. The time sweep (TS) test evaluates the fatigue damage by means of the degradation of material integrity under repeated loading (Bahia et al., 2001). The TS procedure consists of applying repeated cyclic loading at a fixed loading frequency and amplitude to a binder specimen using the DSR. Changes in complex shear modulus (G^*) and phase angle (δ) with number of loading cycles are recorded for the determination of binder fatigue life. This test allows for the binder to go beyond linear viscoelastic behavior and into the damage accumulation range. However, a clear definition of fatigue failure, which is crucial to fatigue performance evaluation and prediction of a binder, is not available in the TS test. Moreover, the TS test was determined not to be a practical method for the specification of asphalt binder fatigue resistance because of the uncertainty in testing time (can be several hours) and poor testing repeatability (Hintz et al., 2011).

Further attempts were made to introduce surrogate tests to estimate binder fatigue resistance in a relatively short period of time, which include the binder yield energy (BYE) test and the linear amplitude sweep (LAS) test. The BYE test is a monotonic constant shear strain rate test that employs the DSR and measures the energy to "yielding" of binders (Johnson et al., 2009). Yield energy can be determined by integrating the area under the stress-strain curve to the maximum stress value. One method of quantifying damage is to relate the undamaged material properties to damaged material properties from destructive (damage-inducing) tests. The undamaged properties are typically estimated from tests employing small loads, under the assumption that no damage is introduced. However, response of polymer-modified asphalt (PMA) binders from the BYE test, during which damage is assumed to have occurred, was found to be above the undamaged response of the same binder. In other words, the increased shear strain did not reduce the material integrity or introduce damage, raising some concern on the appropriateness of the BYE test.

The LAS test was found to be more successful in measuring fatigue resistance of asphalt binders (Johnson, 2010). This test evaluates the ability of an asphalt binder to resist damage by employing cyclic loading at increasing strain amplitudes (from 0 to 30%) to accelerate the rate of damage accumulation, as shown in Fig. 6. The LAS test results can be analyzed using VECD, following Schapery's theory of work potential to model damage growth. The fatigue damage is

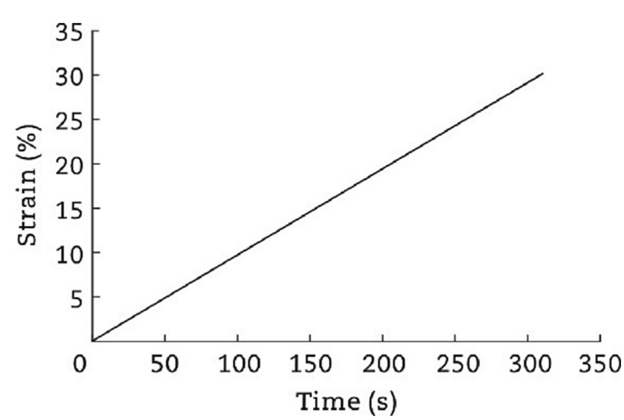


Fig. 6 – Continuous loading scheme for the LAS amplitude sweep test.

defined as the degradation of material integrity (as indicated by the |G*|sin δ parameter) under repeated loading. A power law function has been used proposed to model |G*|sin δ versus damage, from which the number of cycles to a given damage intensity can be determined. While the LAS test is promising, the fatigue failure of asphalt binder where no catastrophic failure or fracture can be observed, is still not well-defined. The damage accumulation at failure (D_f) in the VECD model is associated with a 35% reduction in undamaged |G*|sin δ, which, follows the traditional definition of fatigue failure in asphalt mixture (i.e., 50% reduction in initial stiffness/pseudo-stiffness) (Johnson, 2010). This arbitrarily selected criterion has been criticized by many researchers for lacking, theoretical or phenomenological justification. In AASHTO TP101-R16, the D_f parameter is defined as the level of damage calculated by using |G*|sin δ value that corresponds to the peak shear stress on a shear stress versus shear strain curve. It seems logical to assume that the binder sample reaches fatigue failure when it no longer requires a higher shear stress to maintain or increase the shear strain in the process of accumulating damage.

Wang et al. (2015a) pointed out that the peak stress does not define the ultimate failure or damage tolerance since it only indicates the yield threshold of the material under increasing loading. Recent advances in the S-VECD modeling was applied to the LAS data analysis procedure. The framework of the revised LAS test now contains three material-dependent functions, in terms of linear viscoelasticity, damage property, and failure mechanism. Time-dependent effect of viscoelasticity (i.e., delayed elastic energy) can be separated from damage associated energy by replacing physical strain with equivalent pseudo strain. Fig. 7 shows the simplified pseudo hysteresis loops representing the damage evolution in LAS tests. The undamaged line serves as a reference indicating the response of undamaged binder sample. As loading progresses, damage occurs in the specimen resulting in the damaged line with reduced stiffness. The area under the undamaged line represents the total pseudo strain energy (PSE). For a given loading cycle, the total PSE can be separated into two parts including the released PSE (i.e., area with red lines) of the specimen due to damage and the stored PSE (i.e., area with black lines). When plotting the calculated stored PSE and released PSE for the entire LAS testing, there appears to be a maximum stored PSE, as shown in Fig. 8. A peak in stored PSE indicates that failure has occurred because the material has lost its ability to store more PSE with increased input strain. Thus, the maximum stored PSE is selected as an energy-based failure criterion and the corresponding number of cycles to failure (N_f) is reported as the indicator of the binder fatigue life.

Advancements in asphalt mixture fatigue characterization have been also applied to the study of binder fatigue life. For example, Zhang et al. (2013b) observed that the slope of the total release PSE versus load cycles curve, i.e., the rate of total released PSE of asphalt mixtures. Consequently, they recommended that the stable rate of total released PSE, entitle G^R, can be used to characterize the overall rate of energy loss of a binder sample during the fatigue test. Wang et al. (2015a) followed the G^R approach to analyze the TS and LAS binder testing results. They reported that the relationship between the average G^R and fatigue life (N_f) of a given binder appears to be fundamental one (i.e., it is independent of loading history). Moreover, they performed the LAS tests on the same sample but at different constant strain-amplitude rates to obtain the relationship between G^R and N_f of a given binder. Finally, this characteristic relationship can be incorporated into the S-VECD model by fitting a power law model between G^R and N_f parameter, which allows for fatigue life prediction of a binder specimen at any strain amplitude, as shown in Fig. 9.

In summary, there are at least four procedures that can be followed to interpret LAS amplitude sweep results. As illustrate in Table 8, two of these procedures are based on the VECD model, with the difference being the binder failure criterion. The other two procedures are based on the S-VECD model and more specifically, one for ranking binders and the other one for binder fatigue life prediction.

2.1.3.2. *Damage characterization based on fracture properties.* Another important approach of characterizing asphalt binders at intermediate temperatures is to employ fracture mechanics and fracture properties as indicators of binder cracking performance. Fig. 10 shows an edge fracture occurs

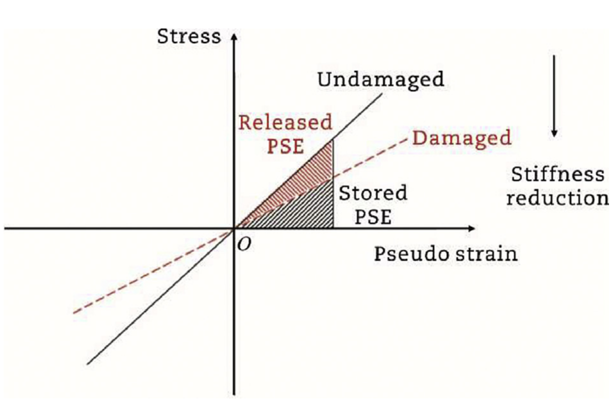


Fig. 7 – Schematic representation of undamaged and damaged lines.

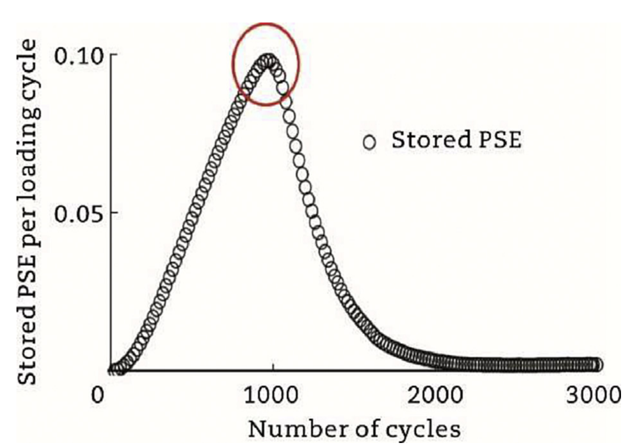


Fig. 8 – PSE based failure analysis.

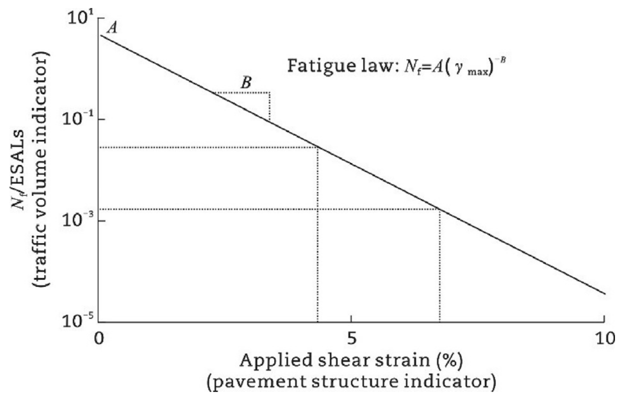


Fig. 9 — Fatigue life (N_f) versus applied binder shear strain on a log-log scale.

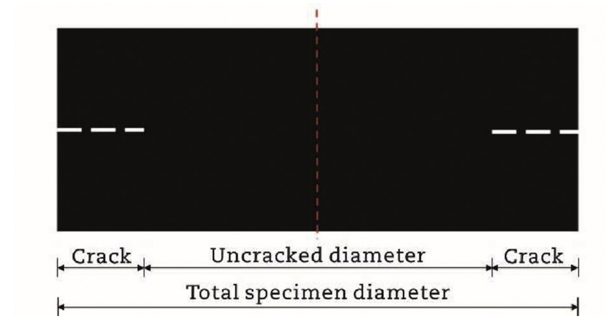


Fig. 10 — Schematic illustration of edge fracture in a DSR sample (Hintz and Bahia, 2013b).

in the DSR sample where a circumferential crack formed at the periphery of a sample that propagates inward as loading is applied, effectively reducing sample size (Aboutorabi et al., 1998; Hintz and Bahia, 2013a). Based on torsion prediction of crack length of DSR specimens, crack growth rate (da/dN) and energy release rate (G_f) were found to correlate with the crack length of binder samples. Moreover, a fracture mechanics-based analysis framework was developed for binder fatigue characterization. As a result, fatigue failure can be linked to the peak in energy release rate (G_f) and crack growth rate (da/dN), both of which occur at the same crack length indicating the transition from shallow to deep crack growth. Furthermore, binder crack growth rate can be analyzed as a function of crack length using LAS testing results (Hintz and Bahia, 2013b). The crack length at failure, which corresponds to the crack length at the local minimum in crack growth rate, was recommended as a parameter to rank the relative damage tolerance of asphalt binder at intermediate temperatures.

Fig. 11 shows the double-edge notched tension (DENT) test developed by Andriescu et al. (2004) to fracture ductile binders at intermediate temperatures. Data interpretation procedure of the DENT test followed the essential work of fracture method. According to this method, the total energy can be separated into essential work (i.e., the work necessary for progression of fracture) and plastic work (i.e., the work necessary for plastic deformation before fracture). Then, the essential work divided by the tensile yield stress results in an approximate critical crack tip opening displacement (CTOD), which is specified as a measure of binder strain tolerance in the ductile state. Gibson et al. (2012) found that the CTOD parameter correlated well with FHWA-ALF mixture fatigue test results. Of note, the required number of replications and the scatter in the analysis were listed as major drawbacks of the DENT tests. Campbell et al. (2018) employed the DENT test to evaluate seven asphalt binders at 15 °C, and they concluded that the CTOD parameter provided a reasonable measurement of ductility, better than the elongation to failure parameter obtained from the direct tension tests.

Binder fracture energy density (FED), which is the energy density a binder can tolerate before fracture, is an important property related to binder fatigue resistance. Asphalt binder exhibits ductile behavior at intermediate temperatures, making the detection of the fracture plane and the determination of the binder FED very challenging. In response, Niu et al. (2014) and Yan et al. (2017) developed a binder fracture energy (BFE) test including the specimen preparation and the associated data analysis procedure. The BFE specimen geometry was designed to introduce a sufficient stress concentration at the middle section of a specimen where fracture is expected, as shown in Fig. 12. The BFE tests were performed at a constant displacement rate of 500 mm/min, during which, time, force, and displacement data are recorded. The measured force and displacement are then transformed to true stress and true strain in the central cross-sectional area of the specimen, where fracture occurs by accounting for the change in cross-sectional area during testing. The binder FED is calculated as the area under the true-stress and true-strain curve until the stress peak. Binder FED was found to be a fundamental material

Table 8 — Different procedures to interpret LAS amplitude sweep results.

Procedure	Failure criterion	Strain amplitude rate (%/s)	Test duration (min)	Data analysis
1	35% reduction in G*sin δ	0.100	5	Viscoelastic continuum
2	Peak shear stress	0.100	5	damage (VECD)
3	Peak stored pseudo strain energy	0.100	5	Simplified viscoelastic
4	Peak stored pseudo strain energy and	0.100	5	continuum damage (S-VECD)
	G^R-N_f relationship (for fatigue life prediction)	0.050	10	
		0.033	15	

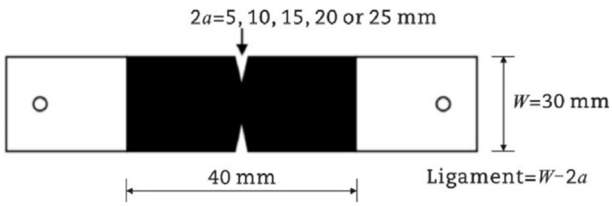


Fig. 11 – Schematic of a DENT specimen design (Andriescu et al., 2004).

property, independent of testing temperature and loading rate, as opposed to other binder properties such as stiffness, failure stress, and failure strain. Moreover, the BFE test successfully differentiated 1) unmodified binders from modified binders, and 2) elastomeric polymer-modified binders from non-elastomeric polymer-modified binders (Yan et al., 2015a, 2016). Furthermore, the FED was found to translate well from binder to mixture such as binders with higher FED resulted in higher mixture FED values, substantiates the use of binder FED to characterize binder cracking performance at intermediate temperatures (Yan et al., 2017).

2.1.4. *Summary and outlook*

In this section, the asphalt binder damage characterization, healing and aging behaviors were systematically reviewed to provide a fundamental understanding of pavement performance modeling. The characterizing approaches for binder healing as well as the various factors that impact the healing performance were briefly summarized. The asphalt binder aging mechanisms, simulation methods and application of anti-aging additives were significantly addressed. Finally, the recent progresses on binder damage modeling by means of damage and fracture mechanism principles were critically reviewed. It should be acknowledged that the binder self-healing potential itself during the loading rest periods and the aging process due to the environmental effects together contribute to a challenging target to reveal the dynamic damage evolution of field pavement materials. Therefore, a comprehensive damage modeling framework is expected to be established in the near future to cover both the material properties and environmental impacts from the asphalt binder scale.

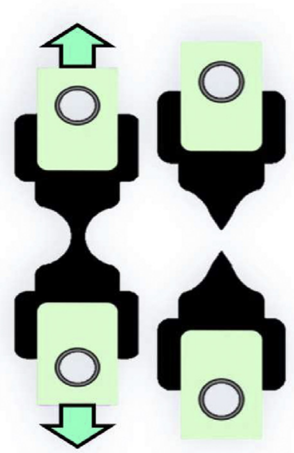


Fig. 12 – A specimen of the binder fracture energy test before and after fracture (Yan et al., 2017).

2.2. *Mechanism of asphalt modification*

The mechanism of asphalt modification has been a hot topic of research in the field of pavement materials engineering. Macroscopic performance tests (e.g., DSR, bending beam rheometer (BBR)) are able to reverse the effect of modifiers from the practical application point of view. Microscopic detecting methods (e.g., atomic force microscope (AFM), scanning electron microscope (SEM), fourier transform infrared spectroscopy (FTIR) can effectively observe the cross-linking relationship between asphalt and modifier. Numerical simulation techniques, represented by molecular dynamics (MD) methods, are able to elaborate the modification mechanism at the molecular level. In this section, the mechanisms of different modifiers in matrix asphalt will be analyzed from different research scales.

2.2.1. *Development of polymer modified asphalt*

The modification of asphalt binder has a long history. People started to modify natural asphalt binder by adding some natural rubber even the generation of refined asphalt binders (Isacsson and Lu, 1995)). After the second world war, synthetic polymers, such as polychloroprene, were widely employed for asphalt modification (Yildirim, 2007). The commonly used additives for asphalt modification can be divided into two categories, which are plastomers and thermoplastic elastomers. The commercial use of plastomers for asphalt modification can be dated back to 1960 (Utracki, 1995). The most widely used thermoplastic elastomers, SBS, was first developed and used for asphalt modification in the USA in 1965 (Holden, 1987). As a by-product of isotactic polypropylene (IPP) manufacturing, the atactic polypropylene (APP) was applied to improve the properties of roofing asphalt in Italy in 1967 (Johnson, 1987).

In the 1970s, researchers recognized that the addition of polymers could improve some performance of the modified asphalt, such as enhance permanent deformation resistance, improve cracking resistance and reduce moisture sensitivity (Lucas, 1976). Although the poor storage stability of the elastomers modified asphalt was reported, but the trial pavement section paved in 1976 was performed well (Chaffin et al., 1978).

With the development of the thin pavement layer in the 1980s, more and more scholars joined in the research of asphalt modification by polymers. Piazza and Verga (1980) studied the influence of plastomers and thermoplastic elastomers on the performance of modified asphalt. Kraus (1982) investigated the modification mechanism of modified asphalt by adding elastomers and revealed that the additive was swelled in the asphalt. Denning and Carswell (1983) reported a type of polyethylene (PE) modified asphalt used for asphalt wearing course, and also mentioned its drawbacks such as phase separation, higher manufacturing and compacting temperatures. Due to the performance enhancement of modified asphalt, Bowering (1984) claimed that the price increase of polymer modified asphalt might be outweighed by the thickness reduction and service life extension of asphalt pavement. In 1987, the implementation of the strategic highway research program (SHRP) promoted the development and popularization of polymer modified asphalt by establishing an evaluation system of asphalt performance based on rheological properties. Reese and Predoehl (1989) mentioned the good ageing and cracking resistance of polymer modified asphalt trial pavement section served after two years in California.

In the 1990s, many countries were involved in the investigation and utilization of polymer modified asphalt (Isacsson and Lu, 1995). Shin et al. (1996) characterized the mechanical performance, temperature sensitivity, thermal resistance, storage stability and ageing resistance of different polymer modified asphalt and revealed the advantages and disadvantages of different polymer modified asphalt. Stock and Arand (1993) concluded the improved properties of asphalt after polymer modification, and mentioned that the SBS modified asphalt behaved better elastic recovery, cracking resistance and rutting resistance. However, some drawbacks of SBS modified asphalt such as the thermal instability and phase separation have also attracted enough attention (Lu et al., 1999). Giavarini et al. (1996) investigated the influence of polyphosphoric acid (PPA) on the properties of polymer modified asphalt and found that the addition of PPA could improve the storage stability of polymer modified asphalt by changing the asphalt structure from sol to gel.

Over the last two decades, the polymer modified asphalt has experienced rapid development. The mechanism of polymer modified asphalt experienced deep research. Zhu et al. (2018b) investigated the microstructure of polymer-modified asphalt by using two-dimensional fast Fourier transform (2D-FFT), with the area fraction of polymer-rich phase was quantitatively evaluated and the phase separation process characterized. In addition, mechanisms of dynamic response, deformation resistance, cracking and fatigue of different polymer modified asphalt were investigated (González et al., 2016; Sengoz and Isikyakar, 2008). The performance of polymer modified asphalt was improved with some disadvantages overcome. There are many composite modified asphalt investigated by incorporating different modifiers to improve parameters such as high-temperature deformation, cracking resistance, ageing resistance and storage stability (Yao et al., 2018b; Zhang et al., 2018k; Zhu et al., 2014a).

2.2.1.1. *Strength formation of modified asphalt*. With the development of modified asphalt binder, more and more polymer products were used as additives to modify asphalt binder. Recently, the polymer products used for asphalt modification can be classified into two categories, which are plastomers and thermoplastic elastomers. Due to the limited elastic component of plastomers, the addition of them improved the modulus of related modified asphalt and has a positive effect on the permanent deformation resistance. However, asphalt binders modified by plastomers are prone to brittle failure and limited their use at low temperatures. With respect to thermoplastic elastomers, they can resist cracking by stretching under traffic or thermal load and are able to resist permanent deformation due to their elastic recovery behavior. Because of the above advantages, plastics are widely used to modify asphalt (Zhu et al., 2014a).

The most popular thermoplastic elastomers used for asphalt binder modification are SBS copolymers. SBS copolymers are composed of styrene-butadiene-styrene triblock chains with a biphasic morphology of rigid polystyrene (PS) domains (dispersed phase) in the flexible polybutadiene (PB) matrix (continuous phase), as shown in Fig. 13 (Zhu et al., 2014). Masson et al. (2003) revealed that once SBS polymer is incorporated into asphalt binder, PB blocks interact with positively charged groups through p-electrons and PS blocks interact with electron-rich groups through aromatic protons. The intermolecular interactions between asphalt and PB blocks are stronger than those with PS blocks. Airey (2003) reported that SBS copolymers absorb light components of asphalt, which resulted in the PS blocks swelling and the asphalt hardening. Once ideal dosages of SBS copolymers are mixed with asphalt binder, the modified asphalt binder can form a rubbery supporting network which in turn enhanced binder performance, such as increased complex modulus and viscosity, improved elastic response and cracking resistance (Chen et al., 2002).

As for plastomers, various polyolefin materials, such as high-density polyethylene (HDPE), low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE), were employed as additives to modify asphalt. Once polyolefin materials mixed with asphalt, they are normally swollen by absorbing light components of asphalt to form a biphasic structure (Pérez-Lepe et al., 2006). As the polyolefin reached to the ideal concentration, two interlocked continuous phases were formed in the modified asphalt and resulted in improved stiffness and rutting resistance (Polacco et al., 2005). Another category of plastomers used for asphalt binder modification are ethylene copolymers, such as Ethylene-vinyl acetate (EVA) and Ethylene-butyl acrylate (EBA) (Sengoz et al., 2009). The EVA has short branches of polar acetate groups, which reduced the crystallization degree and increased the polarity of the polymer, and is considered to be able to improve the storage stability of modified asphalt (Polacco et al., 2006). During modification, the light components of asphalt usually swell the EVA copolymers. With the increase of EVA dosage, the modified asphalt will form interlocked continuous phases and improve the asphalt properties to a large extent. It is noticed that, due to the plastomer nature of EVA, the asphalt binder modified by EVA seems difficult to result in obvious increase of elastic recovery (Isacsson and Lu, 1995).

2.2.1.2. *Modification mechanism by molecular dynamics simulation*. Modifiers are an important way to help improve the performance of asphalt. Typically, rheological indicators and asphalt mixture properties are direct or indirect methods of evaluating the value of modified asphalt for engineering applications. The advantage of this approach is that it is oriented towards engineering applications and is more relevant to real needs. However, macroscopic test methods suffer from

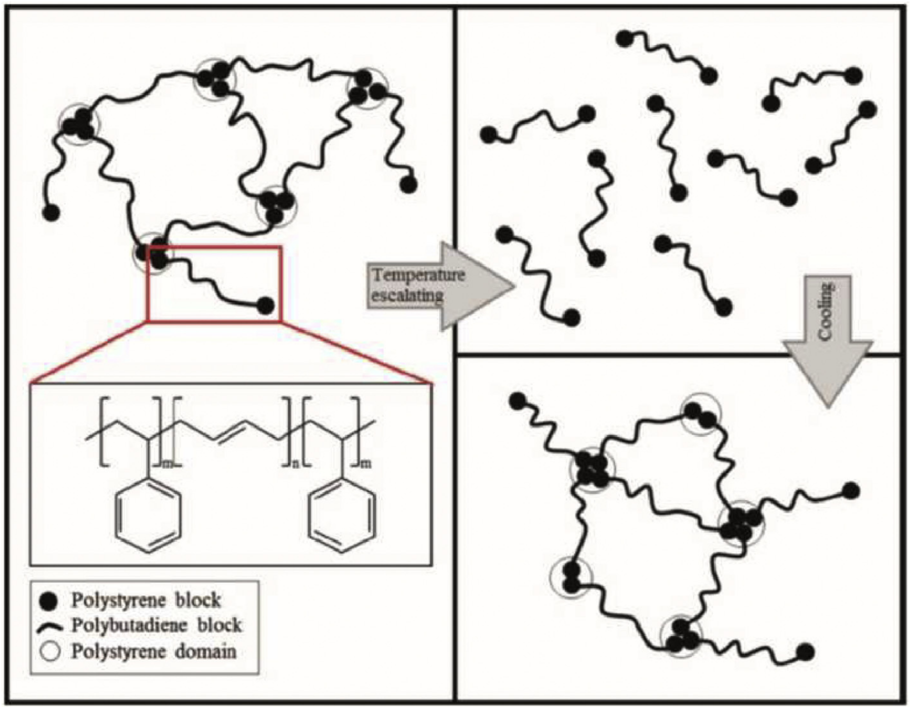


Fig. 13 – Structure of SBS and schematic illustration of reversible crosslinks in SBS (Zhu et al., 2014a).

the general shortcoming of not being able to explain the principles by which the modifier exerts its positive effect. As a research method on the atomic scale, MD simulations have become an important method to remedy the aforementioned shortcomings.

The modifiers were constructed and investigate in MD simulations, such as polymers (SBS, SBR) (Ding et al., 2015; Sun et al., 2016), carbon nanomaterials (Yao et al., 2017, 2018a), nano-oxides (Long et al., 2021; Su et al., 2020b), rejuvenators (Ding et al., 2016, 2021), and paraffin (Qu et al., 2018b). Based on MD simulations, solubility parameters (shown in Eq. (6)) and interaction energy (shown in Eq. (7)) indicators are proposed as a basis for evaluating the compatibility between the modifier and matrix asphalt. Guo et al. (2020b) evaluated the compatibility stability of rubber-modified asphalt by solubility parameter at different rubber contents. Using the same evaluation index, Ren et al. (2020a) analysed the compatibility of phase change microcapsules (melamine formaldehyde) with asphalt components and investigated the effect of temperature and content on their compatibility stability. Expanded by the adhesion work calculation method, Long et al. (2021) used the interaction energy to evaluate the interaction strength between matrix asphalt and nanosilica to reflect the compatibility.

$$\delta = \sqrt{\mathrm{CED}} \tag{6}$$

where CED is the cohesive energy density.

$$E_{\mathrm{interaction}} = E_{\mathrm{total}} - \left(E_{\mathrm{asphalt}} + E_{\mathrm{modifier}}\right) \tag{7}$$

where $E_{\mathrm{interaction}}$ is the interaction energy of asphalt and modifiers, E_{total} is the total potential energy of asphalt and modifiers, E_{asphalt} and E_{modifier} are the potential energy of asphalt and modifiers, respectively.

2.2.1.3. The relationship between microstructure and properties of asphalt. Studies have shown that properties of asphalt are related to the microstructure which includes element composition, functional group distribution and microstructure phase state (Barré et al., 2009; Delgadillo et al., 2006; Redelius and Soenen, 2015). However, limited effective conclusions on the relationship between the microstructure and the properties of asphalt were drawn by experimental methods due to the complexity of asphalt component composition.

Molecular dynamics (MD) simulation has been introduced into the study of asphalt because it can connect microscopic dynamics to macroscopic properties. MD simulation was conducted for investigations on asphaltene molecular motion and accumulation characteristics (Greenfield, 2011), the interaction between polymer modifiers and asphalt (Cao et al., 2021; Tang et al., 2014), the effect of regenerant on asphalt microstructure (Wang et al., 2013), the analysis of microstructure phase composition of asphalt honeycomb structure (Wang et al., 2016a), the compatibility of modifier and asphalt (Lyu et al., 2017a; Yuan et al., 2019), thermodynamic properties of asphalt (Qiu et al., 2020a, b; Qu et al., 2018a) and so on.

Study on MD simulation focuses on molecular structure and intermolecular action of asphalt that has been widely applied to the investigation of various microscopic mechanism. However, current MD simulation technology cannot reach a full understanding of the relationship between the microstructure and macroscopic properties of asphalt. This is expected as asphalt microstructure is simplified to a certain extent by MD simulation so that the simulation results cannot use the existing conventional experimental methods for accuracy verification. On the other hand, although asphalt model composed of 12 types of molecules have been proposed (Li and Greenfield, 2014a), the molecular number of the current model still cannot reach the scale of forming a represented asphalt molecular system.

2.2.2. *Application of the MD simulation*

The molecular structure and motion can be effectively investigated by molecular dynamics (MD) simulation. Therefore, MD simulation was applied to evaluate the physical and chemical properties of asphalt. The asphalt molecular model widely adopted has been proposed in recent years, which laid the foundation for the research of asphalt MD system (Zhang and Greenfield, 2007b, 2007c, 2010). Currently, the application of MD in the research of asphalt mainly focuses on asphalt modification mechanism (Cao et al., 2021; Su et al., 2020b), adhesion (Xu and Wang, 2016a, b), rejuvenation and diffusion (Zadshir et al., 2018), aging mechanism (Ding et al., 2019a; Xu and Wang, 2017), self-healing (He et al., 2020) and so on.

2.2.2.1. Molecular model of asphalt. For the construction of asphalt molecular models, the main design methods include the asphalt average molecular models and multi-components asphalt models from previous literature.

The average molecular model of asphalt is based on nuclear magnetic resonance (NMR), FTIR and E-M-D methods to obtain the average structure of asphalt molecules and to establish a molecular model (Wang et al., 2020d). Jennings et al. (1993) proposed 8 average molecular structures with the help of NMR. Pauli et al. (2005) supported the reliability of the SHRP average molecular model in terms of density, refractive index and surface tension. Cong et al. (2005, 2007) used the E-M-D method to study the molecular structure of Liaoshu asphalt and constructed the corresponding average molecular model to simulate the process of SBS-modified asphalt; Sun et al. (2018b) established four types of average molecular structure models of asphalt (represent PEN 20, 50, 70, and 100), which were used to investigate the self-heal mechanism of asphalt. Their results showed that the healing process of asphalt is closely related to temperature, and that asphalt in the optimum temperature range has the fastest healing rate. Gong et al. (2021) also used average molecular models to investigate the change in adhesion strength at the asphalt/aggregate interface under the combined effect of temperature-moisture, as shown in Fig. 14.

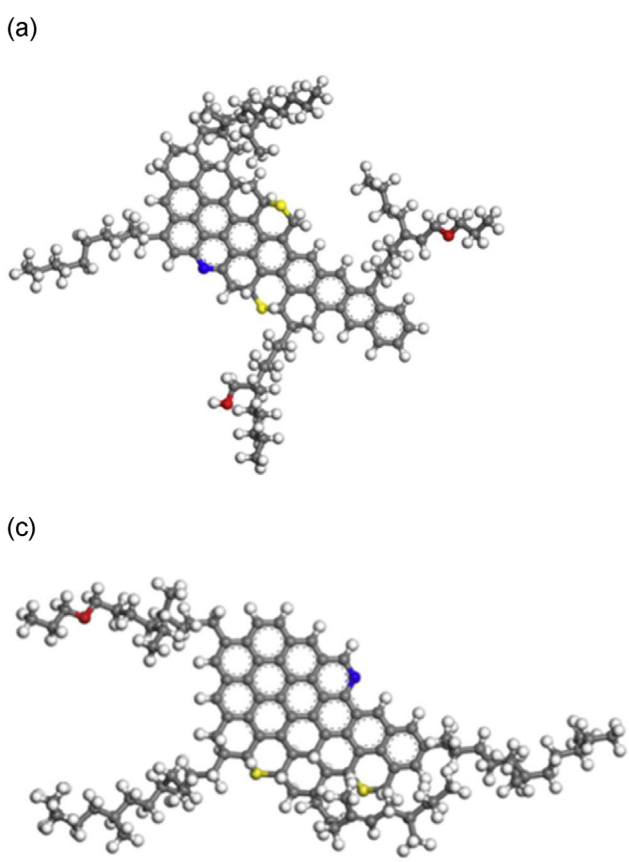


Fig. 14 – Average molecular model of asphalt. (a) Represent PEN 50. (b) Represent PEN 70. (c) Represent PEN 90 (Gong et al., 2021).

The advantages of this simulation approach are that the virtual models correlate well with the real molecules of asphalt, and the elemental composition fits well. However, the structures of molecular models are significantly different from the real situation Information on the interaction between different components (e.g., asphaltenes, resin, etc.) were not available. Therefore, in order to better demonstrate the interactions between the various components of asphalt and to reflect the diversity within the molecular structure of asphalt, the multi-components asphalt models have emerged as the most commonly used simulation approach today. The multi-components asphalt models based on three-fractions or four-fractions (SARA method) has been proposed. In the basis of SARA fractions, the asphalt is divided into saturate, aromatic, resin and asphaltene. For each fraction, the appropriate molecular structures are constructed based on the results of the chemical analysis. The multi-components asphalt models constructed by three-fractions method is a simplified treatment of the previous description. This route can speed up the simulation process. However, it is inferior to the aforementioned method in terms of simulation reliability and extrapolation of results.

For asphalt, asphaltene is the larger relative molecular weight and more polar component of the entire asphalt molecules. However, the internal molecular structure of asphaltenes is extremely complex, and it is impossible to completely and accurately portray the molecular structure of asphaltenes by means of an asphaltene molecular structure model (Rogel, 1995). Therefore, a suitable simplification of the asphaltene molecular structure is an important way to accelerate the simulation progress, while satisfying the required simulation accuracy.

Dozens of asphaltene molecular models have been proposed. These asphaltene molecular models can be divided into two main categories: condensed aromatic cluster models and bridged aromatic models. The condensed aromatic cluster model was mainly obtained by Groenzin and Mullins (2000) based on spectroscopic results. This molecular structure assumes that the asphaltene center is linked by a cluster of benzene rings and saturated side chains surround it. Rogel (1995, 2000), Rogel and Carbognani (2003), Storm et al. (1994), Takanohashi et al. (2003a, b), Mullins (2010), and Li and Greenfield (2011, 2014a, 2014b) have also adopted this approach of asphaltene construction. There are then relevant thermal decomposition reaction results that do not match such models, and in particular, the mass evolution patterns of volatiles are not consistent. Speight and Dekker (1991) and Murgich et al. (1999) proposed a bridged aromatic model based on the results of thermal decomposition and oxidation. This kind model is based on multiple dispersed and low molecular weight aromatic core components connected to each other by the reaction bridge. Wiehe (1994) used the same chemical structure to describe asphaltenes in residues. Artok et al. (1999) constructed a similar bridged asphaltene model.

Although the constructed asphalt molecular structure is closer to the real structure in terms of elemental ratio, chemical bonding and other indicators, the real reliability of the asphalt molecule is still one of the research issues that needs to be paid attention to.

Continuously twisted side chains interact with the benzene ring structure, which in turn generates repulsive dispersion forces. Thus, the pentane effect was proposed by Li and Greenfield (2014a). On the basis of Mullins (2010), Li and Greenfield (2014a) shifted the position of the side chains to achieve the goal of reducing the internal energy of the molecular structure.

The work of Li and Greenfield (2011, 2014a) was to resolve the pentane effect presented in the asphalt molecular structure, avoiding non-normal high energy structures. The electronic arrangement of the FAR region of the molecule was then not fully optimized (Martín-Martínez et al., 2015). In particular, for the formation of asphaltene nano-stacking, electronic alignment optimization is crucial. Martín-Martínez et al. (2015) completed the optimization of the π-electron arrangement in the core of polycyclic aromatic hydrocarbons (PAHs) and the minimization of geometric strain within the asphaltene structure.

Compared to the asphaltene fraction, other fractions (e.g., resin, saturate, aromatic, etc.), are screened using molecular structures with a considerable degree of concentration. In earlier studies, the non-asphaltene fractions of the asphalt model did not strictly follow SARA theory. Three-components asphalt models, which are consisted of asphaltene, resin, and maltene (or saturate), constructed by Zhang and Greenfield (2007a, b). 1, 7-dimethylnaphthalene and liner n-C_{22} are chosen to represent resin and saturate, as shown in Fig. 15.

In the simulation studies published in recent years, many researchers have postulated the polar aromatics and naphthene aromatics molecules in Li and Greenfield (2014a) study as resin and aromatic fractions in SARA theory, respectively (Ding et al., 2021; Du et al., 2021c; Long et al., 2021; Xu et al., 2021c; Yang et al., 2021c). Wang et al. (2015), Zhang and Greenfield (2007b, 2010) screened different structures of saturate, aromatic and resin fractions from various oil sources. Ding et al. (2018) construction of four different resin structures contained heteroatoms (i.e., resin-N, resin-S, resin-1, resin-2).

2.2.2.2. *Molecular configuration of asphalt*. A large number of aromatic rings result in the molecular aggregation, which makes molecules prone to form a colloidal structure for asphalt (Pacheco-Sánchez et al., 2004). Currently, some conclusions have been drawn on the morphology of asphalt molecular aggregation (Canny, 1986; Zanganeh et al., 2012). Researchers have introduced the MD simulation method into the evaluation of the characteristics of the intermolecular aggregation state of asphalt and each component with radial distribution function. The results showed that the variation of aggregation state was affected by π-π effect, temperature, and the intermolecular distance (Tang et al., 2013). The aggregation structure formed due to the parallel stacking of molecules which contains aromatic ring structure allows π-π interaction to happen between asphaltene molecules, while the heteroatomic functional group forms the hydrogen bond between molecules. Therefore, asphaltene tends to form supramolecular aggregates as for aromatic ring stacking effect and hydrogen bonding.

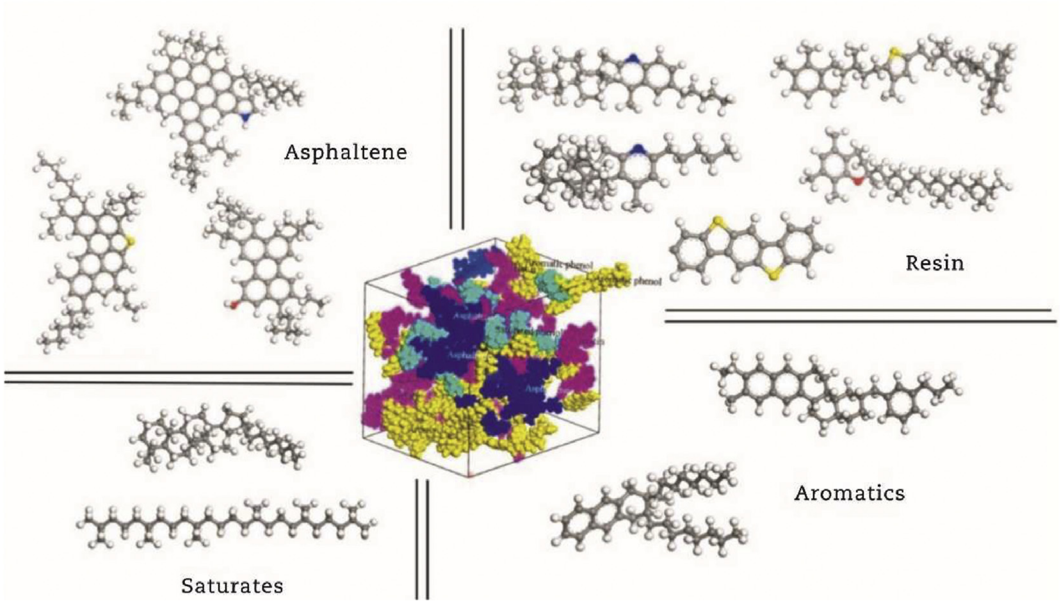


Fig. 15 – 12-components model of asphalt (Huang et al., 2019; Li and Greenfield, 2014a).

Asphaltene molecules are prone to form aggregate structure in the solution due to the interactions between molecules, including Van der Waal, π-π accumulation, hydrogen-bonding interaction, charge transfer, acid-base and electrostatic interaction (Gray et al., 2011; Murgich, 2002). The aggregation of asphalt molecules can be investigated by both theoretical simulation and experimental methods. The MD simulation method was used to explore the factors affecting the formation of asphaltene molecular aggregates from variations on molecular configuration and energy as well as electron distribution, so as to explore the effect of intermolecular interaction on the aggregation state of asphaltene molecules (Cai et al., 2019; Ren et al., 2019). Molecular dynamics (Juyal et al., 2005) and the combination with quantum mechanics (Ren et al., 2019) were applied to investigate the nature of intermolecular interactions.

Although relevant research has been carried out, there are still no widely acceptable conclusions on the decisive factors of asphalt molecular aggregation. Some researchers suggest that π-π stacking is the first motivation for the aggregation of asphaltene molecules (Dickie and Yen, 2002). However, some researchers also conclude that the aggregation structure is formed due to the joint effect of π-π stacking and hydrogen bond between heteroatomic functional groups (Juyal et al., 2005), or by the polymerization reaction, acid-base interaction, electrostatic interaction and other effects (Al-Sahhaf et al., 2002; Junior et al., 2006). MD simulation was also applied to explore the formation and dissociation of asphaltene molecular aggregation (Cai et al., 2020), as shown in Fig. 16.

2.2.2.3. *Self-healing behaviour*. Self-healing is essentially a process of molecular diffusion, which can spontaneously heal the internal micro-cracks and restore fatigue damage for asphalt. Researchers suggest that there is a correlation between the chemical structure of asphalt and the self-healing property of asphalt. Bhasin et al. (2011a) introduced MD simulation into the analysis of asphalt self-healing mechanism, in which the self-healing process occurred at the interface of crack was quantified using a self-diffusion coefficient determined by creating the molecular cracking model of asphalt. The feasibility of using molecular simulation to investigate the relationship among molecular characteristics, self-healing mechanism and molecular diffusion parameters was explored. He et al. (2020) introduced a four-component model into the study of self-healing property of asphalt, concluding that the compression of asphalt volume and the stretching of the asphalt molecules are responsible for the disappearance of vacuum micro-cracks inside the asphalt model. The diffusion coefficient of asphaltene molecules is the lowest in the self-healing process, and the diffusion coefficient of the saturated molecules is the highest.

The influencing factors of self-healing performance of asphalt binder can be divided into internal and external conditions. In terms of internal factors, the influence of polymer modifiers, such as crumb rubber modifier (CRM) and rejuvenator, on the self-healing property of asphalt was investigated by using MD simulation method. Hu et al. (2020a) calculated the thermodynamic parameters of crumb rubber modified asphalt (CRMA) using a four components model, which concludes that the self-healing capability of CRMA decreases as the rubber content increases. Gao and Liu (2019) used Wool-O'Connor model to calculate the influence of bio-oil on the self-healing property of asphalt to explore the best healing temperature and time of bio-oil recycled asphalt.

In terms of external factors, the influence of factors including temperature and cracking width on the self-healing

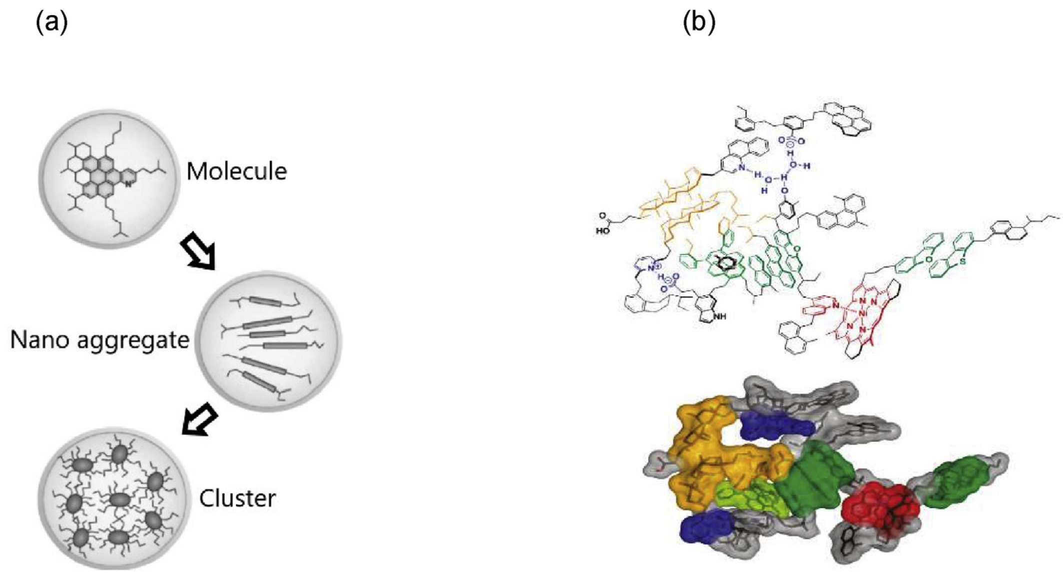


Fig. 16 – Asphalt micro-structure. (a) Yen-Mullins model. (b) Gray model.

performance of asphalt was studied by MD simulation. Sun et al. (2018b) combined MD simulation with differential scanning calorimeter (DSC) test to investigate the influence of temperature on the self-healing property of four asphalt binders. High temperature is conducive to self-diffusion process of the binder and provides energy for rapid molecular motion. The self-healing capability of asphalt is improved in phase transition (PT) temperature. Shen et al. (2016) developed asphalt model with different cracking width to explore the variation of the self-healing behavior with time which concludes that the cracking width is the key factor affecting the self-healing ability of asphalt. The self-healing test under different conditions is summanized in Table 9.

2.2.2.4. *Aging mechanism*. The ageing of asphalt is an important factor influencing the long-term durability of pavement in service. Neither precise chemical analysis, nor macroscopic mechanical testing can explain the microscopic mechanisms of asphalt ageing. MD simulations are a good combination of the two, inheriting the accuracy of instrumental analysis and correlating it with macroscopic mechanical tests, while at the same time being cost-effective (Editorial Department of China Journal of Highway and Transport, 2020).

As far as the available literature is concerned, MD simulations are mainly focused on the category of thermal-oxidative ageing. The mainstream thermal-oxidative ageing asphalt models can be characterized in two approaches, one by adjusting the specific weight ratio of the asphaltene fraction (Ding et al., 2016) to approximately match the heavy asphaltene content of the real ageing asphalt (Table 10). However, such ageing simulations fail to take into account the transformation of functional groups and the volatilization of lighter components during ageing process. Therefore, Yao et al. (2017), Xu and Wang (2017) and Qu

Table 9 – Summary of self-healing test under different conditions.

Reference	Measure of self-healing capability	The effect of different factors
He et al., 2020	Wetting time, work of cohesion and diffusivity	The self-healing capability of asphalt binder decreases as the rubber content increases.
Gao and Liu, 2019	Wool-O'Connor model $I(T,t) = I_0 + K\exp\left(-\frac{E_a}{RT}\right)t^{0.25}$	The best healing temperature and time of BRA: 60 °C, 30 min.
Sun et al., 2018b	$HI = \frac{\lvert G^*\rvert_{healing} - \lvert G^*\rvert_{terminal}}{\lvert G^*\rvert_{initial} - \lvert G^*\rvert_{terminal}}$	The optimal healing temperature: 40.3 °C–48.7 °C.
Shen et al., 2016	The mean square displacement (MSD)	Higher temperature results in higher diffusivity of molecules and higher healing rate, and asphalt heals faster when the width of crack is smaller.

Table 10 – The fractions weight ratio of aged asphalt (%).

Reference	Asphaltene	Resin	Saturate	Aromatic
Pan et al., 2016	16.90	31.10	9.90	38.00
Xu and Wang, 2017	17.70	39.60	10.30	32.40
Xu and Wang, 2017; Xu et al., 2019a (short-term aged)	15.20	29.60	17.20	38.00
Xu and Wang, 2017; Xu et al., 2019a (long-term aged)	17.80	41.30	13.00	27.90
Qu et al., 2018a (short-term aged)	17.87/20.71	33.98/40.18	13.45/11.63	34.69/27.48
Qu et al., 2018a (long-term aged)	21.58/22.85	14.85/14.06	33.35/32.20	30.22/30.89
Xu et al., 2018	16.94	37.98	9.90	31.08
Sun and Wang, 2019 (short-term aged)	17.20	40.80	10.70	31.30
Sun and Wang, 2019 (long-term aged)	17.70	39.60	10.30	32.40
Ding et al., 2021	23.60	29.30	14.50	32.60
Long et al., 2021	17.10	41.40	10.00	31.50

et al. (2018) used an alternative oxidation modeling approach based on the results of the chemical analysis of the functional groups of aged asphalt, i.e., artificially modified or added aged functional groups (e.g., sulfoxide groups, ketone groups, etc.) at chemical sites prone to oxidation (Pan and Tarefder, 2016). Based on the aforementioned ageing asphalt construction, Fallaha et al. (2019) focused on the construction of a molecular model of asphalt under PAV ageing conditions and evaluated the model in terms of density, bulk modulus, viscosity and glass transition temperature. Xu and Wang (2017) investigated the effect of ageing behavior on the adhesion of asphalt. Qu et al. (2018) combined the molecular model of asphalt in different ageing states to reveal the microscopic mechanism of ageing leading to hardening. Ding et al. (2021) investigated the blending of virgin-aged asphalt by bio-rejuvenators.

2.2.2.5. *Adhesion mechanism*. The adhesion mechanism between asphalt and aggregate has been an research area where MD simulation and pavement engineering have been cross applied. The ageing state of the asphalt, the atomic arrangement of the aggregate surface, moisture and temperature are all important factors influencing the adhesion strength. Recent research has shown that surface energy, microscopic work of adhesion and stress curves are the main calculations used to evaluate microscopic adhesion strength.

Theoretically, surface free energy is defined as the energy required to create a new surface of a material. The essence of surface energy is the breaking of chemical bonds and the optimal arrangement of atoms on the surface. The application of surface free energy is mainly focused on the state transition of asphalt. In fact, the surface free energy of aggregates is also a factor influencing adhesion. From the point of view of the contact surface, the surface free energy is the basis for the evaluation of interfacial compatibility in asphalt-aggregate systems (Bhasin et al., 2007). Eq. (8) is used to calculate the surface free energy of the asphalt system (Cui et al., 2020a; Wu et al., 2020b; Xu and Wang, 2016b). The transition from the bulk system to the confined system of the asphalt system is used for the calculation of the surface free energy.

$$\gamma_a = \frac{E_{film} - E_{bulk}}{2A} \quad (8)$$

where γ_a is surface free energy, E_{film} and E_{bulk} are the potential energy of the confined asphalt layer and bulk asphalt, respectively, A is the contact area of asphalt-aggregate.

The adhesion work is a direct indicator and method for investigating the adhesion of asphalt. In essence, it is a measure method of energy required to remove the asphalt from the aggregate surface. High adhesion work at the asphalt-aggregate interface indicates good adhesion of asphalt and good durability of the asphalt mixture. The work of adhesion is usually calculated by Eqs. (8)–(10) (Cui et al., 2020a; Ding et al., 2020; Gong et al., 2021; Liu et al., 2020d; Long et al., 2020; Luo et al., 2020; Sun and Wang, 2020a; Xu and Wang, 2016b; Xu et al., 2020b, 2021c) . It is important to note that a negative value of the work of adhesion does not mean that the asphalt is less adherent. Absolute values should be used as the basis for adhesion analysis. Moisture is a major factor to water damage in asphalt pavements. Moisture is incorporated into Eqs. (9) and (10) and is rewritten as Eq. (11) (Cui et al., 2020a; Gao et al., 2018b; Liu et al., 2020d; Long et al., 2020; Luo et al., 2020; Sun and Wang, 2020a; Xu and Wang, 2016b; Xu et al., 2020b, 2021c). The energy changes on the moisture-asphalt contact surface and on the moisture-aggregate surface must be taken into account (ΔE_{inter_aw} and ΔE_{inter_agw} in Eq. (11)). This is the main reason for the reduction in interfacial adhesion strength. Gong et al. (2021) evaluated directly the decrease in adhesion due to moisture in terms of the adhesion degradation ratio ($D_{adhesion}$ in Eq. (12)). The interfacial stress curve is direct evidence of the dynamic adhesion of the asphalt. As the asphalt is stretched, a peak in interfacial stress is recorded (i.e., the maximum adhesion strength). The maximum adhesion strength is the most important parameter obtained from the asphalt dynamic peeling process. A strongly adherent asphalt necessarily has a higher maximum adhesion strength. In the MD simulation, the interfacial stress is calculated in each frame (based on Eq. (13)) (Ramezani and Rickgauer, 2020; Shishehbor et al., 2018; Wang et al., 2017).

$$W_{adhesion} = \frac{\Delta E_{inter\_aag}}{A} \quad (9)$$

$$\Delta E_{inter\_aag} = E_{total} - \left(E_{asp} + E_{agg}\right) \quad (10)$$

where $W_{adhesion}$ is the work of adhesion when asphalt is separated from aggregate surface, ΔE_{inter_aag} is the potential energy of asphalt-aggregate interface, E_{total} is the potential energy of asphalt-aggregate system, E_{asp} and E_{agg} are the potential energy of individual asphalt and individual aggregate surface, respectively.

$$W_{debonding\_water} = \frac{\Delta E_{inter\_aw} + \Delta E_{inter\_agw} - \Delta E_{inter\_aag}}{A} \tag{11}$$

where $W_{debonding\_water}$ is the work of adhesion in asphalt-aggregate interface considering the effect of moisture intrusion, E_{inter_aw} is the potential energy of asphalt-water system, E_{inter_agw} and E_{inter_aag} are the potential energy of aggregate-water system and asphalt-aggregate system, respectively.

$$D_{adhesion} = \frac{W_{adhesion\text{-}dry} - W_{adhesion\text{-}wet}}{W_{adhesion\text{-}dry}} \tag{12}$$

where $D_{adhesion}$ is the debonding ratio of adhesion strength by the effect of moisture, $W_{adhesion\text{-}dry}$ is the work of adhesion in asphalt-aggregate system without moisture, $W_{adhesion\text{-}wet}$ is the work of adhesion in asphalt-aggregate system after moisture intrusion into the interface.

$$\sigma_{adhesion} = \frac{F}{A} \tag{13}$$

where $\sigma_{adhesion}$ is the interface stress of asphalt and aggregate surface, F is the vertical traction force.

2.2.2.6. Diffusion behaviour. Diffusion is a microscopic and slow dynamic process, which is difficult to be characterized by experimental methods. MD simulations provide capability to investigate the diffusion behavior of asphalt since MD simulation method focuses on the basic forces between molecules, which can describe the motion of molecules under the action of force field and electric field. It was found that oxidative aging affects the thermodynamic properties of asphalt, and the rejuvenator could restore the properties of aged asphalt to a certain level (Xu and Wang, 2018). The effects of three modifiers (one petroleum-based and two bio-based) on the properties of an aged asphalt were investigated by both experimental and simulation methods, which shows that the rejuvenators can effectively reduce the viscosity and stiffness of aged asphalt (Zadshir et al., 2018).

The influence of solubility parameters and interaction energy of aged asphalt on the diffusion rate were analyzed by MD simulation. Research indicates that aromatics can promote the compatibility between virgin and aged asphalt (Zhang et al., 2010a, b, c). Sun and Wang (2020b) found that the diffusion coefficient is affected by the chemical structure of rejuvenator. The diffusion rate of naphthenic aromatic hydrocarbon is larger than that of saturated rejuvenators.

The factors including aging degree, grade, porosity and temperature can influence the diffusion behavior of asphalt and rejuvenator. MD simulation was used to calculate the diffusion coefficient of rejuvenator in asphalt with different aging degrees, which found that rejuvenators have a larger diffusion coefficient in a long-term aged asphalt and a lower diffusion coefficient in a short-term aged asphalt (Xiao et al., 2017a,b). The diffusion coefficient based on MD simulation shows that the diffusion coefficient increases gradually with temperature. However, the increase of diffusion coefficient gradually tends to flatten when the temperature reaches a certain level due to the volatilization of rejuvenator (Cui et al., 2020a).

MD simulation can establish the layered models of virgin and aged asphalt to analyze the diffusion behavior by calculating the diffusion coefficient of two asphalts. The diffusion coefficient of binders is not only determined by the diffusion ability itself, but also influenced by the properties of the diffusion acceptor for an inter-diffusion model of virgin and aged binders (Ding et al., 2016).

The double-layered mutual diffusion system was applied to study the relationship between the regenerators and the diffusion of virgin and aged asphalt. The regulation effect of rejuvenators on the compatibility of aged and virgin asphalt was further analyzed using a mutual-diffusion coefficients. In the absence of rejuvenators, the mixing process of virgin and aged asphalt is slow due to the self-aggregation of aged asphaltene. The miscible effect is remarkably boosted when rejuvenators are incorporated to the inter-diffusion system, and the diffusion coefficient of each component has been considerably improved (Liu et al., 2021c). The radial distribution functions of asphaltene, resin, and aromatic pairs show that the diffusion of rejuvenator promotes the molecular structures of aged asphalt more similar to that of virgin asphalt (Xu and Wang, 2018), as shown in Fig. 17 and Table 11.

2.2.3. *Summary and outlook*

Refinement of the asphalt-aggregate interface model continues to be the focus of research in molecular dynamics simulation. The failure mechanism of interfacial adhesion of asphalt-aggregate is analyzed under the coupling of environmental factors such as moisture and temperature. In addition, the effect of traffic loading can be incorporated into the interfacial adhesion model to establish the microscopic adhesion failure process with the effect of loading.

Based on the results of the chemical analysis, the proportion of SARA fractions in MD simulation is optimized. Structural optimization of existing asphalt molecules in combination with quantum mechanics methods is the basis for subsequent MD simulation applications. A reasonable asphalt molecular structure, whether it is the average molecular model or multi-components molecular models, should be consistent with the real asphalt in terms of physical or chemical indicators.

The diffusion coefficient is a central indicator in the investigation of asphalt self-healing and rejuvenator diffusivity. In fact, molecular dynamics simulation system for asphalt self-healing that includes the coupling of microscopic cracking, moisture, temperature and regenerant is the next step in this research.

2.3. *Modeling and application of crumb rubber modified asphalt*

Recycling end-of-life tire rubber as asphalt modifier is known as a sustainable paving technology with merits including enhanced pavement durability, waste tire consumption and noise reduction. The waste tires, from either passenger cars or

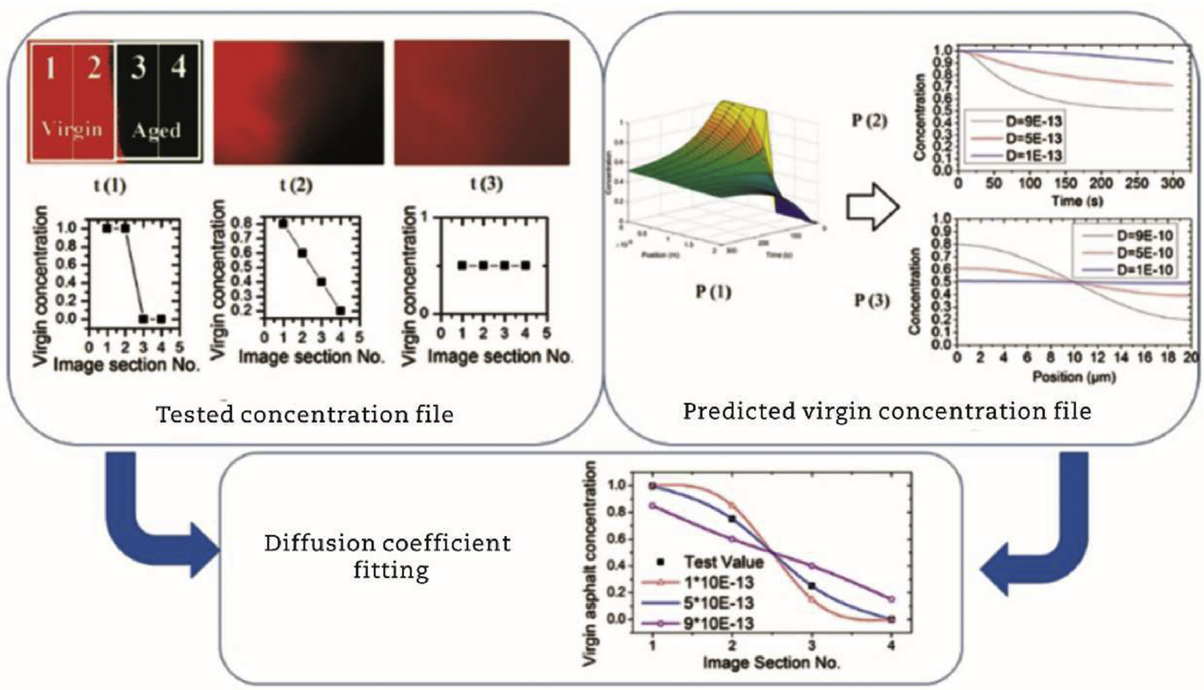


Fig. 17 – Diffusion coefficient calculation of asphalt.

trucks, are shredded into small particles, which are labeled as crumb rubber modifier (CRM) in pavement engineering field. To incorporate CRM into asphalt mixtures, two major processes have been developed, namely the dry process and the wet process. The dry process defines method that adds CRM directly into asphalt mixture to replace part of aggregates or fillers while the wet process refers to the method that modifies asphalt with CRM first, making the modified binder well blended and then mix with aggregates and mineral fillers. In recent decades, successful application of rubberized asphalt pavement, with either dry or wet process, have been reported in different countries and regions. In this section, the recent

Table 11 – Summary of diffusion test under different conditions.

Reference	Research object	Effect of different factors
Xu et al., 2018b	Rejuvenator and RAP binder	Restore thermodynamic properties to those of virgin binder to a certain extent.
Zadshir et al., 2018	Three modifiers (petroleum-based and bio-based) and oxidized asphalt binder	Reduce large molecular size ratio of asphalt.
Zhang and Greenfield, 2010	Rejuvenator components and aged asphalt	The higher the content of aromatics, the better the improvement effect.
Sun et al., 2020b	Four types of rejuvenators (straight saturate, cyclic saturate, naphthene aromatic, polar aromatic) and aged asphalt	Long-term aging had a negative impact. Polar aromatic performs the worst for diffusivity. Naphthene aromatic achieves superior diffusion ability.
Xiao et al., 2017a,b	Two rejuvenators (R-1, R-2) and aged asphalt	Rejuvenator diffuses faster in the long-term aged binder, diffuse slower in the short-term aged bitumen binder. Presents greater ability at lower temperatures.
Cui et al., 2020a	Rejuvenator and water aged asphalt/ultraviolet aged asphalt	Diffusion rate decreased with time. Diffusion speed of aromatic phenol is the fastest.
Ding et al., 2016	Virgin and aged binder	Diffusion rate increase with molecular weight. Influence of temperature is larger than resin and oil. Adding rejuvenator first could accelerate the diffusion.
Xu and Wang, 2018	Rejuvenator and virgin/aged asphalt binder	Rejuvenator diffuses faster into virgin asphalt, improve blending efficiency depending on temperature and causes the structures more similar to virgin asphalt.

developments of crumb rubber modified asphalt in various aspects, including modeling and mechanism, mix design, engineering performance, economic and environmental effects are summarized.

2.3.1. *Modeling and mechanism of rubberized asphalt*

Asphalt binder (bitumen) is a complex viscoelastic material that is commonly used in the construction of flexible pavements. Morphologically, asphalt is a colloidal system made up of asphaltene micelles with high and low molecular weight components such as resins, saturates, and aromatics. Owing to its viscoelastic nature, asphalt behaves differently under various traffic loading and environmental conditions. Thus, the analyses and design of these materials necessitate comprehensive understanding of the materials' innate behavior under various performance conditions.

Historically, asphalt modification has been a commonly employed technique to reduce the viscosity-temperature susceptibility, which is considered one of the major performance issues in asphalt. Also, asphalt modification improves binders' resistance to rutting, fatigue, and fracture problems. In general, modifiers are mainly natural and synthetic polymer additives, of which crumb rubber (CR) has gained positive interest in utilization because of the better performance of the crumb rubber modified asphalt (CRMA) in comparison with the virgin asphalt. The superior performance of CRMA is mainly attributed to the interaction between asphalt and rubber. Depending on different mixing temperature, time and rate, etc., asphalt-rubber interaction generally consists of two mechanisms: 1) rubber swelling in asphalt matrix due to the absorption of the light fractions of asphalt; and 2) rubber degradation through chain disentanglement and chain scission reactions (Wang et al., 2020a). The raw material parameters (e.g., the nature of asphalt and rubber) (Willis et al., 2013) were also reported to significantly influence the interaction process of rubber in asphalt and hence the physical and mechanical properties of CRMA.

2.3.1.1. *Rheology of bituminous binders*. Rheology is the branch of physics in which we study the way in which materials deform or flow in response to applied forces or stresses. The material properties that govern the specific way in which these deformation or flow behaviors occur are called rheological properties. The rheology of asphalt can be broadly defined as the fundamental measurements associated with the flow and deformation characteristics of the material, with considerable research having been undertaken over the last five decades in studying the rheology of asphalt and asphalt.

The rheological properties of asphalt depend on the chemistry of asphalt and modification if any. More importantly, understanding the flow and deformation (rheological properties) of asphalt in an asphalt is important in terms of pavement performance. Asphalt that deforms and flows too readily may be susceptible to rutting and bleeding, while those that are too stiff may be exposed to fatigue and cracking. Fig. 18 demonstrates the importance of the linear viscoelastic (LVE) rheological properties of bituminous materials. Measuring linear viscoelastic properties helps us bridge the gap between molecular structure and product performance. Nowadays, the LVE rheological properties of asphalt are usually determined using an oscillatory type testing apparatus known as a rheometer. The rheometer is a very powerful tool used to determine the elastic, viscoelastic and viscous properties of asphalt over a wide range of temperatures and frequencies.

Fig. 18 – Importance of LVE properties.

The LVE rheological properties of asphalt are normally presented by viscosity, or in the form complex modulus (G^*) and phase angle (δ). $|G^*|$ by definition is the ratio of maximum (shear) stress to maximum strain when subjected to shear loading. Meanwhile, δ is the phase difference between stress and strain in harmonic oscillation. If δ equals 90°, asphalt can be considered to be purely viscous in nature, whereas δ of 0° corresponds to a purely elastic behavior. Between these two extremes, the material behavior can be considered to be viscoelastic in nature with a combination of viscous and elastic responses.

2.3.1.2. *Rheological property prediction of CRMA*. A thorough understanding of the interaction conditions and raw material characteristics will guide the material selection and process optimization to obtain the desired binder properties from the modification. One of the vital questions that needs to be answered is how to effectively predict the performance of modified binders instead of carrying out tedious laboratory work. Numerical and analytical models are often used to accomplish this goal. Although considerable work has been done to measure and even predict empirical and fundamental properties of CRMA, very little work has been reported in which rigorous mechanics-based models have been used to investigate the complicated behavior of CRMA (Medina and Underwood, 2017). Some empirical models were developed to describe the effect of rubber particles in CRMA. These straightforward models are based on the correlations between rubber related variables (particle size, surface area, etc.) and resultant composite response (Shen et al., 2009a, 2009b, 2017), which are incapable of providing generalized insights into the impact of multi-physical interactions between the constituents. The stiffening or reinforcement mechanisms of rubber in asphalt may stem from volume-filling reinforcement, physiochemical interaction and interparticle interaction. How to properly address these reinforcement mechanisms of CRMA using micromechanical modeling remains a challenge. Practically speaking, if the predictions of mechanical properties of CRMA from the known properties and blend percentages of the constituent phases by using micromechanical models are applicable and possess certain levels of accuracy, it can save the time and cost for the tedious laboratory work, which enables a more appropriate selection of source materials (asphalt and rubber type), enhanced material development (binder preparation conditions) and improved design of binders (rubber content and particle gradation).

Micromechanical models, which can predict fundamental material properties of a composite based on mechanical properties and volume fractions of individual constituents, have been introduced to predict the effective viscoelastic behavior of bituminous materials (Buttlar et al., 1999; Underwood and Kim, 2014; Yin et al., 2008; Zhang et al., 2018f). Numerical micromechanical models, i.e., finite element models (FEM) and discrete element models (DEM), have been successfully utilized by many researchers (Aragao et al., 2011; Caro et al., 2010a; Mishnaevsky Jr. and Schmauder, 2001; Sadd et al., 2004) to predict the properties of a mix with complex compositions. However, these studies also highlighted that FEM/DEM-meshes with detailed information (usually by means of X-ray CT scan) require large-scale computational facilities, which limits the utilization of such models in practice. Alternatively, analytical micromechanical models are expected to provide reliable estimations of the mechanical properties of a composite without extensive computational efforts. Analytical micromechanical models developed based on continuum mechanics have increasingly been used to predict the mechanical properties of bituminous materials (Zhang et al., 2019a). In such models, the detailed information of individual constituents is not required. On the contrary, the constituents having same (very similar) mechanical properties are regarded as one phase; and a composite consists of various phases. For a given macroscopic loading condition, each phase's average stress and strain are evaluated and further utilized to obtain the effective properties of the composite on the basis of the volumetric, mechanical and/or geometrical properties of individual phases.

2.3.2. *Micromechanics-based modeling of rheological properties of CRMA*

2.3.2.1. *Composite system of CRMA based on homogenization theory*. In the composite system of asphalt mastics or mixtures, fillers and aggregates are usually regarded as inert rigid materials embedded in the asphalt matrix (Shu and Huang, 2008b). CRMA can be regarded as a binary composite in which asphalt is the matrix while rubber particles are the inclusions. However, unlike asphalt mastic or mixture, the composite system of CRMA is more complicated due to the interaction between rubber particles and asphalt which changes both the mechanical properties and volume fractions of individual constituents. To estimate the effective properties of a heterogeneous composite based on the microstructural description and the local behaviors of its constituents, homogenization theory was developed to derive a homogenized description for the medium based on the assumption of representative volume element (RVE) (Charalambakis, 2010). Fig. 19 schematically illustrates the RVE of the CRMA composite system before and after asphalt-rubber interaction. After the potential physio-chemical interaction, the properties of both asphalt and rubber phases have significantly changed. In general, asphalt-rubber interaction (mainly swelling) has four consequences from a micromechanics-based point of view: 1) changing the component proportions and thus the mechanical properties of asphalt matrix due to the absorption of light fractions by rubber and the potential released components from rubber; 2) changing the mechanical properties of rubber due to the formation of a gel-like structure; 3) changing the volume content of rubber due to swelling (the so-called effective volume fraction); and 4) changing the interfacial properties between asphalt and rubber due to aforementioned factors (Wang et al., 2018e). Therefore, the accurate determination of input parameters from constituents would be a challenge and directly influence the accuracy of the model prediction.

2.3.2.2. *Input parameters for micromechanical models of CRMA*. As described in the previous section, to effectively predict the mechanical properties of CRMA with micromechanical models, the mechanical properties of both asphalt matrix and rubber inclusion are required. In addition, the volume fraction of each phase also needs to be determined.

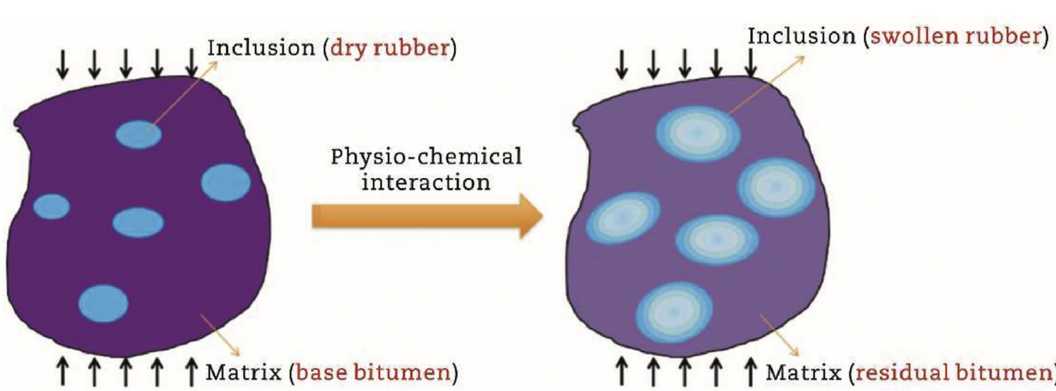


Fig. 19 – Schematic representation of the RVE of the CRMA composite system before and after interaction.

Since the nature of both asphalt and rubber phases changed after the asphalt-rubber interaction, it is of vital importance to measure the representative rheological properties of actual asphalt matrix and rubber inclusion in the CRMA system. Dedicated laboratory tests were performed to obtain these input parameters. The asphalt matrix, which is the liquid phase of CRMA after removing the insoluble rubber particles, was tested by a dynamic shear rheometer (DSR) to obtain the rheological properties. Wang et al. (2020g) carried out DSR measurements on the prepared swollen rubber samples to obtain the mechanical properties of rubber after swelling in asphalt. The effective volume fraction of rubber after swelling has been determined by several methods. Medina and Underwood (2017) estimated the volume content of rubber after swelling based on the scanning electron microscope images. Wang et al. (2019f) developed a finite element model capable of simulating the multiphysics swelling phenomenon (mass diffusion and volume expansion) to predict the effective volume fraction of rubber. After determining the necessary input parameters, they can be implemented into various micromechanical models to predict the viscoelastic properties of CRMA.

2.3.2.3. *Analytical form of micromechanical models of CRMA*. Although many functions and techniques exist to calculate and predict the response of asphalt composites, analytical micromechanical models that are based on the material properties (Poisson's ratio, modulus and volume fraction) and particle interaction via effective medium methods have proven to be most successful (Ahmadinia et al., 2011). Many such models exist, the most well-known ones are summarized as Eqs. (14)–(21).

- Einstein model

$$\frac{G_c}{G_m} = 1 + 2.5C_v \tag{14}$$

- DeBruijn model

$$\frac{G_c}{G_m} = 1 + 2.5C_v + 1.55{C_v}^2 \tag{15}$$

- Roscoe model

$$\frac{G_c}{G_m} = (1 - C_v)^{-2.5} \tag{16}$$

- Parallel model

$$G_c = G_p C_v + G_m (1 - C_v) \tag{17}$$

- Eshelby model

$$\frac{G_c}{G_m} = 1 - \frac{15(1-\upsilon_m)\left(1-\frac{G_p}{G_m}\right)}{7-5\upsilon_m+2(4-5\upsilon_m)\frac{G_p}{G_m}} C_v \tag{18}$$

- Hashin model

$$\frac{G_c}{G_m} = 1 - \frac{15(1-\upsilon_m)\left(1-\frac{G_p}{G_m}\right)C_\upsilon}{7-5\upsilon_m+2(4-5\upsilon_m)\left[\frac{G_p}{G_m}-\left(\frac{G_p}{G_m}-1\right)C_v\right]} \tag{19}$$

- Mori-Tanaka model

$$\frac{G_c}{G_m} = 1 + \frac{5C_v(G_p - G_m)}{5G_m + 2(1 - C_v)(G_p - G_m)} \tag{20}$$

- Generalized self-consistent model

$$a\left(\frac{G_c}{G_m}\right)^2 + b\frac{G_c}{G_m} + c = 0 \tag{21}$$

where G_c, G_m, and G_p are the modulus of the composite, matrix and particles respectively, C_v is the volume concentration of the particle inclusions, υ_m and υ_p are the Poisson's ratios of the matrix and the particles. The detailed explanations and related parameters of the above models can be found in the studies of Underwood (2011) and Zhang et al. (2020a).

2.3.2.4. *Future recommendations for improving micromechanical prediction performance*. With more representative input parameters, micromechanical models yield more accurate predictions. However, while typical micromechanical models give reasonable predictions at low rubber contents while yielding underestimated predictions at low frequencies range with high rubber contents. Considering that the low-frequency range corresponds to the high-temperature range in the frame of master curves, rubber particle interaction will be more prominent in CRMA at high temperatures since the asphalt phase is softer. The underestimation of complex modulus at high temperatures is because these models were primarily developed to address the stiffening effect resulting from the embedded inclusions in a matrix with minimal or limited particle interactions. which is the case of dispersed suspensions (Yin et al., 2008; Zhang et al., 2018a). Under this circumstance, the mechanical behavior of the suspension is dominated by the matrix phase. While at high temperatures, for the case of CRMA, the rubber inclusion may have more dominant effects on the binder mechanical behaviors than the asphalt matrix does. Therefore, to amend the underestimation of the complex modulus of CRMA in the low-frequency range, the interparticle interactions need to be further addressed.

Interparticle interaction is a broad concept. The interparticle-interaction effect increases with increasing rubber content in asphalt, as rubber particles may come into contact and form a polymer network. Besides, the particle's relative configuration (orientations and locations, etc.), and geometrical properties (e.g., size, shape, angularity, surface morphology, etc.) also have a great influence on the model prediction accuracies. It is therefore recommended to further improve the micromechanical model prediction accuracy from the following aspects (Wang et al., 2021h).

- Considering the mutual interaction between rubber inclusions.
- Considering extra phases in the CRMA composite due to physio-chemical interaction.
- Considering the extra reinforcing mechanism.

2.3.3. *Design and performance of rubberized asphalt*

2.3.3.1. *The interaction between rubber and asphalt fractions*. The production of rubberized asphalt is far more complicated than simply mixing and dispersing CRM into hot asphalt binder fractions. As depicted in Fig. 20, once mixed with hot asphalt, the outer part of CRM dissolves with mixing time, releasing natural rubber, synthetic rubber and other components into asphalt fractions. In addition, the light components of asphalt, including saturates and aromatics, are absorbed into CRM polymer chains, forming a thin gel layer around the elastic rubber core of CRM. A study about four fractions analysis of rubberized asphalt binder proved that compared to raw asphalt, rubberized asphalt had a higher percentage of heavy fractions (asphaltenes and resins) and a lower percentage of light components (aromatics and saturates), which should be attributed to the "absorbing effect" of CRM (Leng et al., 2017b). In addition, the peak at 1012 cm^{-1} in FTIR spectrum of rubberized asphalt binder is ascribed to the loss of light components of asphalt binder after the incorporation of CRM (Yu et al., 2016). The swollen CRM plus gel layers are two to three times larger than the original CRM. Meanwhile, some polymer chains in CRM, including natural rubber and synthetic rubber, are released, and mixed with asphalt fractions.

2.3.3.2. *Engineering performance of rubberized asphalt*. Interaction between CRM and base asphalt results in the superior performance of AR at high, intermediate and low temperature. The dissolution and swelling of CRM also dramatically increase the viscosity of asphalt binder. Meanwhile, the storage stability of Rubberized asphalt binder is poorer compared to raw asphalt due to the density difference between CRM and asphalt.

When CRM is incorporated into base asphalt, the penetration value, ductility and phase angle of asphalt binder decrease, whereas its softening point, elastic recovery, viscosity, complex shear increase (Cong et al., 2013). In other words, compared with raw asphalt, Rubberized asphalt binder is stiffer and more elastic, but less consistent and flowable. Then enhanced rheological performance of Rubberized asphalt binder is indicated by higher Superpave rutting factor ($G^*/\sin\delta$), lower non-recoverable compliance (J_{nr}), more loading cycles to fatigue failure and lower stiffness in low temperature (Yu et al., 2016; Zhang et al., 2016c; Gallego et al., 2016). Wang et al. (2018d) evaluated the rheological properties of liquid asphalt phase extracted from rubberized asphalt binders. They found that the enhanced rutting resistance of AR is ascribed to both the polymer modification and particle effect, while the extended fatigue life is mainly can be attributed to CRM's particle effect (Wang et al., 2018d).

The mechanical properties of asphalt mixture considerably vary in a large range depending on the specific asphalt binder, mixture gradation, aggregate type as well as blending condition (Akisetty et al., 2011; Chamoun et al., 2015). Consistent with the superior rheological properties of AR binder, the mechanical properties of hot AR mixture, including moisture sensitivity, stiffness modulus, resistance to cracking and permanent deformation, are obviously superior over that of conventional HMA, due to the increased binder viscosity and higher production temperature (Bai et al., 2016; Cetin, 2013). The air voids content of Marshall samples and the numbers of gyrations of the SGC samples to achieve the same specimen height were employed by Leng et al. (2017a) as the measures of asphalt mixtures' compatibility.

2.3.3.3. *Mixture design*. In most available studies, rubberized asphalt binder is considered as conventional polymer-modified asphalt binders like SBS modified asphalt. The mix design methods, specifications and construction procedures used for conventional asphalt binders can be used with rubberized asphalt binders. Standards or guidelines in designing rubberized mixtures have been developed by several agencies (Chiu and Lu, 2007; Heitzman, 1992; Liu et al., 2012). Marshall (applied in most regions) and Hveem (applied in California) methods with slight modifications were suggested to be used for dense-graded and gap-graded rubberized mixtures while the design procedure in FHWA-RD 74-2 was recommended to be used for open-graded rubberized mixture design) (Chehovits, 1989). All procedures essentially contain five steps, namely, aggregates and binder selection, mixes compaction (with various binder contents), air voids measurement of compacted mix samples, mechanical testing, and finally optimum binder content determination. Table 12 shows the stages of rubberized asphalt mix design and differences in terms of conventional HMA.

In general, in rubberized mixture as a portion of the asphalt is replaced by rubber in asphalt binder, the rubberized asphalt content should generally be higher than the corresponding mixture containing virgin asphalt. An empirical method is the increased binder content should same as the content of crumb

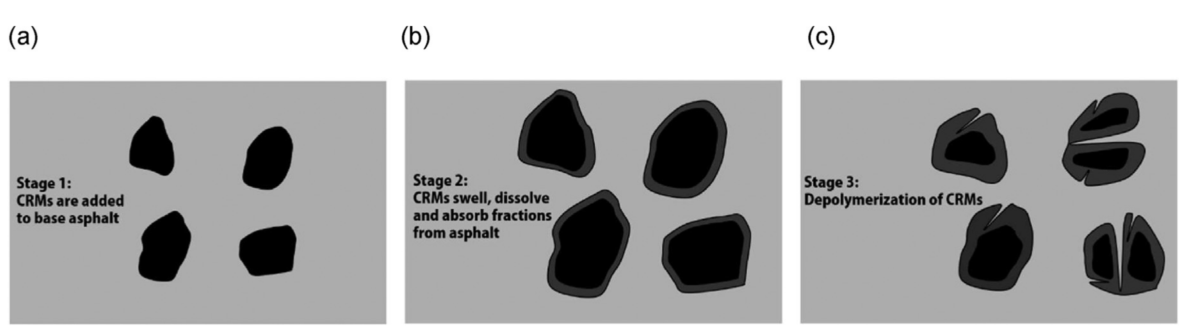


Fig. 20 — Interaction between asphalt and crumb rubber. (a) Stage 1. (b) Stage 2. (c) Stage 3 (Abdelrahman, 2006).

Table 12 – Stages of rubberized asphalt mix design and differences in terms of conventional HMA.

Step number	Stage of conventional HMA mix design	Difference to designing conventional HMA
1	Material selection	Selection of CRM dosage, size and gradation Determining the type and amount of WMA additives
2	Selection of aggregate type and gradation design of aggregates and fillers	Designing aggregate gradation like design HMA Evaluating whether WMA technologies may influence gradation or not, and if it is necessary to make adjustments
3	OAC determination	No changes
4	Determining mixing temperature	Individual setting depending on the aim of using WMA mix based on mix asphalt compatibility studies
5	Determining the conditions of preparing and compacting sample	Using same mixing and compacting equipment
6	Laboratory tests for performance evaluation	No difference
7	Assessment criteria for designed mineral-asphalt mix	No difference

rubber used in rubberized asphalt binder (Huang et al., 2007). A practical experience in California indicated that the optimum asphalt content (OAC) of WAR should be 1.2–1.4 times that of the OAC with neat binder (Cheng et al., 2011). Because of the swelling property of CRM and the increased binder content, gap-graded and open-graded mixes are more preferable for AR/WAR than dense-graded. Gap-graded is speculated to be a variation of dense-graded in which the aggregate gradation is coarsened to provide a greater amount of mixture voids. The increased number of voids allows for higher asphalt binder content and provide rooms for potential swelling of crumb rubber. Open-graded mix can definitely accommodate higher amount of rubberized asphalt binder. Correspondingly, the use of viscous AR and high binder content leads to thicker binder films, improved anti-aging property and better durability. It has to be mentioned that the OAC of asphalt mixture depends on the designed air voids content, aggregate source, compaction method, service condition of the corresponding asphalt pavement, etc. Based on available studies, the OAC of dense-graded, gap-graded, and open-graded asphalt mixture are around 4.4% to 5.5%, 4.5% to 6.2%, and 4.3% to 6.5%, respectively (Chen et al., 2009a; Lyu et al., 2018; Poulikakos and Partl, 2010; Wang et al., 2018f, 2019a; Xu et al., 2015b; Zhang et al., 2015c, 2020; Zhu et al., 2016).

It has to be mentioned that although the design and application of rubberized asphalt pavement has been a practice-ready technology, there are still some limitations needing further investigation. The most outstanding one is the neglect of rubber's volume effect in current design specifications of the rubberized mixture. In the wet process, the volume of crumb rubber can expand by two to three times. The diameter of swelling rubber reaches about 1 mm, which is larger than mineral fillers and some fine aggregates. Additionally, crumb rubber accounts for 1.0%–1.5% of the total mass of mixture. The density and modulus of swelling rubber are distinct from aggregate, which may have a significant influence on the mechanical system of the rubberized mixture. Therefore, a more specific on evaluating the volume effect of swelling rubber in rubberized mixture design is recommended.

2.3.3.4. *Warm mix rubberized asphalt*. One major concern which obstructs the widespread application of rubberized asphalt mixture is the poor workability (Wang et al., 2018d). Due to the incorporation of crumb rubber, rubberized asphalt binder is much more viscous than conventional asphalt binders. Therefore, the blending and compacting temperatures of asphalt rubber and aggregate should be 35 °C–60 °C higher than those of conventional asphalt mixture, resulting in poorer construction environment, more energy consumption and hazardous emissions (Thives and Ghisi, 2017; Zanetiti et al., 2016). WMA effectively reduces the mixing and compaction temperatures of conventional hot mix asphalt mixtures. It has been demonstrated that WMA technologies work effectively with rubberized pavement in different ways, alleviating the concerns of potential higher emissions of rubberized asphalt by decreasing mixing and paving temperatures.

Many studies have investigated the influence of different WMA additives on several rheological properties of rubberized asphalt binders. Previous studies demonstrated that all WMA technologies, regardless of the working mechanism, are able to increase binder's workability by means of decreasing the viscosity of asphalt rubber. However, compared to raw asphalt, the viscosity values of rubberized binders were still much higher. The viscosity-reducing effect of organic additives is constant, which is ascribed to their relatively lower melting point and higher flowability after melting. In terms of chemical additives, it is still unsure whether the enhancement is attributed to the surfactant effect or liquid physical nature. Foaming process and additives only enhance asphalt rubber's workability during the foaming period. Using commercial foaming additive may finally lead to an increased viscosity as the residual zeolite particles act as fillers in WAR system (Ryan and Braham, 2017).

The type and content of WMA additives exhibited significant effects on rheological properties of rubberized asphalt binder and mixture. Table 13 summarized the effect of some WMA additives on the engineering performance of rubberized asphalt. For example, FT-wax was found to enhance rutting resistance but compromised fatigue and low-temperature cracking resistance (Rodriguez-Alloza et al., 2014). However, liner amplitude sweep (LAS) test indicated that the effect of FT-wax on fatigue resistance is positive (Yu et al., 2019b). By comparing the fatigue performance evaluation of WAR binder, mortar and mixture, Yu et al.

Table 13 – Influence of WMA technologies on rubberized asphalt.

Category	WMA additive	Workability	Rutting resistance	Fatigue resistance	Low temperature cracking resistance
Organic additive	Sasobit	Enhanced	Enhanced	Deteriorated	Slightly deteriorated
	Licomont	Enhanced	Enhanced	Deteriorated	Deteriorated
	Asphaltan	Enhanced	Enhanced	N/A	Deteriorated
	56# paraffin wax	Enhanced	Insignificant effect	Deteriorated	Deteriorated
Chemical additive	Evotherm-DAT	Enhanced	Deteriorated	Deteriorated	Insignificant effect
	Bio-modifier	Enhanced	Deteriorated	N/A	N/A
Foaming additive	Aspha-min	Enhanced	Slightly Enhanced	Slightly deteriorated	N/A
	Advera	Enhanced	Insignificant Effect	N/A	N/A
Foaming process	Water foaming	Enhanced	Deteriorated	Enhanced	Enhanced

(2019b) proposed that LAS is a more reliable fatigue test than the Superpave fatigue factor test. The non-commercial additive, 56# paraffin wax, slightly worsen all rheological properties of AR. The negative effect of conventional wax additive on rutting resistance and low temperature cracking resistance is determined by its low melting point and glass transition temperature respectively (Lu and Redelius, 2007). To ensure satisfied low temperature performance, the dosage of wax additive should be controlled. Various types of chemical additives were reported to bring negative effect on the anti-rutting performance of AR binder (Hosseinnezhad et al., 2015; Yu et al., 2014a). Foaming additives has an indistinct effect on rutting performance while the foaming process brings slightly negative influence (Akisetty et al., 2009; Yu et al., 2014b). Nevertheless, it is worth to mention that although some warm rubberized asphalts may perform worse compared to hot rubberized asphalt, they are still much superior to the corresponding unmodified asphalt materials.

2.3.3.5. *Reclaiming potential of rubberized asphalt pavement.* Available studies on reclaiming rubberized asphalt are relatively limited. The reclamation of rubberized asphalt pavement in field has not been a common practice yet. Early studies in the US investigated the in-situ paving properties regarding the feasibility of recycling rubberized asphalt concrete (Caltrans, 2005). In those studies, the rubberized asphalt pavement was reclaimed as conventional asphalt mixtures, and the performance of reclaimed rubberized asphalt pavement was acceptable based on local specifications. For laboratory studies, Lee et al. (2008a) found that the performance properties of the recycled aged rubberized asphalt, prepared by mixing virgin and aged rubberized asphalt, met the Superpave binder requirements. Besides, there was no significant difference between the control and the recycled rubberized mixes in moisture susceptibility and rutting resistance (Lee et al., 2008b).

It is known that rubberized asphalt binders exhibited superior aging resistance compared to unmodified asphalt binder, because the dissolution of natural rubber component of crumb rubber was reported to make the AR binders more flexible after aging (Hou et al., 2018; Wang et al., 2016d). The crumb rubber modifier may also exhibit modification effect on rutting and fatigue performance in the reclaimed rubberized asphalt mixture. The key point to reclaim rubberized asphalt pavement is to analyze the blending efficiency between the new asphalt binder and the aged rubberized asphalt. In addition, how to select optimal rejuvenators towards highly efficient recycling for aged polymer modified asphalt remains a concern for pavement researchers.

2.3.4. *Economic and Environmental Effects*

The economic effects of rubberized asphalt pavement are related to raw material cost, blending temperature, equipment installation or modification fee and WMA additive dosage rate (if used). In addition, long-term pavement performance influences future maintenance cost (Farina et al., 2017). Life cycle cost analysis (LCCA) and life cycle assessment (LCA) studies demonstrated that with the use of recycled waste vehicle tires, rubberized asphalt pavement is beneficial in terms of energy saving, environmental impact, human health, preservation of ecosystems and minimization of resource depletion (Bartolozzi et al., 2015). By constructing the same amount of mixes, rubberized asphalt should exert poorer economic and environmental effect due to its higher production temperature (Chiu et al., 2008). However, the application of rubber modifier may reduce construction cost due to the use of thinner asphalt layer and therefore to the reduced amounts of materials used and reduce amounts of milled materials that are transported and eventually disposed. These energy-saving and material-saving properties render the use of AR technology with an overall advantage in road construction (Wang et al., 2018e).

In terms of warm rubberized asphalt, some studies proved that significant benefit on energy saving can be achieved by incorporating WMA (Hassan, 2010; Rodriguez-Alloza et al., 2014). Economic merits can be also obtained by the enhanced in-place density and smoothness. However, some publications proposed that the energy-saving effect depends on the types of WMA technologies. Moreover, the benefits obtained from lower construction temperature may be offset by the greater impacts of the additional material cost (Vidal et al., 2013). Wang et al. (2018g) believed that warm rubberized requires higher initial cost compared to conventional HMA, but it is a more cost-effective in life-cycle due to the enhanced engineering performance and lower maintenance cost. Cao et al. (2019a) analyzed the long-term energy-reducing effect of different WMA additives in rubberized asphalt pavements by LCA framework incorporated with uncertainty analysis. They found that a noticeable energy saving can be obtained by the incorporation of WMA technologies during the construction period. Nevertheless, compare to the abundant studies focused on engineering performance of rubberized asphalt, research on the economic effect is relatively limited. Future investigation is suggested on more comprehensive LCA to provide quantitative references for decision-making.

In terms of the construction environment, it is known that construction odors during the production of asphalt pavement is highly dependent on the paving temperature (Chong et al., 2018; Xu, 2016). Besides, the rubber particles itself could release some hazardous components (volatile organic compounds (VOCs), primarily benzene, toluene, ethylbenzene, and xylenes (BTEX) and sulfur compounds) at elevated temperatures (Cheung et al., 2015; Gagol et al., 2015). Therefore, emissions of hazardous organic chemicals from rubberized asphalt have been longstanding environmental and occupational health concerns. Previous studies have shown that levels of pollutants (total suspended particles (TSP), VOCs, and polycyclic aromatic hydrocarbons (PAHs)) varied with the raw materials and blending/compacting condition. Odor of asphalt is one of the concerns influencing paving workers and residents living near the construction site, which is the resultant of interactions of certain VOCs with the sense of smell (Autelitano et al., 2017). A study by the US National Institute for Occupational Safety and Health (NIOSH) concluded that exposure to emissions from asphalt containing CRM may be more harmful to workers than conventional paving materials (Burr et al., 2001). However, a recent study indicated that both conventional and rubberized asphalt generated similar levels of particles and PAHs contributing to human exposure (Nilsson et al., 2018).

WMA has been reported to exert significant environmental benefits during the construction period (Carmen et al., 2012). Studies on the environmental and impacts of warm rubberized asphalt are relatively limited. A field investigation in California revealed that no smoke or haze was emitted when AR and surfactant additive were used together (Ghavibazoo et al., 2016). By both lab scale and full-scale emission analysis, they proved that the emission concern of hot rubberized asphalt pavement can be greatly alleviated when the paving temperature drops (Rodriguez-Alloza et al., 2015). Their study proved that in comparison with traditional hot mixing process, warm mixing is able to reduce energy consumption and gas emissions by 18%–36% and 15%–87%, respectively (Wang et al., 2005a, b). By comparison, chemical WMA additive conserved the most amount of energy and produced the least emissions. A comprehensive LCA conducted by Rodríguez-Alloza showed that with the aid of organic additives, the energy consumption and greenhouse gas (GHG) of hot AR production can be reduced by 18% and 20%, respectively (Yang et al., 2018).

Another significant environmental effect of rubberized asphalt pavement is the noise reducing function. The resilient rubber particles provide a "cushion" effect on the noise generation from vibration source. Rubberized pavements with the open- or gap-graded mixtures have been reported reduce noise levels by up to 3–5 dB compared to traditional dense-graded asphalt pavements (Freitas et al., 2012; Huang et al., 2007). A study by the Rubber Pavements Association (RPA) proved that the use of tire rubber in open-graded mixture reduced tire noise by at least 50% compared to concrete pavements (Leng et al., 2017a). Sandberg (2010) compared the old SMA16 to the new rubberized SMA11 and rubberized SMA8 by CPX. The rubberized SMA11 and SMA8 obtained a noise reduction of 2.3dB and 3.9dB, respectively. Since the noise reduction effect is mainly ascribed to the properties of rubber particles remained in asphalt pavement, effect of WMA technologies on this function is limited.

2.3.5. *Summary and outlook*

Although the binder rheological properties, mixture mechanical performance and interaction mechanism of rubberized asphalt materials were reported in the literatures, it still deserves further research, like how to efficiently recycle, how to control the interaction of asphalt and rubber by WMA additives and how to optimize the performance for specific regions. In turns of the control of the interaction among asphalt and rubber by WMA additives, an optimal blending parameter (materials dosage, mixing time/temperature/rate/sequence) for a typical design of rubberized pavement should be developed. Besides, the interaction level among different components should be evaluated by both rheological properties and micro/chemical characteristics. For the combination optimization for specific regions, decision support methods, such as analytical hierarchy process (AHP), fuzzy comprehensive evaluation (FCE), decision trees, etc., could play a greater role. By means of these methods, service condition of pavement in the specific regions and the effects of combination method on the properties of WAR can be taken into consideration. Furthermore, life cycle cost analysis (LCCA) and life cycle assessment (LCA) are suggested to be conducted to identify rubberized pavement with balanced economic and environmental performance. It is also believed that the further investigations on construction technology, maintenance technology and operation parameters will have deeper theoretical and practical understandings, which could lead to more extensive applications of rubberized asphalt pavement.

3. Mixture performance and modeling of pavement materials

3.1. *The low temperature performance and freeze-thaw damage of asphalt mixture*

The durability problem of asphalt pavement in cold region is prominent. Due to the low temperature in winter, the low temperature performance of asphalt mixture is the key to affect the durability of asphalt pavement. At the same time, the existence of water inside the asphalt pavement causes freeze-thaw damage at low temperature, which has a more adverse effect on the durability of the asphalt pavement. Therefore, scholars have carried out a lot of research on the low temperature performance and freeze-thaw damage behavior of asphalt mixture, and proposed methods to improve the low temperature performance and freeze-thaw damage resistance.

3.1.1. *Low temperature performance of asphalt mixture*

3.1.1.1. Low temperature cracking mechanisms. The mechanism of asphalt materials' low temperature cracking can be divided into two periods, the first failure mechanism is before macro cracking occurs. The failure mechanism in this period can be attributed to the born thermal stress exceeded the tensile strength of the asphalt materials (Canestrari and Ingrassia, 2020; Readshaw, 1972). Due to the temperature sensitivities characterization of asphalt binder (Marasteanu et al., 2007; Marasteanu and Cannone Falchetto, 2018), it is the dominant reason for the macro cracking. At temperatures lower than the freezing point, asphalt binders become stiffer and more brittle when temperatures become lower (Wang et al., 2020b). Hence, accumulated thermal stress will ultimately lead to the occurrence of macro crack. This is especially true for the materials under short- and long-term aging processes (AASHTO T313) (AASHTO, 2019). It should be noted that the accumulated threshold exceeded thermal stress can be caused by a single extreme low temperature event (single-event thermal cracks) or multiple warming-cooling cycles (thermal fatigue cracks) (Kim, 2009). The second failure mode is the cracking propagation after the macro cracking occurs, this can be mainly attributed to the adhesion failure, the mutual peeling and eventually failure bonds among the mixture clusters, which lead the initial crack propagates to macro crack (Zheng et al., 2012). The evolution of carking can be caused by the further low temperature environmental, traffic loads, and/or water damage (Mobasher et al., 1997).

3.1.1.2. Experimental methods to evaluate the low temperature performance of asphalt binders. As mentioned in Section 3.1.1.1, asphalt binders play an important role in the response of asphalt mixtures. Hence, the current specifications to evaluate the low temperature performance properties of asphalt materials focus on the asphalt binder and asphalt mixtures scales. It should be noticed that the experimental work on asphalt mixture could reflect better the field performance of asphalt pavement.

For asphalt binder, the commonly used specifications were developed during the Strategic Highway Research Program (SHRP) in the 1990s (Anderson and Kennedy, 1993), two experimental instruments, bending beam rheometer (BBR) (AASHTO T313) (AASHTO, 2019) and the direct tension tester (DTT) (AASHTO, 2012), were proposed to evaluate the strength properties of asphalt binders at low temperatures. BBR was creep tests performed relies on the three-point bending configuration (3 PB) on small pressure aging vessel (PAV) aged binder beams (102 mm × 12.5 mm × 6.25 mm). The asphalt binder beam was conditioned at the desired temperature for one hour, in the purpose of maintaining a stable temperature condition, the cooling medium of ethanol was used. Two critical temperatures at the related values, creep stiffness (S) = 300 MPa and m-value (m) = 0.300, which represents the slope of stiffness vs. time curve in a double logarithm plot, were calculated at 60 s. Such proposed low temperature criteria relied on the assumption that the mixture creep stiffness after 2 h of loading correlated well with the severity of thermal cracking in the field (Anderson and Kennedy, 1993; Readshaw, 1972). To facilitate the testing procedure, the time-temperature superposition principle (TTSP) (Christensen, 1971) was used to shorten the testing duration from 2 h to 60 s at 10 °C above the critical temperature. Normally, DTT strength tests (AASHTO T314) (AASHTO, 2012) were performed when the two BBR critical conditions on stiffness and relaxation are not met. An uniaxial tension (UT) tests are conducted by using dog-bone specimens made of PAV aged binder at a constant strain rate of 3%/min in the cooling medium of potassium acetate. The nominal stress and nominal strain are recorded until failure. Even though the BBR methods are widely used currently, there are still some drawbacks. To keep the specification to a reasonable level of simplicity, some influence factors are not considered in the testing condition, such as physical hardening (Basu et al., 2003), cooling rate (Laukkanen, 2016), and cooling media (Wang et al., 2019b, c). Moreover, the low temperature properties of modified binder are underestimation in most of the cases, this is especially true when SBS polymers are used (Lu et al., 2003). Furthermore, a relatively large amount of materials (15 g for each sample) may be inconvenient for extracted binders from recycled materials.

In the recent past, novel experimental approaches, asphalt binder cracking device (ABCD) (Kim, 2008), and low temperature 4 mm dynamic shear rheometer (DSR) (AASHTO, 2020; Farrar et al., 2015; Sui et al., 2011), were proposed to evaluate the low temperature properties of asphalt binders. The ABCD could indirectly estimate the strength of binders. First, binders are directly poured into a circular mould with an internal invar ring with a diameter of 50.8 mm. Then, this mould is placed into a climate chamber with steadily reduced temperature. The binder sample undergoes a progressive contraction imposing stress on the internal ring. Temperature and strain are continuously recorded by sensors attached to the ring until the initial crack occurs, the failure temperature is defined as the critical temperature. The low temperature 4 mm DSR could indirectly measure the creep stiffness of asphalt binders at low temperatures; hence, this method was used as an alternative approach to BBR (Sui et al., 2011). The DSR method was originally developed to evaluate the high and intermediate temperature properties of asphalt binder. Due to its instrument compliance error, results obtained below 5 °C are not reliable. Consider this, a smaller plate geometry was used to reduce the compliance effect (Schröter et al., 2006), and then numerical equations were applied to correct the compliance error (Franck and Instruments, 2006a, b). Next, the DSR shear results were converted into the relaxation modulus, and correlation was established between the DSR and BBR results. Several following up studies (Laukkanen, 2017; Lu et al., 2017; Wang et al., 2019b, c) were conducted to implement this method. The new proposed experimental procedure has been validated to measure the low temperature properties of asphalt binder, and the sample preparation methods have been further developed. However, poor correlation between BBR and DSR results were observed. This is especially true for the critical temperatures determined by each method, up to 10 °C difference was found in some cases (Lu et al., 2017), while different critical criteria and correlations were found among different studies (Farrar et al., 2015; Lu et al., 2017; Riccardi et al., 2017; Wang et al., 2019b, c). This may be partially attributed to the differences in experimental conditions, such as cooling medium and thermal history, between DSR and BBR. Moreover, the difference between stiffness and shear testing mode may also lead to different results.

Due to the limitation of strength property, only part of the asphalt materials' failure mode could be evaluated. Hence, the fracture mechanics were involved in asphalt pavement since the 1960s (Moavenzadeh, 1967). Currently, two experimental methods, single edge notched beam (SENB) (ASTM, 2002) and double-edge notched tension (DENT) (Dongré et al., 1989), are widely used to evaluate the fracture properties of asphalt binders, while most fracture tests focus on mixture scale.

For the SENB test, an initial notch is fabricated at the middle point of the span on the bottom side of the beam (thickness equals half of the height). A vertical load is applied on the top center of the beam that is supported by two rollers (four times of the height). A vertical crack (0.45 to 0.55 times of the height) will occur and propagation along with the upside of pre-notch due to the stress concentration. The stress intensity factor, K_{IC}, of mode I fracture and related fracture parameters are used to describe the fracture behavior (Bazant and Planas, 1997). Several researchers use this method to evaluate the low temperature performance properties of asphalt binders. Lee and Hesp (1994) and Lee et al. (1995) found that the addition of modifiers could significantly increase the fracture resistance of the asphalt binder instead of the strength. Different notch lengths (Dongré et al., 1989) were used to estimate the effect, it was found that the fracture energy and K_{IC} are better parameters to distinguish asphalt binders rather than the stiffness used in the performance grading (PG) system, this is especially true for the modified binders. This finding was validated in several studies (Anderson et al., 2001; Di Benedetto et al., 2004). No size effect phenomenon was observed in this method (Hoare and Hesp, 2000); however, the BBR dimension beam is not a good option to perform the SENB test due to the uncontrollable and short crack propagation post-peak (Velasquez et al., 2011).

In the case of DENT test, a similar geometry was used as the SENB test, while the 45° notch angle was used to facilitate cutting initial notches at both top and bottom sides of the beam and five different notch lengths were tested. The initial attempt conducted by Dongré et al. (1989) concluded to use J integral J_{IC} and elastic plastic fracture mechanics (EPFM) analysis to evaluate the fracture behavior, it was also found that the value of K_{IC} highly relies on the initial crack depth. Followed-up studies (Roy and Hesp, 2001; Zofka and Marasteanu, 2007) also found that the notch has significant impact on the fracture behavior of asphalt binders. Better repeatability was found within DENT test compared to the DTT ones; hence, DENT is suggested to determine the critical cracking temperatures of asphalt binders (Zofka and Marasteanu, 2007).

3.1.1.3. *Experimental methods to evaluate the low temperature performance of asphalt mixtures*. Similar to asphalt binder, the evaluation methods of asphalt mixture can be divided into strength and fracture properties. For the strength properties, indirect tension tester (IDT) (AASHTO, 2007) and thermal stress restrained specimen test (TSRST) (British Standard Institute, 2012), are the most commonly used experimental methods. For IDT test, a cylindrical specimen is loaded in compression along the diameter at the selected temperature for 2 h. The creep stiffness and low temperature nominal strength, σ_{N_IDT}, are measured and calculated for comparison (AASHTO, 2007). TSRST is commonly used to obtain the critical temperature and strength of asphalt mixtures, both prismatic and cylindrical samples are available. The sample's two ends are glued to platens with a constant length during the entire test, while its temperature is decreased from a starting temperature with a constant cooling rate. Due to the prohibited thermal shrinkage, the specimen is subjected to an increasing (cryogenic) tensile stress. The final failure temperature and strength are used to evaluate the low temperature strength of asphalt mixtures. Recently, the asphalt concrete cracking device (ACCD) (Kim et al., 2010) was proposed as a simpler alternative method of the TSRST. The principle of ACCD is to use the thermal shrinkage stress to lead to failure. A double ring structure was used to restrict the shrinkage of mixture samples in this method.

Besides IDT and TSRST, uniaxial tension stress test (UTST), relaxation test (RT), tensile creep test (TCT), and uniaxial cyclic tensile stress test (UCTST) are suggested by the European standard (British Standard Institute, 2012). In the recent past, Marasteanu et al. (2009) proposed a modified BBR testing method to evaluate the creep compliance of asphalt mixtures at low temperatures. A BBR geometry mixture sample together with a higher loading force of 4 N and a longer loading duration of 1000 s was applied for this purpose. Results indicate that the aggregate spatial distribution could significantly influence the low temperature creep properties of asphalt mixtures.

For the fracture properties of asphalt mixture, the evaluation methods can be simply divided into the beam and cylindrical by the samples' geometries. All the specimens for the fracture test are pre-notched or drilled. Even though the sample dimensions of beam geometry are quite different; however, all the tests can be considered as a three-point bending SENB test. Rely on experimental works conducted on testing control method, crack front development, repeatability, testing temperature, and mixed-mode fracture, the SENB was recognized as the most promising fracture test for asphalt mixtures (Wagoner et al., 2005a, b). In most cases, the fracture mode of SENB tests is mode I; hence, fracture toughness, K_{IC}, and fracture energy, G_F, are used to evaluate the fracture properties of asphalt mixtures. The critical J integral, J_{IC}, is found to be as an efficient parameter to ranking the properties of asphalt mixture (Dongré et al., 1989). Moreover, it was found that for the SENB test, the notch length (Cannone Falchetto et al., 2017) and sample dimension (Le et al., 2013) have significant influences on the fracture behavior of asphalt mixtures which can be attributed to the size effect phenomena.

Due to the restriction of beam sample preparation (slab samples), to simplify the sample preparation procedure, cylindrical, disc, and semi-circular shaped mixture specimen that can be easily produced rely on the Superpave gyratory compactor was proposed in the US. The fracture toughness, K_{IC}, and the fracture energy, G_F, are commonly used to evaluate the fracture properties of asphalt mixtures at low temperatures for these three testing methods. The modified Superpave IDT was developed by Roque et al. (1999) as a cylindrical shape sample. An 8-mm diameter hole is drilled in the center of an IDT specimen to simulate the initial crack. For the disc-shaped sample, disc-shaped compact tension (DCT) test (ASTM, 2020) was proposed, a single edge notched specimen under the tension load was used for this purpose. For both modified IDT and DCT test, the cracking propagation under different traffic loading can be evaluated by applying different loads.

For the semi circular bend (SCB) test (Chong and Kuruppu, 1984), a semi-circular shaped mixture sample with a dimension of diameter of 150 mm, the thickness of 30 mm, and a straight vertical central notch of 15 mm (20% of the height) was produced for this purpose. The sample was placed on a frame consisting of two fixed rollers and having a span of 120 mm. Then a vertical loading was applied on the top of this sample, the loading rate can be controlled by a load line displacement (LLD) and/or a crack mouth opening displacement (CMOD) displacement sensors. According to its configuration, SCB test can be also recognized as a kind of single edge notched three-point bending test. It was found that the dimension of the specimen has limited influence on the results, while the diameter has a more remarkable influence compared to the thickness. In addition, besides the conventional fracture mode I, the mixed-mode I and II stress intensity factors can be determined relying on the SCB test by adjusting the notch's angle (Lim et al., 1994). In a study conducted by Li (2005), fracture energy is a more efficient parameter to rank the fracture properties of asphalt mixtures.

3.1.1.4. *Low temperature behavior of asphalt materials*. Plenty of models were developed in the past decades to describe the low temperature behavior of asphalt material, includes asphalt binder, asphalt mixture, and correlations between binder and mixture. For asphalt binders, all the models are mechanistic-based models since no direct field data is related to asphalt binders. Both rheological and analogical modeling were proposed to describe its rheological and mechanical behaviors at low temperatures. At low temperature, when asphalt binders bear low strain/stress levels, then the materials' behavior can be simplified to linear viscoelastic behavior. Hence, creep compliance, $D(t)$, relaxation modulus, $E(t)$, are used to calculate the thermal stress evolution in the asphalt binder when temperature decrease. Meanwhile, several analogical models, general Maxwell model, general Kelvin-Voigt model, Huet model (Huet, 1963), Huet-Sayegh model (Sayegh, 1965), and the most recent 2S2P1D model (Di Benedetto et al., 2004), were developed to estimate and predict the asphalt binders' low temperature behavior. Among these models, Huet model shows the possibility to generate correlations between asphalt binder and the corresponding asphalt mixtures. A transformation equation named shift-homothety-shift in time-shift (SHStS) (Di Benedetto et al., 2004; Pouget et al., 2010) can be used for this propose. The principle of this model is based on the simple linear relationship between the characteristic time, τ, of binder and corresponding mixture. Very well predicted results were observed in the implementations.

For asphalt mixture, both empirically-based and mechanistic-based models were proposed. For the empirically-based model, Fromm and Phang's models (Fromm and Phang, 1972) developed a regression equation to predict the cracking index and critical temperature rely on field investigation in Ontario, Canada. Eleven parameters were selected for this purpose. Two measured parameters, coefficient of thermal contraction and viscous flow properties at different temperatures, are used as inputs to calculate the final critical temperature. Another well-known empirically-based model was also developed in Canada (Haas et al., 1987). However, this model only focused on the pavements in airports. It should be noted that the empirically-based model could provide accurate prediction within the climate region and traffic load the researchers studied. It is risky to use as a general prediction model. In the case of mechanistic-based ones, different models were developed to estimate and predict the critical failure temperature, thermal stress. Hills and Brien (1966) developed a prototype model to predict the fracture temperature, the assumption of this model is the pseudo-elastic representation of asphalt mixture. The model is easy to be used, however, only the predicted critical temperature limited the wide application in a high technology readiness level (TRL) level. A followed up study (Finn et al., 1977) further developed this model to widen its application to binder selection, potential cracking location and amount, and standardization the pre-paving procedure.

3.1.1.5. *Effect factors of low temperature performance of asphalt mixture*. Asphalt mixture is a kind of temperature sensitive material. The decrease of temperature will lead to the hardening of asphalt material and the fracture of asphalt mixture under the action of temperature stress. The low temperature performance of asphalt mixture is mainly affected by environmental factors and its own properties.

The environmental factor mainly refers to the air temperature, which can describe the temperature stress in the asphalt mixture. Among them, the duration of low temperature, low temperature extreme value and variable temperature rate are the main factors leading to the failure of asphalt mixture. Research shows that extreme low temperature in winter will lead to the change of heat transfer process, which increases the risk of low temperature cracking (Bronfenbrener and Bronfenbrener, 2012; Frich et al., 2002; Hermansson, 2004). The prediction of extreme temperature of pavement in winter is the basis of accurate calculation of temperature load. Some researchers predict the pavement temperature by atmospheric temperature. Akiyama (1976) showed that the relationship between asphalt pavement temperature and atmospheric temperature followed exponential relationship on sunny days, and linear relationship in cloudy days. Liu et al. (2011) pointed out that the surface temperature is related to the air temperature and can be determined by the daily maximum and minimum temperatures. Some researchers focus on the temperature distribution of pavement depth range. Southgate (1968) suggested that the 5-day average temperature should be taken as part of the input to determine the temperature of each depth in the road surface. Li et al. (2018b) predicted the temperature at different depths based on the average temperature. The duration of low temperature and cooling rate may affect the temperature distribution of pavement structure depth (FHWA, 1998).

The properties of asphalt mixture that affect low temperature performance include asphalt type, asphalt content, aggregate type, aggregate gradation and void ratio. There are more adhesion failure zones in the asphalt mixture with the density suspension structure than in that with the void skeleton structure (Zheng et al., 2012). Mineral powder and asphalt form asphalt mortar, and bond aggregate to form strength. The ratio of mineral powder to asphalt directly affects the interface strength and embrittlement state of asphalt mixture at low temperature (Du et al., 2021b; Zheng et al., 2017).

3.1.1.6. *Improvement of low temperature performance of asphalt mixture*. In asphalt mixture, asphalt is greatly affected by temperature. Therefore, improving the low temperature performance of asphalt directly affects that of asphalt mixture. Polymer modifier is the main method to improve the low temperature performance of asphalt. Polymer modifier mainly includes rubber, thermoplastic elastomer and resin. Rubber particles can block the generation of cracks, leading to the improvement of low temperature properties of the binder. Thermoplastic elastomer include styrene butadiene styrene (SBS) and styrene isoprene styrene (SIS) (Wang et al., 2017g), which can effectively reduce the temperature sensitivity of asphalt (Li et al., 2019a; Liu et al., 2019b). At the same time, it can reduce the low temperature creep resistance and cracking resistance of asphalt (Wang et al., 2012b). SBS is a kind of thermoplastic elastomer, which is currently the most commonly used modifier for asphalt, has a good effect on improving the low temperature performance of neat asphalt. Because SBS can effectively improve the ductility of neat asphalt, the deformation ability and the crack resistance of asphalt mixture are improved (Hao et al., 2017a; Lin et al., 2017b). polyethylene (PE) includes low density polyethylene (LDPE) and high density polyethylene (HDPE). PE used to modify asphalt mainly comes from waste plastics. At 140 °C, the polyethylene can be readily dispersed in heated liquid bitumen by high-shear mixing to form a colloidal suspension (Jew et al., 1986). In general, the addition of PE can improve the tensile strength of asphalt at low temperature and reduce the cracking potential of asphalt (Punith and Veeraragavan, 2007). For some PE materials, such as glycidyl methacrylate modified PE, the epoxy group in the side chain of glycidyl methacrylate has been achieved with the functional group in universities (Li et al., 2008). As a result, the fatigue and crack resistance at low temperature is improved. Because PE improves the performance of asphalt, the low temperature performance of asphalt mixture and cement asphalt material are enhanced (Panda and Mazumdar, 2002).

3.1.2. *Freeze-thaw damage of asphalt mixtures*

Asphalt mixture is a commonly used porous material for pavement, and water easily enters the material through rainfall and runoff. However, in cold regions, especially in early spring and early winter, the existence of moisture in the asphalt mixture and the alternative effect of temperature make the asphalt mixture constantly eroded by ice and water, resulting in serious freeze-thaw (F-T) damage, such as stripping, raveling and other pavement diseases, affecting the durability of asphalt pavement in cold region. Therefore, the mechanism of F-T damage of asphalt mixture, and the evaluation method of F-T damage have caused widespread concern in academic circles. On this basis, asphalt mixture F-T damage behavior characteristics and the influence of different factors on the damage behavior are clarified. Meanwhile, to improve the freeze-thaw resistance ability of asphalt mixture, some improvement measures have also been proposed.

3.1.2.1. *F-T damage mechanisms*. At present, the mechanism of F-T damage of asphalt mixture mainly has the following viewpoints. The expansion force is generated due to the phase change of water during the freezing process. When the expansion force exceeds the adhesion strength between the asphalt and the aggregates, the asphalt mixture F-T damage occurs (Fig. 21) (Lyu et al., 2020). During the freeze-thaw cycle, moisture penetrates into the asphalt-aggregate section, and the freezing of moisture causes the asphalt to separate from the aggregate. As the number of freeze-thaw cycles increases, the interface displacement increases (Xu et al., 2020e). Yi et al. (2014) believed that under repeated freezing and thawing, the asphalt mixture exhibited more elastoplastic properties after F-T damage, and the main reason for the decrease in strength is the loss of adhesive cohesive force. And the F-T damage will also change the plastic potential surface, causing greater volume strain. Yu (2019) regarded freezing and thawing as the accumulation of ice swelling and water erosion. F-T damage has resulted from crack propagation caused by frost heaving and cement cohesive failure caused by erosion. In addition, the migration, aggregation, and freezing of water have also attracted the attention of scholars. Under the permeation action, water aggregates along with the void structure to the frozen area, resulting in the expansion of ice, the increase of damage, and the propagation of cracks, resulting in serious F-T damage (Cao, 2008; Xu et al., 2016a; Yang, 2005).

3.1.2.2. *Evaluation method of F-T damage*. The F-T damage performance of asphalt mixture is mainly evaluated by the Lottmen method. For example, the AASHTO (2013) adopts the Lottmen method to divide the samples into two groups. One group of samples are subjected to vacuum saturation. Then the samples are pretreated in 60 °C inundation condition for 24 h, and then subjected in −18 °C air-freezing environment for 16 h and 60 °C water condition for 24 h. After that, the two groups are subjected in water immersion condition at 25 °C. The splitting strength ratio of two groups of specimens is taken as the evaluation index of F-T damage. What's more, this method has clear requirements for the void ratio and water saturation ratio of asphalt mixture. Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering T0729-2000 (MTPRC, 2011) is adjusted on the basis of the Lottmen method. Instead of making specific requirements on void content and water saturation, it stipulates the compaction times of the specimen. And the specimens are directly subjected to freeze-thaw treatment.

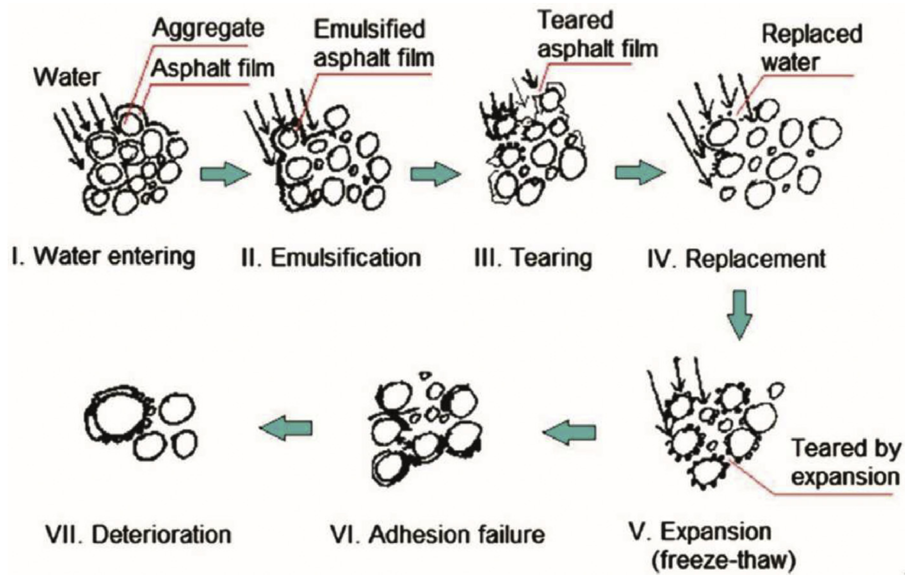


Fig. 21 – The mechanism of F-T damage in asphalt mixture (Lyu et al., 2020).

In Lottmen method, the evaluation of asphalt mixture F-T damage only takes one freeze-thaw cycle to the specimen. However, asphalt pavement is often subjected to multiple freeze-thaw cycles in the actual service. Therefore, on the basis of this method, most studies have increased the number of freeze-thaw cycles. Meanwhile, considering the actual water temperature condition of asphalt pavement in different areas, some scholars have also adjusted the water and temperature conditions of freeze-thaw cycles (Li et al., 2020d; Xu et al., 2018a; Yu, 2019). Some scholars also used the freeze-thaw test of concrete for reference in the process of the asphalt mixture specimens (Badeli et al., 2018; Tarefder et al., 2018).

After freeze-thaw cycle treatment of asphalt mixture, the indirect tensile test according to the Lottmen method is often used to evaluate the F-T damage of asphalt mixture. Other mechanical tests are also applied to the evaluation of F-T damage of asphalt mixture. For example, the uniaxial compression test (Fan et al., 2020b), complex modulus test (Badeli et al., 2016), semicircular bending (SCB) tests (Fakhri et al., 2020; Karimi et al., 2021). These mechanical property tests are combined to evaluate the variation of F-T damage property of asphalt mixture from different perspectives. Macroscopic physical property tests, such as mass loss (Yan et al., 2015b) and void content (Chomicz-Kowalska et al., 2020) are also occasionally used in the evaluation of F-T damage of asphalt mixtures. In addition, in order to evaluate the degree of F-T damage of asphalt mixture, some scholars established a prediction model based on the evolution of mechanical performance. Based on the F-T damage residual life prediction model of asphalt pavement, Tan et al. (2011) took the compressive rebound modulus as the main index to evaluate the F-T resistance of asphalt mixture. Cheng et al. (2019) and Zhu (2018) described the relationship between the failure probability and time of the internal points of the asphalt mixture during the freeze-thaw cycle based on the Weibull statistical model. The shape factor, scale factor, and gradient factor are used to evaluate the interior of the asphalt mixture. Zhu (2018) used the logistic model to describe the degree and speed of F-T damage of different types of asphalt mixtures, evaluated the degree of damage of different asphalt mixtures in the process of 15 freeze-thaw cycles with saturation factor, and expressed the growth rate of damage speed of asphalt mixtures with growth rate factor.

With the development of microscopic structure detection technology, the evaluation of F-T damage has gone into the microscopic level, and the computed tomography (X-ray CT) is a common method. Based on the tomography images of asphalt mixture before and after the F-T test, the internal structure is extracted to evaluate and describe the spatial distribution and evolution process of damage. The commonly used meso-structural parameters include void content, void number, and void size (Xu et al., 2020d; Wu et al., 2018), void tortuosity (Xu et al., 2015b), fractal dimension, and angular property (Ma, 2018), and so on. These parameters can accurately describe the damage evolution process of asphalt mixture void structure during the F-T process.

However, when using X-ray CT to evaluate the F-T damage of asphalt mixture, the test process is relatively complicated. Therefore, some scholars have adopted some nondestructive testing methods to test and evaluate it. Zhang et al. (2016b) found that the freeze-thaw resistance of different asphalt mixtures can be better evaluated by the dynamic nondestructive test. Meng et al. (2020) also used the dynamic nondestructive test method to evaluate the F-T damage of asphalt mixture, and found that there was an obvious linear relationship between the second-order damping ratio and the F-T damage of asphalt mixture. Therefore, the change of the second-order damping ratio was adopted to evaluate the evolution of the F-T damage of the asphalt mixture.

3.1.2.3. *F-T damage behavior of asphalt mixture*. The understanding of the F-T damage behavior of asphalt mixture is mainly carried out from three aspects. Firstly, the performance attenuation and damage development of asphalt mixture in the process of freeze-thaw cycles were defined on different scales. Secondly, the damage evolution equation or damage evolution model of asphalt mixture were established. Thirdly, the spatial distribution characteristics and development of F-T damage was defined. Meanwhile, the influence of different factors on F-T damage of asphalt mixture was also analyzed.

(1) Evolution of F-T damage of asphalt mixture

In the study of the F-T damage evolution of asphalt mixture, the macroscopic mechanical performance is mainly studied. Yan et al. (2015b) pointed out that the freeze-thaw cycle would lead to a gradual decrease in the stability and splitting strength of the asphalt mixture. Wang et al. (2020b) fitted the stability, uniaxial compressive strength, and fatigue life of asphalt mixture in the process of freeze-thaw cycles, and found that the variation of loss rate of different properties with the number of freeze-thaw cycles could be fitted as a convex quadratic function. Karimi et al. (2021) pointed out that the fracture resistance of asphalt mixture decreased gradually with the number of freeze-thaw cycles according to the change of fracture parameters in the semi-circular bending test of asphalt mixture. Fakhri et al. (2020) indicated that the fracture toughness of asphalt mixture decreased with the number of freeze-thaw cycles and tended towards stability after 7 cycles. Fan et al. (2020b) investigated the evolution of the fatigue life of asphalt mixture in the process of freeze-thaw cycles and pointed that the fatigue life of asphalt mixture decreased with the increase of the number of freeze-thaw cycles. Xu et al. (2016a) analyzed the evolution process of F-T damage of asphalt mixture based on the evolution of permeability. With the increase of hydraulic gradient, the sensitivity of permeability velocity to the freeze-thaw cycle increased. The freeze-thaw cycle increased the hydraulic conductivity of the asphalt mixture in a laminar flow state, and the freeze-thaw process promoted the water migration in the asphalt mixture.

With the development of microscopic detection technology, the variation of microscopic damage evolution has been gradually recognized. Xu et al. (2015b) believed that the F-T damage of asphalt mixtures consisted of three forms, expansion of a single volume, the combination of two separation voids, and the generation of new voids (Fig. 22). In Fig. 22, red means existing void without F-T cycle, green means voids increment after 15 F-T cycles compared with existing void, pink means voids increment after 30 F-T cycles compared with that after 15 F-T cycles. Wu et al. (2018) obtained the evolution of meso-voids of asphalt mixture during freeze-thaw process by combining CT and mercury injection method (Fig. 23). The freeze-thaw cycle mainly caused the variation in the void size and void number, in which the number of voids in the range of 0.2−0.6 mm increased significantly, while the number of voids in other sizes changed slightly. Ma (2018) indicated that in the process of freeze-thaw cycles, the fractal dimension, angular, roundness, and long-short axial ratio of void in asphalt mixture showed a three-stage trend, increasing first, then decreasing, and finally becoming stable. Lyu et al. (2020) observed the changing aggregate-asphalt mortar interface of asphalt mixture in the process of the freeze-thaw cycle by using scanning electron microscopy, and found that under the action of the freeze-thaw process, microscopic cracks appeared at the interface, and the interface phase structure was damaged.

(2) F-T damage evolution model of asphalt mixture

In order to describe the F-T damage evolution of asphalt mixture more accurately, scholars have established the damage evolution equation or evolution model. The commonly used damage evolution models are the mechanical model (Li and Tan, 2014; Lovqvist et al., 2019; Yi et al., 2014; Zhang et al., 2016c, 2021g) and the thermodynamic model (Lovqvist et al., 2020). With the help of these models, the evolution and characteristics of freeze-thaw damage of asphalt mixture were described. The models are summaried in Table 14.

(3) Distribution and development of asphalt mixture F-T damage

Asphalt mixture is a heterogeneous material and the distribution of F-T damage is related to its heterogeneous

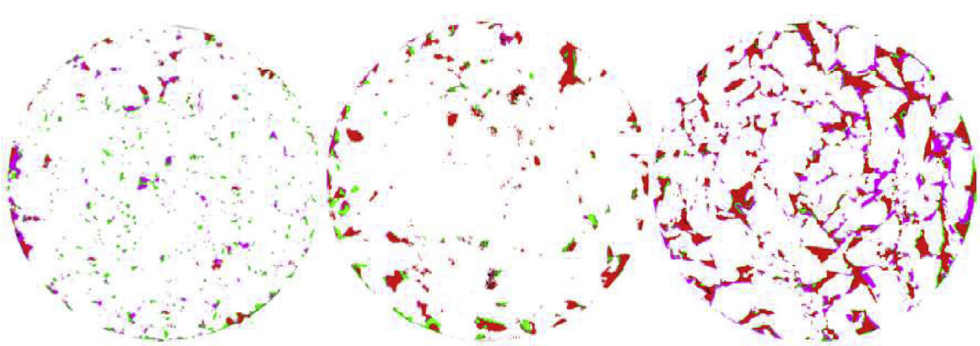


Fig. 22 − 2D meso void structure evolution during F-T cycles (Xu et al., 2015b).

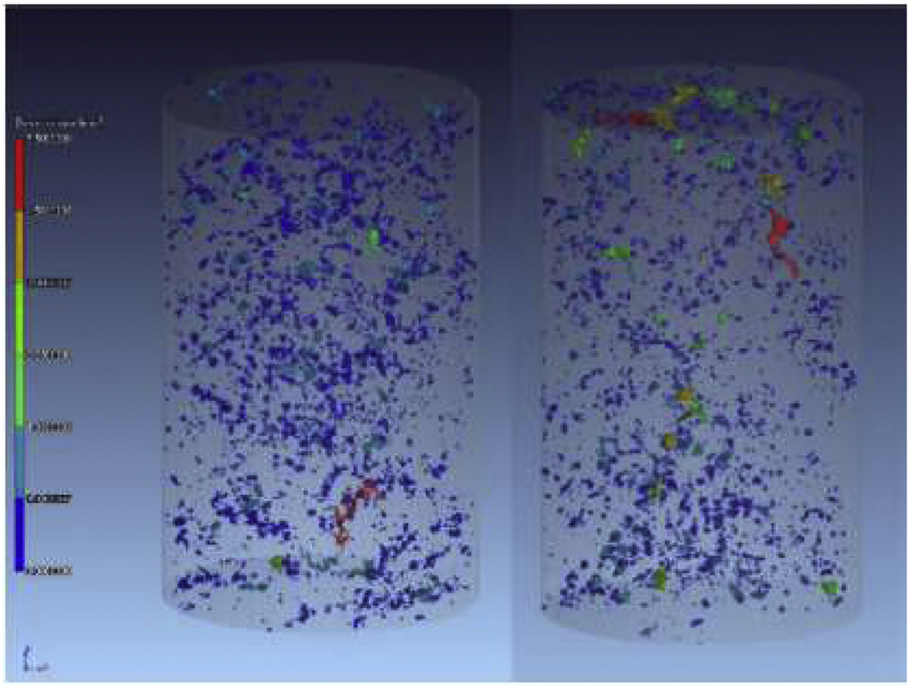


Fig. 23 – 3D void variation of asphalt mixture before and after F-T process (Wu et al., 2018).

properties. In most studies, CT technology was used to clarify the vertical distribution and evolution of F-T damage based on the distribution characteristics of mesoscopic void structure (Wu et al, 2018; Xu et al, 2015b, 2018, 2021a). Du et al. (2017a) analyzed the distribution of F-T damage of asphalt mixture based on the characteristics of the microscopic damage distribution before and after the freeze-thaw splitting test. The damage mostly appeared in the places where the initial void was densely distributed, and the F-T damage increased in the section with larger void content. Hou (2015) used digital image correlation technology to obtain the variation in the splitting strain field of asphalt mixture before and

Table 14 – Summary of F-T damage model of asphalt mixture.

Reference	Model type	Model formulation
Lovqvist et al. (2019)	Micromechanical model	$\overline{\sigma} = \tilde{\overline{\sigma}}(1 - d_\theta - d_\psi + d_\theta d_\psi)$
Yi et al. (2014)	Viscoelastoplastic damage model	Viscoelastic formulation $\bar{s}_{ij}(t) = 2\int_0^t \overline{G}(t-\tau)\frac{\partial \bar{d}_{ij}(\tau)}{\partial \tau}d\tau$ $\bar{\sigma}_{ij}(t) = 3\int_0^t \overline{K}(t-\tau)\frac{\partial \bar{\epsilon}_{ij}(\tau)}{\partial \tau}d\tau$ Elastic-plastic formulation $d\bar{\sigma}_{ij} = C_{ijkl}\left(d\bar{\epsilon}_{ij} - d\lambda\frac{\partial g}{\partial \bar{\sigma}_{ij}^{ep}}\right)$
Zhang et al. (2016c)	Damaged mechanics model	$f(n,\epsilon) = (1-D_n)\frac{\partial D_1}{\partial \epsilon} + (1-D_l)\frac{\partial D_n}{\partial n}$
Li et al. (2014)	Maxwell model	$\sigma(t) = (1-D)\left[\eta_0\dot{\epsilon} + \eta_1\dot{\epsilon}\left(1-e^{-\frac{E_1^t}{\eta_1}}\right) + \eta_2\dot{\epsilon}\left(1-e^{-\frac{E_2^t}{\eta_2}}\right)\right]$
Zhang et al. (2021g)	Continuous damage model	$D = D_c\left[1-\left(1-\frac{N}{N_D}\right)^{\frac{1}{1+\alpha}}\right]$
Lovqvist et al. (2020)	Thermodynamic model	$\dot{d}^{FTC} = -\frac{\partial f^{FTC}}{\partial Y^{FTC}}\dot{\lambda}^{FTC} = -\dot{\lambda}^{FTC}$ $\dot{\eta} = -\frac{\partial f^{FTC}}{\partial \Gamma}\dot{\lambda}^{FTC} = \kappa\dot{\lambda}^{FTC}$

after freeze and thaw. The strain of asphalt mortar increased obviously, and the damage mainly occurred inside the asphalt mortar and at the interface between the asphalt mortar and aggregate.

3.1.2.4. *Effect factors of freeze thaw performance of asphalt mixture*. As for the factors of F-T damage of asphalt mixture, the material composition of the asphalt mixture and environment were mainly studied. Different types of asphalt mixtures can lead to differences in void structure, so this is an important factor affecting F-T damage (Xu et al., 2015b). Asphalt content (El-Hakim and Tighe, 2014) and filler properties (Wang, 2020a, b) also affect the freeze-thaw resistance of asphalt mixtures. Void is the carrier of moisture, and it is also the main factor affecting the freeze-thaw performance of asphalt mixture. The number of open voids (Yi, 2012), connected voids (Zhang et al., 2021g), and initial voids (Du et al., 2017a; Xu et al., 2021a; Yan et al., 2015) also have an important impact on the development of F-T damage. From an environmental point of view, the presence of water is important to affect the F-T damage of asphalt. The phase state of saturation and moisture affects the degree of F-T damage and the development speed (Fan et al., 2020b; Li et al., 2020d; Sun et al., 2020a; Xu et al., 2015b). The effect factors of freeze thaw performance of asphalt mixture are summaried in Table 15.

3.1.2.5. *Improvement of freeze thaw resistance of asphalt mixture*. There are mainly two ways to improve the F-T damage resistance of the asphalt mixture. One is to strengthen the damage resistance of the asphalt mixture. The F-T damage resistance of asphalt mixture was improved by increasing asphalt content (Sun et al., 2020a), optimizing gradation design (Wang et al., 2021i). Adding modifiers to the asphalt mixture, or compound modification of the asphalt mixture through a variety of modifiers, can also improve the resistance of the asphalt mixture to F-T damage, such as rubber modified asphalt (Huang et al., 2005a; Liu et al., 2020a; Zhang et al., 2016b) and polymer modified asphalt (Nian et al., 2018; Teltayev et al., 2019; Yu et al., 2019c). The fiber has a strengthening effect on the interface between aggregate and asphalt, mainly including basalt fiber (Cheng et al., 2018; Wang et al., 2018a; Yu, 2019), bamboo fiber (Xia et al, 2021), ceramic fiber (Wang et al., 2021j) and aramid pump fiber (Badeli et al., 2018). There are also scholars using a variety of fiber to enhance the freezing and thawing performance of asphalt mixture (Gong et al., 2018a; Zhu, 2018). Adding lime, cement, bentonite, and other materials to asphalt mixture as anti-stripping agents can improve the ability of asphalt mixture to resist stripping and improve the anti-freeze thaw erosion performance (Kok and Yilmaz, 2009; Qiao et al., 2018). Steel slag could be used to replace aggregate, and through the physical anchorage and adhesion between steel slag and asphalt, the adhesion performance of asphalt mixture was improved and the freeze-thaw resistance of asphalt mixture was enhanced (Lyu et al., 2020).

The second method is to reduce the impact of environmental such as water condition and temperature on the damage of asphalt mixture. Water can be sprayed on the surface of the asphalt mixture to prevent or reduce the water into the asphalt mixture and reduce the damage caused by the water frost heave. Waterproof material can be sprayed on the surface of the asphalt mixture to prevent or reduce moisture from entering the asphalt mixture and reduce the damage caused by moisture frost heave. Lin et al. (2012) used silicone protective materials to reduce F-T damage of the asphalt mixture. The silicone protective materials could change the connected void into a closed void, and improve the indirect tensile strength and stability after the freeze-thaw cycle. Hou (2015) optimized the design of organosilicon water-repellent protective materials to improve the freeze-thaw resistance of asphalt mixture. In addition, adding the anti-icing agent to asphalt mixture can reduce the freezing point of water inside the asphalt mixture, which can also reduce the F-T damage caused by the expansion of the phase change volume of water (Hou, 2015). Li et al. (2012a) proposed that the conductive ultra-thin anti-skidding wearing course (CUAWC), mixed with graphite, carbon fiber,

Table 15 – Summary of effect factors of freeze thaw performance of asphalt mixture.

Influence factor		Differences in freeze-thaw damage behavior	Reference
Material composition	Asphalt mixture types	Void structure evolution	Xu et al., 2015b
	Asphalt content	The attenuation of dynamic modulus	El-Hakim and Tighe, 2014
	Filler properties	Adhesion of filler and asphalt	Wang, 2020a
Compactness	Compaction	The freeze-thaw damage resistance	Gong et al., 2016
Void structure	Connected void content	Degradation velocity	Zhang et al., 2021g
	Open void number	Damage degree in the initial stage of F-T damage	Yi, 2012
	Initial void ratio	The strength loss	Yan et al., 2015 Du et al., 2017a Xu et al., 2021a
Environment	Water saturation	The fatigue life	Fan et al., 2020c Sun et al., 2020a
	Water phase	Damage degree and injury development speed	Xu et al., 2015b Li et al., 2020d
	Salt water	Salt water causes damage to the interface	Feng et al., 2010

and epoxy resin adhesive, was used to remove snow and ice on asphalt pavement to reduce F-T damage.

3.1.3. *Summary and outlook*

In summary, the mechanism of the F-T damage of asphalt mixture has been explained from different perspectives, and the F-T damage behavior of asphalt mixture has been studied from different scales. The influence factors of F-T damage were also clarified, and the measures to improve the F-T resistance of asphalt mixture were put forward. However, the relationship between the F-T damage behavior at different scales has not been established. And, climate conditions in different regions are different, such as temperature, rainfall, and so on. These differences can bring different effects on the evolution of F-T damage of asphalt mixture. Future research can be carried out from these aspects, which can provide an important reference value for the research on the climate division of F-T damage of asphalt mixture.

3.2. *Long-life rigid pavement and concrete durability*

The concept of long-life pavements has been widely accepted in the world. After field practices for decades, several types of rigid pavements exhibit the capacities or potentials of being long-life pavements. This article summarized the efforts of scholars and engineers on investigating long-life rigid pavements, including continuous reinforced concrete pavement (CRCP), fiber reinforced concrete pavement (FRCP), two-lift concrete pavement (2LCP). The CRCP, as a popular rigid pavement structure in Europe and North America, was introduced elaborately on its structure, materials, distresses, and maintenance treatments. On the other hand, the durability of concrete is also a critical factor influencing the performance and the service life of rigid pavements. This article introduced the state-of-art knowledge of sulfate attack, alkali-aggregate reaction, freeze-thaw impacts on concrete. The summary work in this article can be a reference when designing and building long-life rigid pavements.

3.2.1. *Long-life cement concrete pavement*

After field practice for decades, long-life pavements exhibit lower cost and better benefits than conventional pavements, which therefore become more and more popular in the world. Currently, A pavement with a service life longer than 35 years, defined by the United States, or 50 years defined by the United Kingdom, or 40–60 years defined by Japan without structure failure can be assumed as a long-life pavement (Liu et al., 2016b).

Among the rigid pavements, the continuous reinforced concrete pavement (CRCP), fiber reinforced concrete pavement (FRCP) and two-lift concrete pavement (2LCP) are believed as groups or at least candidates of long-life rigid pavements after field practices for decades. Concrete pavement only occupies a small proportion on highways in China (Editorial Department of China Journal of Highway and Transport, 2020). However, with the increasing demand for resource conservation and environmental protection, it is necessary for China to vigorously develop long-life rigid pavements (Liu et al., 2016a).

3.2.1.1. *Continuous reinforced concrete pavement*. The CRCP is the most widely used long-life rigid pavement. The main distress to the joint plain concrete pavement (JPCP) are spalling and faulting at the joints, which result in high maintenance costs in service, further contributing to the popularity of CRCP (Kim et al., 2020). In other words, the concept of CRCP was developed to eliminate lateral cracks, reduce maintenance costs and improve service life (Ren et al., 2013a, 2014). The CRCP design concept is to allow the pavement to crack naturally during its service life and to be constrained by continuous longitudinal reinforcement, resulting in internal stress in the concrete. Under the combined impacts of environmental load and internal stress, the CRCP develops various random cracks in the early stage (Chen et al., 2011a; Chorzepa et al., 2018; Citir et al., 2020; Kim et al., 2019; Sofi et al., 2019). The main function of longitudinal reinforcement is to prevent excessive crack openings (Ryu et al., 2013a).

In the last few decades, most European countries have been using CRCP for the construction of advanced heavy load roads, with Belgium and France being the only two countries that use CRCP on a large scale (Oh et al., 2016a, b). CRCP is widely used in at least 35 states, with Texas and Illinois leading the way. As of 2012, the Texas Department of Transportation has built more than 20,930 km of CRCP, accounting for about 6.8% of the total length of local highways (Zhou et al., 2014a). Currently, Texas's CRCP performs well, but it used to face serious spalling problems. The Texas Department of Transportation carried out a series of project studies to identify spalling and improve pavement conditions, which require the use of coarse aggregate during CRCP construction to produce concrete with a thermal expansion coefficient of no more than 5.5 microstrain/F to reduce spalling (Choi et al., 2020b).

The two significant drawbacks of CRCP are high construction costs in the early stage and random cracks that develop unevenly (Kim et al., 2020). Advanced reinforced concrete pavement (ARCP) is based on CRCP using crack induction and local reinforcement instead of continuous longitudinal reinforcement to eliminate unnecessary reinforcement in CRCP, thus reducing construction costs and random cracks (Kashif et al., 2021; Kim et al., 2020). The passive nature of crack induction is one of the main factors leading to the erosion and spalling development of CRCP section (Ren et al., 2013b). In Belgium, partial surface sawing, which eliminates the randomness of early crack patterns by inducing cracks at predetermined CRCP locations, is considered to be the most effective crack induction method (De Winne et al., 2018; Ren et al., 2014). Kim et al. (2020) defined the concept of ARCP and put forward the design method. Kashif et al. (2021) proposed a reinforcement scheme for ARCP and evaluated that the ARCP of local surface sawing had the same mechanical behavior and cracking characteristics as CRCP through a three-dimensional finite element model.

3.2.1.2. *Fiber reinforced concrete pavement*. Fiber reinforced concrete is aimed at improving the strength, toughness and durability of concrete (Afroughsabet et al., 2016). Ordinary rigid pavements are lack of self-healing capability like flexible pavements. In the early stage, micro cracks are easy to appear under the combined impact of environmental loads and in service. The further development of micro-cracks eventually causes structural failure of pavement. The fiber bridging mechanism can effectively control the cracks of concrete, improve the toughness and flexural strength of concrete, and thus improve the durability of concrete (Lau et al., 2020). Therefore, adding fiber has become one of the hot research directions for realizing long-life pavement. The research of FRCP started in the 1960s, and since the 1980s, it has been widely used in the United States, Japan and other developed countries (Shen et al., 2012). FRCP has been widely used in the construction of special pavements (such as airport pavements) and in the protection, repairment and reconstruction of cement concrete pavements (Pramod et al., 2015). FRCP overlay can effectively reduce the thickness of overlay, improve fatigue performance, and increase service life (Ali et al., 2020).

The fibers added to enhance the service life of cement concrete pavement mainly include steel fiber and polypropylene fiber. Steel fiber reinforced concrete pavement (SFRCP) has high elastic modulus and stiffness modulus, which improves the compressive cracking resistance of concrete pavement, but reduces the construction workability of concrete, and the corrosion of steel corrodes concrete (Fiore et al., 2015; Jiang et al., 2014; Sarkar and Hajihosseini, 2020). SFRCP is usually used in the construction of airport pavements due to its high cost. In China, the development and application of SFRCP began in the mid-1970s, and the application of SFRC in pavement engineering began in the early 1980s, available in Taiyuan, Shenyang, Anqing, Daqing and other cities.

As a non-structural reinforcing material, polypropylene fiber (PF) can improve the stress distribution of concrete, reduce bleeding and isolation, and improve the internal uniformity of concrete (Shen et al., 2012). Through compression tests, Liu and Wang (2020) found that PF cement slurry had better ductility than ordinary cement slurry, maintained the integrity of the specimen under load, and did not collapse even in the process of failure. Yew et al. (2015) studied the properties of different PF reinforced concrete. PF reinforced concrete can effectively improve the cohesion and crack resistance of concrete, and significantly inhibit the plastic shrinkage cracking and temperature deformation of concrete, thus prolongs service life of concrete (Yew et al., 2015; Zhang et al., 2013c).

In addition to the above two kinds of FRCP, there are also basalt fiber (Branston et al., 2016; Sun et al., 2019) and other polymer fiber. However, a single fiber can only enhance the individual properties of concrete. Therefore, mixed fiber reinforced concrete (Afroughsabet et al., 2016; Ayub et al., 2014) was studied. It is expected that the fiber reinforced concrete pavement structure with better performance and longer service life can be designed.

3.2.1.3. *Two-lift concrete pavement*. Two-lift concrete pavement (2LCP) refers to the laying of two different layers of concrete (wet-on-wet), rather than the traditional homogeneous single-layer pavement structure, and has ideal surface characteristics (Hu et al., 2019). Compared to traditional concrete pavement, the bottom layer allows for the use of more economical concrete such as local or recycled aggregates, and by optimizing the mix design of the top layer, 2LCP can exhibit good surface characteristics (superior durability as well as low noise and skid resistance) (Fig. 24). One of the typical applications of modern 2LCP is to provide a high friction surface by exposing the concrete aggregate of the bottom layer to improve the bonding between layers and enhance durability. 2LCP can also use roller compacted concrete (RCC) or permeable concrete on the bottom layer to improve the pavement life (Hu et al., 2014a).

2LCP has been studied and applied in the United States for more than a century. The first 2LCP occurred in Bellefontaine, Ohio, in 1891, and is still in service today (Snell and Snell, 2002). Another classic 2LCP project in the United States, the Belknap Place project in San Antonio, Texas, in 1914, is still in service today. The 1976 LOWA US-75, with recycled aggregate for the bottom layer and new aggregate concrete for the top layer, has performed well so far. The 2LCP structure was also adopted on U.S. Highway 2 in the same year. Until 1997, the pavement deteriorated and was repaired with asphalt cladding (Lan, 2018).

In Europe, 2LCP is more commonly used than in the United States. For instance, standard concrete pavements in Austria are constructed according to the 2LCP code. Moreover, 2LCP is already widely used in countries such as Switzerland, Belgium, the Netherlands, France and Germany (Tompkins et al., 2012). Belgium's current road projects are all devoted to the repair and renovation of old cement concrete pavement. The main type of pavement is two-layer paved continuous reinforced concrete pavement (2L-CRCP). In the

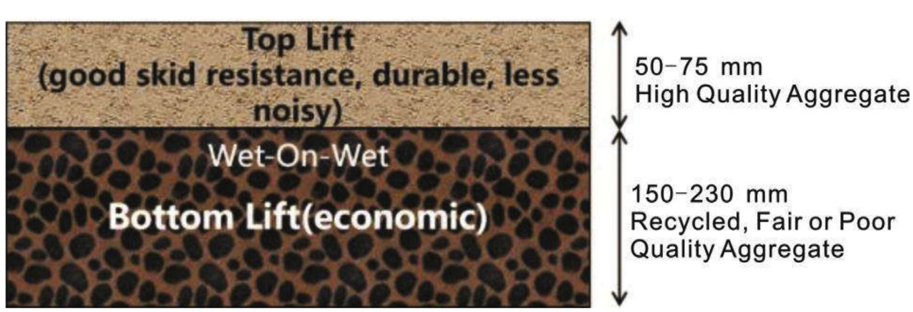


Fig. 24 – Structure diagram of 2LCP.

2L-CRCP, coarse aggregate with a high coefficient of thermal expansion can be used as the bottom layer (in a single CRCP, since the maximum temperature and humidity variation is 5−7.5 cm (2−3 inches) on the pavement surface, the aggregate with a high coefficient of thermal expansion could lead to potential spalling problems) (Hu et al., 2014a).

The cracks in concrete caused by freeze-thaw cycle is one of the main distresses of cement concrete pavement in seasonal frozen soil area. In seasonal frozen soil area, freeze-thaw cycle leads to internal damage of concrete, especially in interfacial transition zone. Interfacial transition zone is the weak link of multiphase composites, which is the most likely to deteriorate first under the comprehensive action of environmental load. At present, 2LCP is a good choice for resisting freeze-thaw environment. The top layer of PF reinforced concrete has better freeze-thaw damage resistance and less mass loss than that of ordinary Portland cement concrete (Zhou et al., 2020a). Yeon and Kim (2018) found that phase change materials (PCMs) have a positive effect on alleviating freeze-thaw degradation of concrete pavement, which became minimal when the ambient temperature was much lower than the transition temperature. In India, 2LCP is often constructed by paving pavement quality concrete (PQC) over dry lean concrete (DLC) and adding micron plastic sheets between layers to eliminate interlayer reflective cracks (Swarna et al., 2021).

Considering the wide application of CRCP pavement structure globally in recent years, it is necessary to review its design, construction and road performance.

3.2.2. *Design, construction and performance of CRCP*

CRCP gains popularity in many countries for its high performance and low maintenance cost under heavy traffic loadings and challenging environmental conditions provided proper design and construction practice are implemented (Gh et al., 2021; Hall et al., 2007; Li et al., 2017b; Li and Liu, 2014; Oh et al., 2017; Stempihar et al., 2020; Tyson and Tayabji, 2012; Yang et al., 2020b; Zhang and Huang, 2020; Zuo, 2010). The majority of these CRCPs have provided long-term service life, while few countries stopped building CRCP because of some unsatisfactory experiences due to inadequate design, nondurable materials, and construction-related deficiencies. However, some countries and their provinces made continuous improvements to evolve CRCP into a much more reliable pavement type.

3.2.2.1. CRCP distress and its mechanism. In the 1993 AASHTO guide, the performance criteria of CRCP include crack spacing, crack width, and the tensile stress in the steel. It was used to believe to carefully analyze the CRCP structural design, selected materials, and the construction process so that an optimal transverse crack pattern develops, which in turn minimizes the development of premature pavement distress. However, there are several confounding factors which cannot be as readily controlled during construction practices (Jung et al., 2012; Ren et al., 2013a, b; Zhao, 2015). A new comprehensive mechanistic based design was developed for CRCP under the NCHRP 1-37A program, and the performance criteria comprise punch-out development and smoothness, as well as crack width if deemed necessary. Several field investigations recognized the influence of crack pattern on punchout development (Tayabji et al., 1998; Vandenbossche et al., 2012; Won, 2011). The analysis of several long-term pavement performance (LTPP) sections in the United States has shown that the majority of punchouts occur in CRCP that has transverse cracks spaced from about 0.3 to 0.6 m and especially in clusters of closely spaced cracks. However, CRCP with a crack spacing of less than 0.6 m has been reported performed well under good base support conditions and tight crack width (Hall et al., 2007; Tyson and Tayabji, 2012). Besides, several investigations tentatively revealed that many distresses identified and recorded as punchouts in Texas were not actually caused by structural deficiency. Rather, most of the distresses were caused by imperfections in design details, inadequate construction activities and/or variation in the material quality issues (Won, 2011).

Horizontal cracking appears to be another major cause of distresses in CRCP, which is especially frequently reported in Texas. The interactions between longitudinal steel and concrete in response to dynamic wheel loading applications appear to be the cause of horizontal cracking (Choi et al., 2011a; Kim and Won, 2004; Won et al., 2002). Significant tensile stress occurred in concrete near the longitudinal steel because of environmental load and steel restraint. In addition, horizontal cracking could be affected by concrete material properties, environmental conditions, and longitudinal steel layout (Kim and Won, 2004; Won et al., 2002). Lastly, the distress of spalling is reported only when siliceous river gravel is used, and considered being construction practices and the weather condition at the time of the construction (Choi et al., 2020b; Wang and Zollinger, 2000; Zollinger et al., 1994). To further improve CRCP performance by minimizing distresses not related to the structural capacity of the pavement system, an enhanced understanding of the behavior of CRCP on a meso-scale when subjected to environmental loading is needed.

3.2.2.2. The importance of crack pattern on CRCP performance. To a large extent, the performance of CRCP depends on its early-age behavior. Thus, some researchers have studied the early-age behavior of CRCP (Cho et al., 1997; Johnston and Surdahl, 2006, 2007; Kim et al., 2000, 2003; Kohler and Roesler, 2004; Nam et al., 2006; Tayabji et al., 1999; Zhang and Wang, 2011). In addition, there are a lot of differences in climate, material, traffic, structure, design level, and construction techniques among the CRCP of different countries, which have significant effects on the early-age behavior of CRCP.

Transverse crack spacing is the most frequently used performance indicator of the structural response of CRCP, mainly because it is the most visible one. It was commonly regarded nowadays that the shorter crack spacing is not desirable, as it will increase the potential of punchouts development (FHWA, 2009). However, many field investigations show that the slab support and construction conditions, not crack spacing, are more responsible for punchouts (Verhoeven, 1993; Won, 2009; Zollinger, 1989). Thus, the latest CRCP design procedure in China and United States does not provide recommendations on the control of minimum crack spacing (NCHRP, 2004). Finally, it should be noted that with respect to crack spacing, cluster cracking and Y-cracking that could be problematic in terms of their contribution to punchouts. Thus, the efforts to evaluate the causes of cluster cracking in CRCP, and subsequently methods to reduce them are believed to improve the CRCP performance.

To assure excellent long-term performance of CRCP, one of the most important factors that should be considered is the width of transverse crack. The transverse crack width is not always constant and varies due to environmental loads. The crack width and its movements should be retained as smaller as possible toward better performance of CRCP. For instance, due to the formation of small crack width movements, limited reflection cracking in asphalt or concrete overlays on existing old CRCP (Mokarem et al., 2007; Volle, 2001) as well as good performance of composite pavements of asphalt layer on CRCP have been observed (Rao and Darter, 2012; Tompkins et al., 2010; TRB, 2013a). However, even though the crack width is used as one of important design variables of CRCP, the relationships between crack width and other variables are not clearly verified based on in-situ tests (AASHTO, 1986; FHWA, 2004, 2012; Ha et al., 2012; Kohler, 2005; Nam et al., 2007; Suh et al., 1992). Different models have been proposed to predict the crack width in CRCP (Beyer, 1949; Kohler and Roesler, 2005; Oeser et al., 2012; Palmer et al., 1988; Reis, 1965; Sato et al., 1989; van Breugel et al., 1998; Won, 1989; Oeser et al., 2012). Therefore, comprehensive studies to understand crack width behaviors of CRCP are needed.

3.2.2.3. *Corrosion of longitudinal steel*. Although CRCP yields a longer life span than jointed plain concrete pavements by maintaining its smoothness for at least 20−30 years (Roesler et al., 2016), steel corrosion remains a major problem, which reduces its service life and increases maintenance costs (Choi and Chen, 2005). The corrosion of the longitudinal steel can result in a poor bond relationship between the steel and the concrete, affecting the load transfer efficiency between the adjacent panels and being responsible for the development of CRCP distresses (Benmokrane et al., 2008; Choi and Chen, 2005, 2015; Liu and Lin, 2012; Walton and Bradberry, 2005). Verhoeven (1993) found that the degree of corrosion was nevertheless extremely low for a pavement service of 20 years. Similar findings were reported by as well, the sampled cores showed that the rebar corrosion appeared only within approximately 150 mm from the transverse cracks even though horizontal cracks along the rebar were extended at a greater length (Hong et al., 2021a).

Recently, corrosion-resistant materials such as glass fiber-reinforced polymer (GFRP) or blast fiber reinforced rebars (BFRP) have been proposed as an alternative longitudinal reinforcement in CRCP in order to improve the bond condition between the longitudinal reinforcement and concrete (Benmokrane et al., 2020; Chen and Choi, 2011; Choi and Chen, 2015; Gu and Dong, 2012; Liu and Lin, 2012). Based on the field results after several years of service under actual traffic conditions, competitive performances were reported in comparison to CRCP with steel bars (Hong et al., 2021a).

3.2.2.4. *AC+CRCP composite pavement*. The composite pavement, which combines the high strength of continuously reinforced concrete (CRC) with the driving comfort of the asphalt pavement (AC), has longer service life and lower maintenance cost, and is believed as one prospective type of long-life pavement. China has vigorously promoted the construction of composite pavement structures with continuously reinforced concrete under layer and asphalt concrete upper layer (CRC+AC) in many provinces, such as Hunan, Hubei, Jiangsu, and Zhejiang (Li et al., 2011, 2012c; Chen et al., 2007a; Liu et al., 2008). The main obstacles of extend to implement composite pavement of CRCP include the transverse cracking of the CRC layer due to temperature reduction, the shrinkage of cement concrete materials, and the reflection fatigue cracks at the transverse cracks of AC layer due to vehicle cyclic loading (Chen et al., 2017a).

Continuously reinforced concrete pavements (CRCP) with porous asphalt (PA) wearing course have been built on several major motorways in the Netherlands in the past two decades (Ren et al., 2016). In general, the PA/CRCP pavement sections are in good condition without severe distresses, rutting, or raveling in the PA wearing course. However, there are few minor-severity to medium-severity transverse reflective cracks in the PA wearing course in several sections.

3.2.2.5. *CRCP maintenance and rehabilitation*. Although CRCP is structurally sound and provides acceptable ride quality for the major portion of its service life, continuously moving traffic polishes the pavement surface and often leads to undesirable skid levels, which lead to the potential for skid-related accidents (Alauddin and Tighe, 2008; Volle, 2001). Factors such as tire pressure, wandering patterns, and traffic loads may also influence the deterioration of the surface properties. Thin-layer surfacing has been predominantly used for functional improvements, particularly in Texas and some other European countries (Ryu et al., 2013b). Diamond grinding (DG) is another type of the relatively inexpensive maintenance techniques for CRCP to maintain concrete pavements in good structural condition (Buddhavarapu et al., 2013, 2017; Chen and Hong, 2014; Rao et al., 1999). From Texas DOT's experience, the cost of resurfacing with diamond grinding is less than half the estimated cost of an asphalt overlay (Buddhavarapu et al., 2013). Despite such appreciable immediate functional improvements, the durability of the reported benefits remains unclear. It is necessary to quantify the deterioration tendencies overtime of the diamond-ground surface in terms of the relevant functional properties.

3.2.3. *Durability of the cementitious materials in concrete pavement*

Under the real service condition, the cementitious materials in the concrete pavement can be affected by various environmental factors, including deicing salts (Shi et al., 2009), salty underground water (Jackson and Jobbagy, 2005), freeze-thaw cycles (Li et al., 2012e) and etc. The developed durability issues can lead to the deterioration of the cementitious materials in the concrete pavement, and reduce its service life (TRB, 2013b). Then it is essential to study the durability mechanism of the cementitious materials and propose durability enhancing protocols. The major durability issues for the cementitious materials in concrete pavement include sulfate attack (Lossing, 1966), freeze-thaw issues (Li et al., 2012e; Sharifi et al., 2019), alkali-aggregate reaction (West, 1996). The detailed durability mechanism and latest findings in the related area are shown below.

3.2.3.1. *Deterioration mechanism of sulfate attack and its influence on concrete pavement*. The sulfate attack was mainly caused by the sulfates in the external environment (Müllauer et al., 2013), which can be separated into the chemical and physical sulfate attack. The chemical sulfate attack was generated by the reaction between the sulfates and the aluminates, and the produced expansive ettringite will crack the cementitious materials (Müllauer et al., 2013). The physical sulfate attack was caused by the crystallization pressure of the sulfates under wet-dry cycles (Guo, 2021; Najjar et al., 2017). The developed sulfate attack in the concrete pavement can lead to surface crack and deterioration of its mechanical performance. The sulfate attack can be severe in the saline environment, salt lakes and coastal environments (Chang et al., 2021). To enhance the resistance to sulfate attack, it is recommended to use cementitious materials with low aluminate content (Hossack and Thomas, 2015). The enhanced density and reduced permeability can also enhance the durability under the salty condition with high sulfate content (Atahan and Dikme, 2011; Nie et al., 2015).

The study by Liu et al. (2020c) indicates the sulfate attack in concrete pavement can be accelerated by fatigue loading and the wet-dry cycles. Both the wet-dry cycle and the fatigue loading can accelerate the entrance of the sulfates into concrete pavement.

3.2.3.2. *Development of alkali-aggregate reaction in concrete pavement*. The alkali-aggregate reaction indicates the interaction between the alkaline pore solution and the aggregate in concrete (Dentglasser and Kataoka, 1981), which can be separated into alkali-silica reaction (Hobbs, 1988) and alkali-carbonate reaction (Grattan-Bellew et al., 2010). The alkali-silica reaction was caused by the dissolution of the reactive silica in the alkaline concrete pore solution (Hobbs, 1988). The generated alkali-silica gel will expand under high humidity condition and crack the cementitious materials. Meanwhile, the report on the alkali-carbonate reaction is quite rare and it can be mainly observed in the concrete with Dolomite (Grattan-Bellew et al., 2010). The developed alkali-aggregate reaction will lead to the typically mapping cracking in the concrete pavement and can accelerate the rebar corrosion due to the enhanced permeability (Hong and Shim, 2015). To enhance the resistance to alkali-silica reaction, it is recommended to use the cement with low-alkali. The introduced pozzolanic materials can also mitigate the alkali-silica reaction by lowering the alkalinity of the pore solution and consolidating the alkali content. Currently, the practical protocols to resolve the alkali-carbonate reaction issues are still quite limited.

The reactive aggregate in concrete pavement can lead to mapping cracking and deterioration on its mechanical performance (Wang et al., 2019d). The degradation rate for the tensile strength is much more significant than that for compressive strength. The study by Wang et al. (2019d) indicated the alkali-silica reaction (ASR) damage can be effectively mitigated by optimizing the cementitious system with fly ash or glass powder. Further study (Guo et al., 2018a) through X-ray CT analysis indicated the added supplementary cementitious materials can obviously reduce the crack development in concrete with reactive aggregate. The study by Guo et al. (2019a) unveiled the mitigation mechanism of lithium salt on alkali-silica reaction. It is found that the lithium salt can form the Li-Si compound on the surface of the reactive aggregate and prohibit its further development. This protocol has been applied to treat the concrete pavement deteriorated by the ASR damage. The study by Guo et al. (2017b) simulated the crack development process due to ASR damage through the displacement discontinuity method. It is found the expansion pressure of the ASR gel can exceed 10 MPa.

3.2.3.3. *Influence of freeze-thaw cycles on concrete pavement*. The freeze-thaw is one of the most severe durability issues for the concrete pavement in the cold regions (Cai and Liu, 1998; Sun et al., 1999). Currently, the freeze-thaw mechanism has not been fully understood. The major theoretical model includes the hydrostatic pressure theory (Powers, 1958), osmotic pressure theory (Powers, 1975) and the crystallization pressure theory (Scherer, 1999). The freeze-thaw damage level can be influenced by the air void structure and the saturation degree of the concrete materials. The freeze-thaw damage can lead to D-cracking in concrete pavement and the surface spalling (Janssen and Snyder, 1994). The freeze-thaw durability can be enhanced by optimizing the air void structure of the concrete by using air entrainment agent.

The study by Guo et al. (2017a) indicated freeze-thaw damage can reduce the elastic modulus of the concrete slab through the analysis with falling weight data. The developed freeze-thaw damage will lead to the transverse crack and the joint spalling. The study by Ma et al. (2020a) indicated the freeze-thaw cycles can reduce both the compressive strength and elastic modulus of the base for pavement. The long-term performance under freeze-thaw cycles can be enhanced through treatment with polyurethane. It is found the soft organic aggregate can provide additional space for the expansion of the pore solution under frozen state and thus enhance the freeze-thaw resistance of the concrete (Hu and Dai, 2018). The study by Si et al. (2017) indicated the long-term performance of concrete under freeze-thaw cycles can be enhanced by using rubber aggregate.

3.2.4. *Summary and outlook*

After the field practices and researches by scholars and engineers reviewed, the CRCP is proved to be the best option for the long-life rigid pavement. However, the CRCP still exhibits distresses such as punchout. With the 2LCP concept, the advantages of FRC, and the durability issues considered, the CRCP with a top lift of FRC and a bottom lift of concrete with reclaimed concrete/asphalt materials would be the future trend for the long-life rigid pavement. Especially, this kind of rigid pavement totally meets the call of carbon emission reduction. Specifically, the use of reclaimed concrete/asphalt materials reduces the carbon emission while the FRC top lift has less cracks, which protects the steel from corrosion and the concrete with reclaimed concrete/asphalt materials from moisture, salts or freeze-thaw impacts.

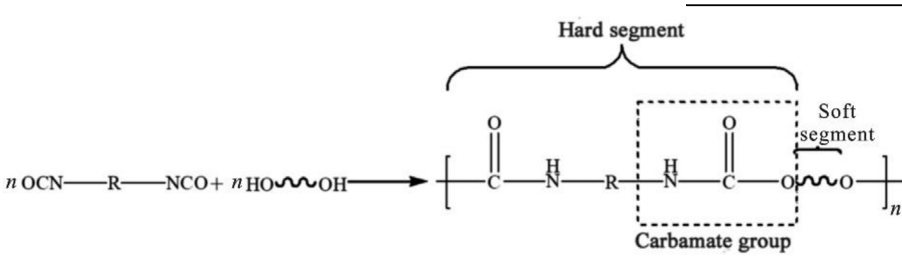
The freeze-thaw cycles, sulfate attack and alkali-silica reaction damage can all reduce the mechanical performance of the concrete slab and the deterioration on tensile strength is more obvious than that for compressive strength. The sulfate attack in concrete pavement can be accelerated by the repeated transportation loading. The ASR damage in concrete pavement can be mitigated by optimizing the cementitious system with supplementary cementitious materials or using lithium salt. The freeze-thaw resistance of the concrete pavement can be enhanced by using soft organic aggregate.

3.3. Novel polymer pavement materials

In recent years, a novel polyurethane (PU) material, whose backbone contains a repeating carbamate group (–NHCOO–) which is synthesized from isocyanates and polyols (Sharmin and Zafar, 2012), has been gradually considered to be a substitute for the conventional asphalt binder (Cong et al., 2018; Di Graziano et al., 2020; Lu et al., 2019b) due to its excellent adhesion with aggregates, high elasticity, chemical corrosion resistance (Hong and Xian, 2018; Hong et al., 2018), light resistance (Hong et al., 2020a), abrasion resistance, strong shock absorption, tear resistance, designable hardness and softness, low-energy (Hong et al., 2021b), environmental conservation (Hong et al., 2021b), etc. In addition, polyurethane can be also used as the asphalt modifier (Li et al., 2021a).

3.3.1. Designable PU material

3.3.1.1. PU binder. The reaction mechanism of PU can be seen in Eq. (22) (Hong et al., 2021b). As shown, PU is made up of hard segments and soft segments which provide the strength and toughness (Hepburn, 1992), respectively.



(22)

Contrary to the non-designability of conventional asphalt binder due to its composition complexity and uncertainly, PU is a "designable" polymer material that can have a variety of properties by changing the type and chemical structures of raw materials and even their mix proportion in accordance with the materials genome initiative (MGI) proposed by the United States (Drosback, 2014). According to the method of material genome design, the genetic characteristics of PU mainly include material composition, special functional groups, void structure and processing parameters. The material composition consists of isocyanates, polyols and additives, among which the additives consist of catalysts, crosslinking agents, solvents, plasticizers, durability additives, chain extenders, flame retardant, fillers, colorant, etc. Therefore, the PU binder can be designed on the requirements for road performance.

3.3.1.2. PU mixture. Due to the various advantages mentioned above, in recent years, PU mixtures have been considered for use on a variety of pavements, such as light-load pavements (park roads, sidewalks, sports grounds, runways, etc.), bridge deck pavement, permeable pavement (Chen et al., 2018b; Lu et al., 2020a), ultra-thin friction course (UTFC) (Hong et al., 2021b), etc. Considering the applications environment, polyurethane mixture (PUMs) are also inevitably subjected to the complex environment caused by external environmental and traffic load. Different areas, traffic volumes and uses of roads have different requirements on the performance of pavement materials. Therefore, the on-demand design of pavement materials is urgent.

3.3.1.3. Material genome design. Similar to asphalt mixtures (Xing et al., 2020), PUM also consists of aggregates, voids and binder. Thus, the genetic characteristics of PUM mainly include the mineral composition and morphological characteristics of aggregates, micro-structure and meso-structure of PUM, the above genetic characteristics of PU and processing parameters.

The material genome design involves three basic elements, such as computational tools, experimental tools and digital data. In general, the material genome design for PUM consists of three steps: 1) create a material and processing genome database; 2) establish the corresponding relation between the genome characteristics and the performance of PUM based on the high throughput characterization and a small number of tests; 3) determine the genomic characteristic parameters of PUM on demand.

3.3.2. Novel polymer bridge deck pavement material

3.3.2.1. Requirements for the bridge deck pavement material. The bridge deck pavement is a protective layer laid on the bridge deck, which is designed to prevent the wheels or tracks from wearing the bridge deck directly, to spread the wheel load and to provide a smooth and non-skid driving surface for vehicles (Huang, 2019). The bridge deck pavement should meet the following basic requirements (Xu et al., 2015c): 1) light weight; 2) good flexibility or extensibility under repeated vehicle loads; 3) cracking resistance at low temperature; 4) good deformation stability under repeated vehicle loads or at high temperature;

5) imperviousness; 6) good smoothness; 7) high wear resistance and skid resistance. Therefore, it is essential for the bridge deck pavement material to have excellent performance, including high temperature performance, low temperature performance, mechanical properties, fatigue performance, water stability, imperviousness, skid resistance performance, smoothness, etc.

3.3.2.2. Polyurethane bridge deck pavement material (PUBDPM). In recent years, the environmental protection and carbon neutrality have gradually become global and social requirements. However, the conventional asphalt bridge deck pavement material can produce a lot of asphalt fume containing mainly volatile organic compounds (VOCs), which is not conductive to both environment protection and carbon neutrality. Moreover, the material genome design will also become a trend (Drosback, 2014). In addition, Li et al. (2018a, b) indicated that it is of great theoretical significance and engineering value to develop a long-life polymer concrete bridge deck pavement material with low temperature sensitivity and strong water and corrosion resistance. To sum up, a novel polymer binder meeting the above requirements, a substitute for conventional asphalt binder, is imperative.

As mentioned above, PUM has been considered to be designed as the bridge deck pavement material, which was mainly reported by the Prof. Shifa Xu's team from Beijing University of Civil Engineering and Architecture (Li et al., 2018a; Shi, 2018; Wang et al., 2018b; Xu et al., 2020b). Li et al. (2018a) also indicated that the novel polyurethane bridge deck pavement material (PUBDPM) is a high-performance and durable pavement material. In contrast to the commonly used epoxy asphalt bridge deck pavement material (EABDPM), the PUBDPM has a series of excellent performance (Li et al., 2018a), including high temperature performance, low temperature performance, fatigue performance and water stability. For the high temperature performance, the dynamic stability of PUBDPM is more than 5 times that of EABDPM; for the low temperature performance, the maximum bending tensile strain at −10 °C of PUBDPM is more than 6 times that of Gussasphalt concrete; for the fatigue performance, the fatigue life of PUBDPM is more than 10 times that of EABDPM; for the water stability, the residual splitting strength of PUBDPM is stabilized after the first freeze-thaw cycle while the residual splitting strength of EABDPM is still going down with a big drop after several freeze-thaw cycles (Li et al., 2018a). Therefore, this novel polyurethane bridge deck pavement material could lead to a major change in the bridge deck paving industry (Li et al., 2018a).

Wang et al. (2018b) has listed the road performance of PUBDPM (Table 16), and indicated that: 1) both the dynamic stability and maximum flexural-tensile strain at −10 °C of PUBDPM is more than 10 times than that of the optimal asphalt mixture; 2) the fatigue life of PUBDPM is approximately 8 times that of stone matrix asphalt (SMA) mixture; 3) the residual splitting strength of PUBDPM after the freeze-thaw cycle can still reach 0.8 MPa, which can fully meet the requirements of road use.

In terms of the durability of PUBDPM, Xu et al. (2020b) investigated the long-term performance of polyether polyurethane concrete (PPC) under the photothermal coupling aging and thermo-oxidative aging, compared to the SBS modified asphalt mixture (SBSM). In contrast to SBSM, the results showed that PPC possessed better anti-loose performance, low temperature crack resistance, stronger ability of permanent deformation resistance, water stability and fatigue resistance. However, although PUBDPM has been investigated, the previous studies are still in the preliminary stage since there is lack of field engineering project application (Xu et al., 2020b).

3.3.3. *PU permeable pavement*

3.3.3.1. Permeable pavement. Permeable pavements can support the restoration of the natural hydrological cycle and mitigate the risk of urban flooding as well as the urban heat island effect. In general, permeable pavements are implemented by using porous materials with large void contents to allow the rainwater to seep directly through the pavement surface (Sun et al., 2018a). During a rainfall event, water can infiltrate through the pavement structure into subsoil quickly, which consequently reduces the requirements to urban drainage systems and facilitates the restoration of the natural water cycle (Scholz and Grabowiecki, 2007). At the same time, the evaporation of water in the structure can reduce excessive heat, thereby counteracting the urban heat island effect (Santamouris, 2013). Because of these superior environmental-friendly features, permeable pavement systems are particularly suitable for applications in residential, commercial and industrial areas under light traffic loading.

To achieve the high permeability, a void-rich pavement structure is currently recognized as the most feasible and effective way, such as porous asphalt (PA), pervious concrete (PC) and permeable interlocking concrete pavement (PICP)

Table 16 – The road performance of the polyurethane bridge deck pavement material (PUBDPM) (Wang et al., 2018b).

Technical index	Test result	Technical requirement	Test method*
Dynamic stability (70 °C, 0.7 MPa) / (passes/mm)	69,750	≥6000	T 0719
Residual splitting strength after freeze-thaw (MPa)	0.80	–	T 0729-2000
Fatigue life (15 °C, 1200 με) (10^4)	168	–	T 0739
Low temperature bending tensile strain (−10 °C) (με)	48,762	≥2000	T 0728
Water permeability coefficient (mL/min)	Completely impervious to water	≤200	T 0730

Notes: * All the test methods are derived from the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011, China) (MTPRC, 2011).

(Oeser et al., 2012; Scholz and Grabowiecki, 2007). In this case, an open-graded grain size distribution ensures the required void contents and pore-structures within the pavement. Different models and design methods have been proposed by considering the grain size distribution to analyze the effect on the hydraulic properties (Martin and Kaye, 2016). Furthermore, three types of permeable pavement structures have been evaluated based on their water-filtration properties, especially for cold regions (Huang et al., 2016a). To optimize the hydraulic conductivity of permeable pavements, a combined approach was proposed; a combination of bio-retention ponds, infiltration galleries and permeable pavements enhancing surface runoff behavior (Perez-Pedini et al., 2005). To fundamentally understand the void distribution in the open grade asphalt concrete, X-ray CT was performed, where the effects of void diameter, void tortuosity and minimum sectional dimension on the hydraulic behavior were analyzed (Xu et al., 2017). Based on X-ray CT measurements, a numerical permeability model was proposed for the open-graded asphalt concrete. In addition to the high hydraulic conductivity, the porous structure can also reduce the air pumping effect observed in the tire/pavement interaction, which is the major cause of traffic noises (above 1000 Hz) at high speeds (Hernandez-Olivares et al., 2007; Meiarashi et al., 1996). The absorption properties of porous pavement structures also contribute to a reduction of noise emissions, based on the same absorption principle as acoustical wall treatment.

Apart from the functionality, the mechanical properties of permeable pavements were also widely investigated to evaluate the durability. To develop an effective life-cycle maintenance strategy to mitigate the risk of permeability deterioration, an artificial soiling test was developed to simulate the clogging process during the service life of porous asphalt (Meiarashi et al., 1996). A wide range of fatigue tests were performed in comparison to conventional rigid pavements to characterize the mechanical behavior. Most studies were performed at the most ideal conditions. In a complex service environment, various water levels may occur in the porous pavement structure, resulting in various possible combinations of air, liquid and solid. Moreover, the downward filtration and the upward movement of moisture in the sublayer and soil, porous pavement structures are mostly found to be in an unsaturated state. Here, multi-physical processes occur such as freezing and spalling, drying and shrinkage, hydro diffusion and subsidence, and capillarity and cracking (Coussy, 2005). Each one of these processes, involving more than two physical phases, result in complex loading conditions, which have a significant influence on the pavement behavior (Kettil et al., 2005). To address this problem, several coupled-phase models have been established, with experimental validations. Results from numerical models and experiments begin to reveal the underlying mechanisms of porous pavements under partially saturated conditions (Loret and Khalili, 2000).

3.3.3.2. *PU porous pavement materials*. Compared to conventional pavement structures, porous pavements are not only designed to bear traffic loads, but also play an important role in noise reduction and water management (Fan et al., 2016; Jin et al., 2020; Sun et al., 2018a). To achieve a high permeability, a void-rich pavement structure such as PA and PC with open-graded aggregate are currently the most feasible and effective approach to ensure sufficiently high void contents. However, the open porous design results in a significantly weakened pavement structure as stated before; adhesion failure and the limited durability of porous pavement mixtures has been the most prominent obstacle, limiting the widespread application of permeable pavements (Bu and Cheng, 2016; Li et al., 2021a).

PU binder is one of the new potential binders initially developed through the research at RWTH Aachen University, exhibiting a high mechanical and chemical durability to overcome the challenges of conventional porous asphalt mixtures. The excellent performance of PU indicates that the material provides a favorable combination of functionality and mechanical properties (Lu et al., 2019a, b). A high resistance to deformation and fatigue of polyurethane bound pervious mixture (PUPM) pavements are proven in previous research (Chen et al., 2018a, b; Cong et al., 2018, 2019; Leng et al., 2019).

The mechanical strength of PUPM is formed based on the reaction of polyol and polymeric methylene diphenyl isocyanate (PMDI) (Desai et al., 2000). During the reaction process, the 2 liquid components cure and become solid polyurethane, thereby proving the mechanical strength between the aggregates. The manufacturing process of PUPM is illustrated in Fig. 25.

Based on the excellent properties of PU binder, a number of functional and sustainable pavement materials have been developed. Among those materials, the most widely known is poroelastic road surface (PERS). PERS is a novel type of pavement surface, which includes recycled tire rubber into low-noise pavements as aggregate (Fig. 26) (Meiarashi et al., 1996; Sandberg and Goubert, 2011; Sandberg et al., 2013), seeing in Fig. 26. Based on the PU binder applied in the previous research, the tensile strength was improved significantly in cold temperature (Wang et al., 2017d, f). The sound absorption coefficients of PERS have higher and wider peaks compared with conventional PA. It proved the suitability of PERS for urban roads in cold regions and outlined the significant economic and social benefits.

The increase of requirements for pavements in tunnels including safety, comfort and environmental friendliness, asphalt pavement has gained popularity in long tunnels due to its low noise and dust emissions, easy maintenance and good comfort. However, conventional tunnel asphalt pavements also have safety and environmental shortcomings (Hu et al., 2008; Qiu et al., 2019; Zhao et al., 2010). The innovative polyurethane thin overlay (PTO) has been developed for maintenance of existing roads and constructing new roads. Compared with conventional tunnel pavement materials, significant improvements were observed in mechanical and functional properties as well as the environmental performance. Based on the ignition tests in a previous study (Leng et al., 2019), PTO exhibited a better flame retardancy compared to asphalt mixtures, e.g., open-graded friction course (OGFC) and stone mastic asphalt (SMA), as well as a lower heat release rate (HRR). Particularly, the ignition time of PU is larger than that of OGFC and SMA, indicating that PU is more difficult to ignite than asphalt (Fig. 27).

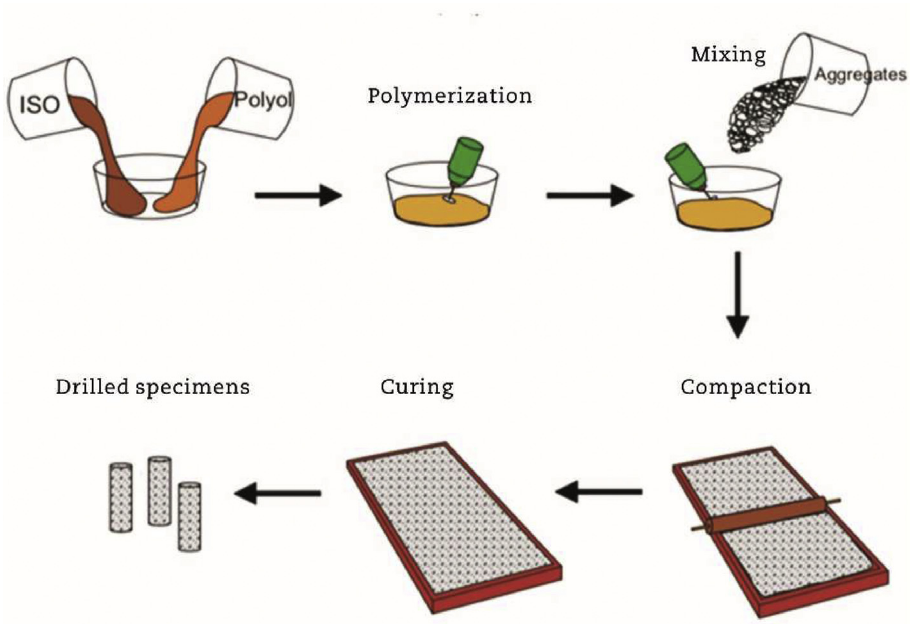


Fig. 25 – Manufacturing process of PUPM.

3.3.3.3. *Hydraulic properties of PU permeable pavement materials*. The ability to facilitate the flow of water has long been recognized as one of the main properties of pervious pavements. However, the quantification of anisotropic flow and the relationship to complex pore microstructures in pervious pavement material has yet to be completed. The objective of this chapter is to quantify the Darcy and the non-Darcy flow in pervious pavement mixtures, and to carry out investigations on the different flow models to predict the hydraulic conductivity. Conventional PA and innovative PUPM were included in a comparative study in the scope of this research. A custom-made permeameter was used to quantify and analyze the water flow characteristics in the previous pavement mixtures subjected to different hydraulic gradients. The results show that a high coefficient of vertical permeability can be achieved by both PUPM variants, reaching values 2 to 3 times higher than those exhibited by the conventional PA. The horizontal permeability of PUPM variants is similar to each other, yet twice as high as the ones observed in PA. The application of a different binder can be considered as the reason for the difference. The PU binder provides a smoother coating of the aggregate, which promotes the development of optimized pore structures and pore connectivity for the infiltration process.

(a) (b)

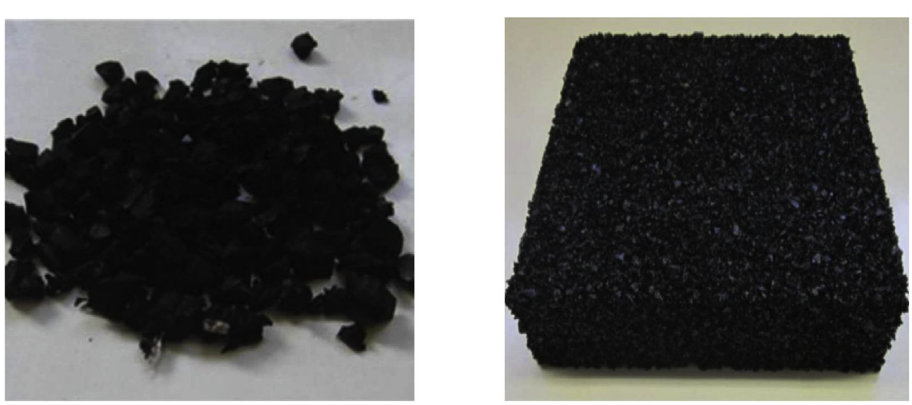


Fig. 26 – Comparison of coarse rubber aggregate and PERS specimen. (a) Coarse rubber aggregate. (b) PERS specimen (Wang et al., 2017f).

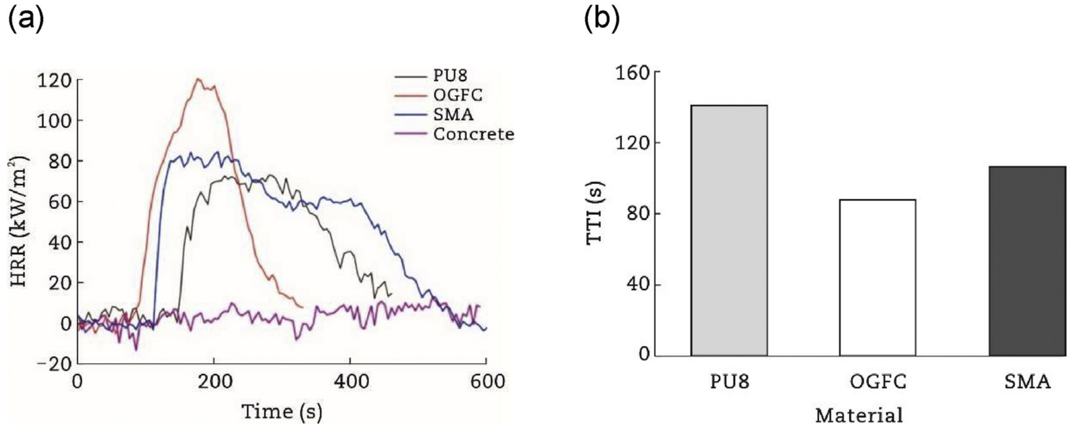


Fig. 27 – Characteristics of PU, OGFC and SMA. (a) Comparison of heat release rate (HRR) of PU, OGFC and SMA. (b) Comparison of ignition time (TTI) of PU, OGFC and SMA (Leng et al., 2019).

3.3.3.4. *Mechanical properties of PU permeable pavement materials*. From the preliminary mechanical tests, PUPM shows a significantly higher compressive strength in comparison to the PA. The compressive strengths of the PUPM variants are observed to be nearly 5 to 6 times higher than that of PA. PA and PUPM have very similar grain size distributions; therefore, the results can be evaluated regardless of the gradation and infer a higher cohesive strength between PU binder and aggregate.

To further understand the mechanical properties of PUPM, the stress-strain diagrams were also studied. In general, PUPM generally follow the same development of stress-strain curve as seen in Fig. 28. To be more precise, PUPM with bigger aggregate size (0/8 mm) depicts higher compressive strength in terms of both axial and radial deformation compared to the PUPM with smaller maximum aggregate size (0/5 mm). Basic parameters of PUPM are concluded in Table 17. The mechanical properties of PUPM were further validated and analyzed based on the full-scale accelerated pavement testing (APT) (Lu et al., 2020b, 2021).

3.3.3.5. *Environmental advantages of PU permeable pavement materials*. Besides the benefits mentioned above, another environmental benefit is found in potential energy savings and the reduction in greenhouse gas (GHG) emissions by using PU binder with recycled waste aggregates. During conventional asphalt mixture production, temperatures of the aggregate and the bitumen must be raised sufficiently high to facilitate the coating of aggregate with bitumen. This temperature must be maintained during construction to ensure the workability of the asphalt. As a result, conventional asphalt production is an energy intensive process. The PUPM, however, can be produced and constructed at room temperature and only a common compactor is requested during construction. The difference in energy use and GHG emission for producing and placing the two materials was analyzed in detail.

It is assumed that bitumen and PU have similar embodied energies, and the energy use and GHG emission in producing natural aggregate and ceramic aggregate based on C&D wastes is also comparable. The difference in energy use and

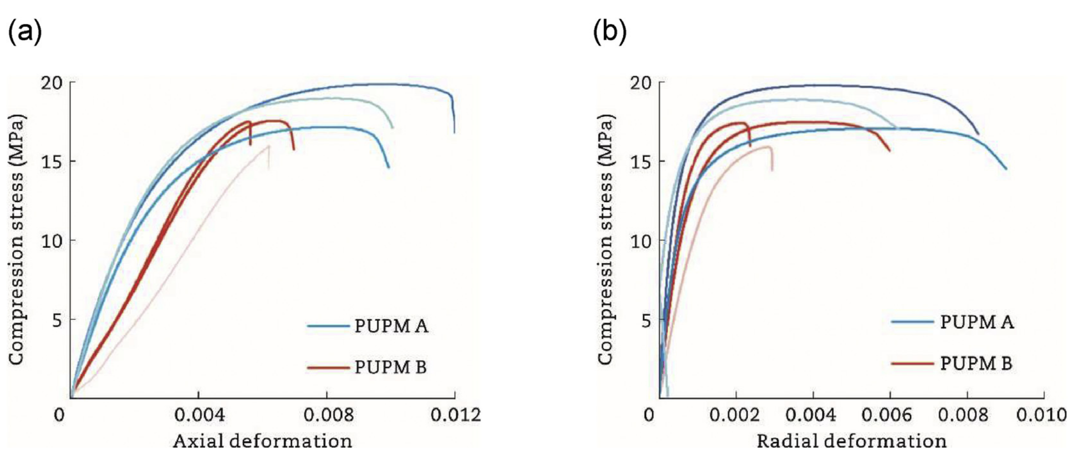


Fig. 28 – Stress vs. axial/radial strain behaviour until compressive failure. (a) Axial deformation. (b) Radial deformation (Lu et al., 2019b).

Table 17 − Mechanical data obtained by the uniaxial compressive test.

Parameter	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (E) (GPa)	Poisson ratio	Shear modulus (G) (GPa)
PUPM A	18.63 ± 1.39	3.36 ± 0.38	6.64 ± 0.08	0.210 ± 0.032	2.75 ± 0.08
PUPM B	16.98 ± 0.90	2.18 ± 0.29	3.31 ± 0.29	0.164 ± 0.024	1.42 ± 0.15

GHG emissions between the two materials is mainly manifested in mixture production and construction. Energy use and GHG emission in producing PA were estimated by using a software toolkit named green asphalt calculator (Chong et al., 2016). The software uses "a system of integrated thermodynamic models" for the prediction of energy use and GHG emission in asphalt mixture production with validation from actual production processes. In producing PUPM, the only equipment is a mixer with an electrical motor. Major pieces of equipment used for the construction of PA include a paver and compactors, while the equipment for the construction of PUPM is limited to a compactor. Data on fuel consumption during construction is obtained from the ROADEO software developed by the World Bank (Chong and Wang, 2017).

As discussed above, the differences in energy use and GHG emissions between PA and PUPM materials are mainly attributed to different mixture production and construction conditions. The production of the PA material is calculated by using the "green asphalt calculator" software, which is based on the operation of typical asphalt batch plants. The temperature of the stockpiled aggregate before production is assumed to be 20 °C, and the asphalt mixture temperature is assumed to be raised to 170 °C after production. In addition to diabase, other possible aggregate types are evaluated, and three types of fuels are evaluated. For comparison purpose, a common portable pug mill mixer is assumed for making the PUPM mixture, which does not need to be heated. The mixer has a capacity of 272 t/h with an energy consumption rate of 44.7 kW. Hence, producing one ton of the PUPM mixture requires 0.16 KW·h, equivalent to 0.58 MJ. PUPM consumes much less energy and generates less GHG emissions since it does not need to be heated for mixing and pavement manufacturing (Lu et al., 2019a).

In a typical situation, the construction of one lane-kilometer of road pavement, is assumed for comparing the different materials. The thickness of the pavement is assumed to be 40 mm and the lane width is assumed to be 3.8 m. For pavement construction using PA 8, the construction equipment includes a paver and compactors. According to data provided in the ROADEO software developed by the World Bank, diesel consumption is 0.34 L/m^3 of asphalt mixture for pavement and 0.3 L/m^3 of mixture for compaction. For pavement construction using PUPM, only compactors are needed. It is also assumed that the diesel consumption for compaction of the PUPM mixture is also 0.3 L/m^3. The results suggest that the production and construction of PUPM mixture requires much less energy and generates much less GHG emissions (less than 10% in comparison to conventional porous asphalt pavements).

3.3.4. *Polyurethane-based asphalt modifier*

3.3.4.1. Chemical and genetic characteristics of bitumen and polyurethane-based modifier. Bitumen, a by-product of oil refining, is an organic mixture of various hydrocarbons and their derivatives with a large range of molecular weights. The composition of bitumen is usually given in terms of the relative quantity of its so-called SARA (saturate, aromatic, resin and asphaltene) fractions. In terms of chemical composition, bitumen is a mixture of complex hydrocarbons and derivatives of oxygen, sulfur and nitrogen, with a large number of saturated, cyclic or aromatic structures on the whole (Lesueur, 2009). In addition to the main carbon and hydrogen (usually more than 90% of the mass), a small number of heteroatoms, such as sulfur, nitrogen and oxygen, exist in bitumen (Silva et al., 2016; Wang et al., 2021d). As a common component of polar functional group, sulfur atoms usually exist in the form of sulfide, mercaptan and sulfoxide; oxygen atoms usually exist in the form of ketone, phenol and a small amount of carboxylic acid; nitrogen atoms usually exist in pyrrole and pyridine structure.

The −NCO functional groups in polyurethane-based materials contains highly active unsaturated bond structures arranged by overlapping double bonds, so they can easily react with various compounds containing active hydrogens such as hydroxyl groups, amino groups, amino ester groups, urea groups, epoxy resins and water. The most common reactions occurred between isocyanates and hydroxyl groups, which comes together into clusters by urethane linkages. Due to the wide existence of polar aromatics and functional groups containing active hydrogen atoms in asphaltene molecules, polyurethane-based materials and bitumen have good affinity in chemical composition which lays a chemical foundation for modification (Jin et al., 2019, 2021a). Based on the unique characteristics of polyurethane in molecular structure and function, polyurethane-based materials were developed as active modifiers for bitumen modification.

3.3.4.2. The performance and modification mechanism of polyurethane modified bitumen. Various kinds of modified bitumen, such as isocyanate-polyhydric alcohol, isocyanate-natural polyol, isocyanate-nanoparticles, nano-polyurethane emulsion, polyurethane-functional materials and polyurethane-precursor modified bitumen, were prepared and investigated. The process conditions of polyurethane-based materials as a reactive modifier to prepare modified bitumen were studied. Research showed that the chemical activity of polyurethane-based modifier is presented based on the isocyanate group. Isocyanate can react with the polar groups containing nitrogen and oxygen atom groups (mainly −OH, −NH and −COOH). These functional groups in bitumen provide targeted sites for the modification (Partal and Martínez-Boza, 2011). As respect to the performance of polyurethane modified bitumen, various test methods including the dynamic shear rheometer (DSR), multiple stress creep recovery (MSCR), bending beam rheometer (BBR) and double-edged notch tension test (DENT) were carried out to evaluate the performance of polyurethane modified bitumen. The summary of related studies is listed in the Table 18.

According to the above investigations, the modifications delivered both good pavement properties and well-developed networks. However, due to the performance of polyurethane modified bitumen is strictly restricted to the raw material of polyurethane, and the modification methods are various, it is difficult to provide a consistent conclusion to the polyurethane modified bitumen. Therefore, it is an urgent task to establish a systematic evaluation system for polyurethane modified bitumen.

Based on the above foundations, a novel polyurethane-precursor-based modifier (PRM) was developed by the authors' team and employed as an eco-friendly approach to improve performance of asphalt (Carreno Gomez and Oeser, 2021; Li et al., 2021a). Based on the chemical and mechanical investigations, there are obvious chemical changes in the modification process. The covalent crosslinking network is expected to be established in PRM modified asphalt. The scheme of PRM modification is illustrated in Fig. 29.

The incorporation of PRM to the asphalt matrix can remarkably improve the high temperature performance of bitumen. Besides, the PMA presents desirable low temperature crack resistance, fatigue resistance and aging resistance. Based on the urethane and urea functional linkages formed during modification, the covalent crosslinking network structure based on the presence of asphaltene components can be established in asphalt. This process not only promotes the selective aggregation of asphalt fractions and the reconfiguration of asphaltenes, but also increases the surface free energy of asphalt, so as to obtain a more stable internal structure.

3.3.4.3. *The performance of polyurethane modified asphalt mixture*. The good mechanical performance and storage stability indicate that the polyurethane modified bitumen is an ideal material for pavement construction. The high temperature performance, low temperature performance and water stability of polyurethane modified asphalt mixture were investigated by the dynamic modulus test, rutting test, low temperature beam bending test, immersion Marshall test, freeze-thaw splitting test, etc. (Guo et al., 2018c; Jin et al., 2021b; Zhang et al., 2021j). Similar to the polyurethane modified bitumen, the basic properties of polyurethane modifier show prominent influence on the polyurethane modified asphalt mixtures. Although the polyurethane modified asphalt mixture shows good high temperature and low temperature performance, there is no consistent conclusion on water stability. In the following research, more efforts should be made on how to ensure the moisture resistance of the polyurethane modified asphalt mixtures.

Table 18 – Modification of asphalt binder using polyurethane-based modifiers.

Reference	Preparation temperature (°C)	Modifier type	Performance feature
Singh et al. (2003)	180	Isocyanate production waste particles	The modified bitumen exhibits high softening point, reduced penetration, high stiffness, low coefficient of linear thermal expansion, and reduced moisture uptake.
Fang et al. (2016c)	90	Isocyanate and nanoparticles (SiO_2 and ZnO)	The optimal high temperature stability can be obtained by isocyanate and SiO_2 nanoparticle. The ZnO nanoparticle can be used to improve the asphalt's low temperature performance.
Carrera et al. (2009, 2010a, 2010b); Martin-Alfonso et al. (2009)	90	4,4'-diphenylmethane diisocyanate and polypropylene glycol	The water-addition can bring benefits on the viscous and viscoelastic properties at high in-service temperatures.
Yu et al. (2018d)	150	Nano polyurethane emulsion	The modified bitumen shows an improved resistance to deformation and can be stable stored at high temperature.
Xia et al. (2016)	140	Renewable castor oil and liquefied MDI	The modified bitumen shows an improved resistance to deformation and can be stable stored at high temperature.
Jin et al. (2020)	145 and 150	Polyurethane and rock bitumen	The use of polyurethane can improve the low temperature performance, the introduction of rock bitumen can improve the high temperature performance.
Sun et al. (2018c)	170	4,4'-diphenylmethane iisocyanate and polyether polyol	The modified bitumen shows a greater PG grade than SBS modified bitumen, and a lower low temperature performance than SBS modified bitumen, but greater than that of base bitumen.
Fan et al. (2016)	180 and 160	Polyurethane and rubber powder	The modified asphalt shows an improved resistance to deformation.
Bu and Cheng (2016)	120	Polyurethane and epoxy	The addition of polyurethane can effectively improve the flexibility of epoxy asphalt.

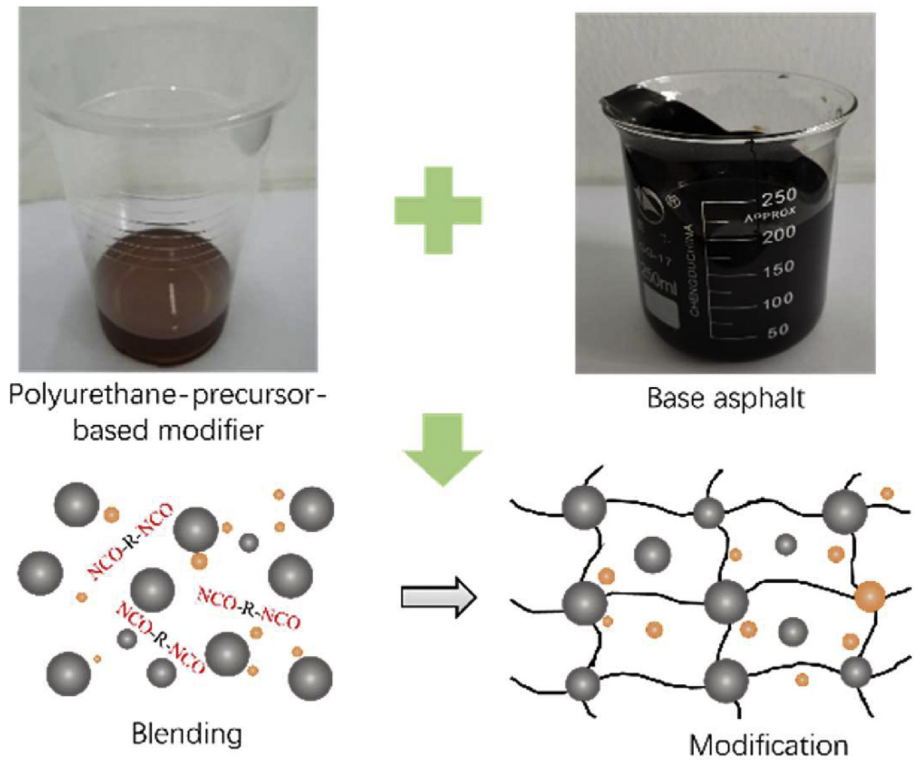


Fig. 29 – Illustration of the asphalt modification by polyurethane-precursor-based modifier.

In terms of the PRM modified asphalt mixture, the above tests have been performed on the dense-graded AC-13 according to JTG E20-2011 of China (MTPRC, 2011). Compared to the SBS modified asphalt, PRM has obvious advantages in improving high temperature performance, fatigue resistance and thermal-oxidative aging resistance of bitumen. PRM modified asphalt mixture with 2.5% concentration shows equivalent low temperature performance as well as better high temperature performance and water stability as SBS modified asphalt mixture with 4% concentration. PRM has significant advantages in improving pavement performance of asphalt mixture.

3.3.4.4. *Environmental and economic assessment of polyurethane modified asphalt*. With the rapid growth of traffic demands, using environmental modifier to prepare high performance modified asphalt demonstrates dual values is environmental protection and performance improvement of pavement.

The production of the polyurethane modified bitumen is illustrated in Fig. 30. As a consequence of the liquid pattern of polyurethane-based modifiers, the facility of colloid mill that used for the grinding of modifier particles such as the SBS, styrene-butadiene rubber (SBR) and crumb-rubber modifiers can be omitted, which leads to the simplification of production process and reduction of equipment cost. Due to the liquid-liquid blending is much easier to be facilitated than liquid-solid blending, the production temperature can be reduced to a range from 140 °C to 150 °C that the bitumen can flow fluently, which leads to a remarkable reduction of energy consumption and exhaust emission. Furthermore, the decrease of temperature can effectively weaken the damage of neat bitumen caused by high temperature, thus helping to improve the comprehensive performance of modified bitumen. Therefore, the usage of polyurethane-based modifier in the production of high performance modified asphalt demonstrates unique advantages in the simplification of production process, the improvement of blending efficiency and the protection of ecological environment.

In conclusion, polyurethane-based modifier has attracted much attention due to its good modification effect. Although

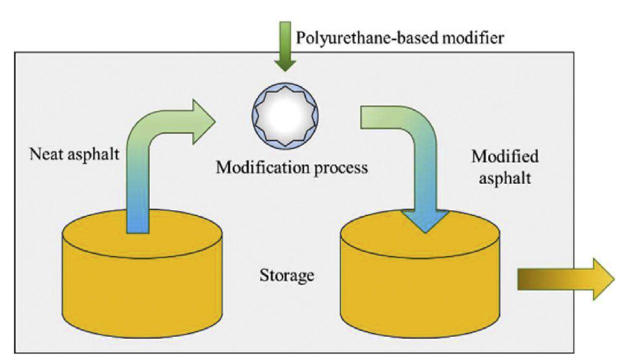


Fig. 30 – Illustration of the production of polyurethane modified asphalt.

polyurethane modified asphalt exhibits excellent high temperature performance, anti-aging performance and storage stability, the technical specifications for asphalt modified with polyurethane are not uniform. The modification mechanism of polyurethane modified asphalt still need to be further clarified, and the compatibility between asphalt and polyurethane-based modifier needs to be explained in more detail, so as to better guide the preparation and production of polyurethane modified asphalt.

3.3.5. *Summary and outlook*

With the rise of intelligent transportation and the improvement of people's demands, including high performance, high durability, environmental protection, carbon neutrality, etc., a novel polyurethane mixture (PUM) has been considered for use on a variety of pavements, such as light-load pavements, bridge deck pavement, permeable pavement, etc., due to their excellent performance, including strong adhesion with aggregates for the PU binder, high elasticity, chemical corrosion resistance, light resistance, abrasion resistance, strong shock absorption, tear resistance, designable hardness and softness, low-energy, environmental conservation, etc.

In contrast to the commonly used asphalt-based bridge deck pavement material (EABDPM), the novel polyurethane bridge deck pavement material (PUBDPM) possesses a lot of excellent performance, including high temperature performance, low temperature performance, fatigue performance and water stability. However, the previous studies are still in the preliminary stage since there is lack of field engineering project application. In the future, the practical engineering application for PUBDPM will be a focus until the necessary performance characterization and mechanism explanation are completed.

Overall, polyurethane bound pervious mixture (PUPM) is proved to be a suitable replacement for conventional porous asphalt with both excellent mechanical and functional properties. However, the improved permeability and flow velocity inside the pore structure increases the potential of water induced damaging of the PUPM-based pavement structure. Further investigations on the flow mechanism and the hydro-mechanical interaction between the PUPM and the FPP structure are necessary. Moreover, the abrasion effects due to the presence of particles combined with pore-water pressure still need to be assessed.

The pore characteristics play an important role in determining the macro flow behavior in pervious pavement materials. To further understand the flow mechanism in pervious pavement material, a more comprehensive study on the correlation between pore parameters and flow behavior is highly recommended. Apart from it, the analysis on the pore characteristics was only performed in 2D in the present research. Actually, the 3D analysis of pore structures is more close to reality, which is quite necessary for the future research. Nevertheless, the theoretical models and the analyses of pervious pavements should also be enhanced.

Polyurethane modified bitumen exhibits good high temperature performance, low temperature performance, fatigue resistance, and reduced stripping and temperature susceptibility. As an "active" method for asphalt modification, its modification mechanism and mechanical behaviors are different from the traditional polymer modified bitumen. However, there is no specialized specification for the evaluation of polyurethane modified bitumen, which leads to a gap between the laboratory research and filed application. More efforts should be made to establish the relationship between the asphalt and pavement performance. Besides, due to the polyurethane-based modifier's function depends on the chemical composition of bitumen and the source of crude oil, the modification mechanism of polyurethane modified bitumen need to be further clarified in order to maximize the modification efficiency, so as to better guide the preparation and production of polyurethane modified asphalt.

3.4. *Reinforcement materials for road base/subrgrade*

With the continuous advancement of infrastructure construction, the highway construction for special areas is increasing year by year. The performance deterioration and diseases of pavement caused by the deformation and damage of road base/subgrade gradually attract the attention of more and more scholars. Subgrade and base are the bottom bearing structure of pavement, and their excellent mechanical strength and stability are essential for the durability of pavement. At present, there are some new theories, new materials and new technologies for the stabilization and reinforcement of road subgrade and base. Novel geo-materials such as flowable solidified fill, stabilization materials for problematic soil, and geogrids are gradually applied in road base/subgrade reinforcement engineering to promote the green development of highway construction while strengthening the base and subgrade.

3.4.1. *Flowable solidified fill*

Flowable solidified fill (FSF) is a new type of material which is gradually popularized and applied in the backfilling engineering of large civil infrastructure such as highway subgrade, and can be used to replace traditional compacted fills. Different regions have different expressions about FSF. Terms used to describe this materials include controlled low-strength material, flowable fill, self-compacted backfill material, plastic soil-cement or slurry, and foamed lightweight soil. Compared with compacted backfill technology, FSF has significant advantages such as controllable performance, stable uniformity, convenient construction, wide applicability, and low carbon when used in subgrade backfill. In the early stage, FSFs were mainly composed of cement, fly ash, soil, fine sand, water and other materials (ACI 229R-13). With the increasingly severe situation of global environmental governance, more and more waste materials are used to prepare FSFs. At present, the studies on FSFs are mainly carried out from the aspects of material composition design, performance control, curing mechanism, construction applications, and environmental impact assessment.

3.4.1.1. *Material composition design*. The composition of FSFs mainly includes solidified soil (mud), binder and water. Different solidified soils have different formation methods and mineral compositions, so the binders used in the preparation of FSFs are quite different. If necessary, the solidified materials should be ground or dehydrated (Lan et al., 2020). At the present stage, the composition design of FSFs is mostly conducted based on existing experience and trial-and-error experiments (Kaliyavaradhan et al., 2019). Some scholars (Alizadeh, 2018, 2019; Pujadas et al., 2015) have introduced independent proportional parameters such as the volume ratio of paste to mixture, mass ratios of water to cementitious materials, and proportion of binders into the composition design to realize the effective regulation of the plastic and in-service properties of FSFs on the basis of reducing the amount of testing, the FSFs mix design procedure is summarized in Fig. 31. Combining the type of solidified soil, application scenes, and the type of bulk waste materials to design the composition is the main direction of the current research and development of FSFs.

There are many types of solidified materials used to prepare FSFs, such as silt, muddy soil, engineering spoil (mud), sludge, industrial waste mud (slag), and tailing (Lan et al., 2020; Qian et al., 2019a; Ran et al., 2017; Zhen et al., 2012; Zhu et al., 2013). Among them, the FSFs with silt, muddy soil, and industrial waste mud (slag) as raw materials have been applied most widely. When silt and sludge with high content of water and organic substances is used to prepare FSFs, the composition design is mainly carried out from the aspects of reducing the thickness of electric double layer, adding swelling components, increasing pH value, cracking the structure of organic substances, and adjusting the activity of soil particles (Guo et al., 2008a). The binders include cement and industrial wastes such as lime, fly ash, and blast furnace slag. At the same time, sodium hydroxide, sodium silicate and quicklime can be added to improve the pH value of the FSF, so as to reduce the consumption of humic acid on hydration products, and further promote hydration reaction and pozzolanic reaction (Chen et al., 2018c). When engineering spoils and other materials with low content of water and active ingredients are used to prepare FSFs, a small amount of mineral components in the spoil can react with the binders, and the strength of FSF mainly depends on the cementitious material generated by hydration of the binders (Chen et al., 2018c). However, when the industrial waste slag with high content of active SiO_2 and Al_2O_3 are used to prepare the FSFs, the industrial waste slag also participates in the solidification reaction after mixing with inorganic binders, so the early strength of the prepared FSFs is higher after the solidification. For the problem of drying shrinkage caused by the consumption of free water in the curing process of the FSFs, gypsum, carbide slag, active MgO and other materials can be introduced in the composition design to reduce the drying shrinkage (Do et al., 2019; Wang et al., 2020p).

3.4.1.2. Performance control. High quality FSFs should have excellent early fluidity, uniformity, self-compacting, rapid setting, adjustable mechanical strength, as well as good stability and durability (Wang et al., 2018h). The existing studies mainly focus on plastic and in-service properties when regulating the performance of FSFs. With more and more waste resources being used to prepare the FSFs, it has become an important direction to clarify the influence of various materials composition and amount on the performance of the FSFs.

Fluidity is one of the essential properties for the plastic properties of FSFs. With the increase of water content, the fluidity of FSFs increases significantly, but excessive water content can induce bleeding, segregation and strength reduction (Das et al., 2020; Ran et al., 2017). Different binders have different effects on the fluidity of FSFs. For example, the fluidity of FSFs prepared with Class C fly ash partially replacing cement is relatively high, while the fluidity of FSFs prepared with Class F and high carbon fly ashes is relatively poor (Kaliyavaradhan et al., 2019). The fluidity of FSFs is related to the fineness, hydrophilicity, particle shape, pore structure, and activity of the solidified materials (Kaliyavaradhan et al., 2019; Wu et al., 2016). Previous studies (Lan et al., 2020; Wang et al., 2018h) reported that the addition of superplasticizer can reduce the water consumption while ensuring fluidity, but excessive superplasticizer has a negative impact on the performance of FSFs after hardening.

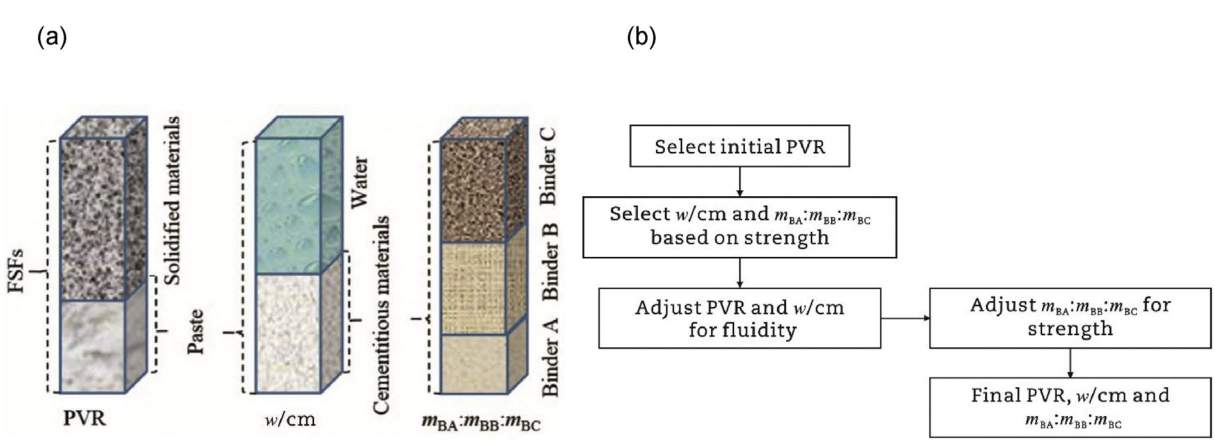


Fig. 31 – Mix design methodology of FSFS. (a) Independent parameters used for FSFs. (b) FSFs mix design procedure (Alizadeh, 2018).

The FSFs gradually changes from a plastic state to a hardened state after being uniformly mixed. According to the hydration degree of the FSFs, the hydration process can be classified into initial hydrolysis, dormant period, accelerated hydration, decelerated hydration, and the steady-state (Wang et al., 2018h; Yuan et al., 2020a). The regulation of setting time is mainly related to the dormant period and accelerated hydration period. The mineral type, organic substances content, and active ingredients of the solidified soil can affect the hydration process of FSFs. The content, particle shape, fineness, and pore structure of the binders also affects the hydration process (Wang et al., 2018h). Wang et al. (2018h) compared the effects of alum sludge replacement ratio, binder formulation, and additives on the setting time of FSFs. With the increase of alum sludge replacement ratio, the setting time of FSFs increased, and Ca-based admixtures and organic accelerators could effectively shorten the setting time.

Bleeding and segregation are also important plastic properties of FSFs. Bleeding is closely related to the free water content in FSFs. It can reduce the bleeding rate by using the material with strong water absorption to prepare the FSFs. In addition, the incorporation of gypsum is beneficial to reduce the bleeding rate, but it can delay the setting time (Do et al., 2019). The degree of segregation is used to characterize the uniformity of FSFs, and it is mainly affected by the water content and the proportion of binders. Appropriately increasing the amount of binders is beneficial to eliminate potential segregation (Qian et al., 2015).

Bearing capacity is one of the important properties of in-service properties of FSFs. The bearing capacity of the FSFs are mainly characterized by uniaxial compression test and ball drop test. The hydration reaction and pozzolanic reaction of active components such as SiO_2, Al_2O_3, and CaO is the important basis for the formation of mechanical strength. Do et al. (2019) found that the 28 d compressive strength of the FSFs linearly increased upon increasing the molar ratio of (Al_2O_3+CaO) to SiO_2. Kuo and Gao (2018) indicated that the strength of the FSFs would decrease when the porosity and water absorption of the solidified material increased. When the FSF is used in subgrade backfill, its strength requirement is relatively low. After curing, the 28 d unconfined compressive strength of the FSFs reaches 0.4–0.8 MPa, which can meet the requirements of subgrade backfill under different traffic loads. The shrinkage of the FSFs is closely related to its internal pore structure and free water dissipation. When the content of internal pores is higher after hardening, the more free water dissipation involved in hydration reaction and evaporation, the more obvious the shrinkage deformation of the FSF (Mneina et al., 2018; Qian et al., 2019a). Mixing appropriate amount of gypsum, active MgO and fiber into the FSFs can alleviate or even eliminate the drying shrinkage.

3.4.1.3. *Curing mechanism*. The formation of cementitious products is an important basis to ensure the long-term strength through polymerization of the FSFs. The formation of hydration products of FSFs is mainly divided into alkali activated mode and sulfate activated mode (Do et al., 2019; Kim et al., 2016), and the hydration products mainly include calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), $Ca(OH)_2$ crystal and ettringite (AFt) (Zhang et al., 2021a). At present, the research methods adopted in determining the curing mechanism of the FSFs include nuclear magnetic resonance technology, X-ray diffraction (XRD) analysis, microstructure analysis, ultrasonic impulse method and electrical conductivity measurement (Das et al., 2020; Do et al., 2019; Lim et al., 2017; Yuan et al., 2020a).

The pH and the proportion of active components can affect the hydration process of the FSFs (Do et al., 2019; Kim et al., 2016). As shown in Fig. 32, when the pH value of the FSFs is higher, the active SiO_2, Al_2O_3 and CaO in the reaction system are prone to hydration reaction to form C-S-H and C-A-H, and the mechanical strengths of FSFs linearly increases upon increasing the molar ratio of (CaO+Al_2O_3) to SiO_2. When the SO_4^{2-} content increases, C-A-H can be further converted to AFt (Do et al., 2019). The formation of products such as C-S-H and AFt can guarantee the long-term strength of the FSFs. C-S-H has good cementation, while AFt plays a positive role in filling the internal pores and strengthening

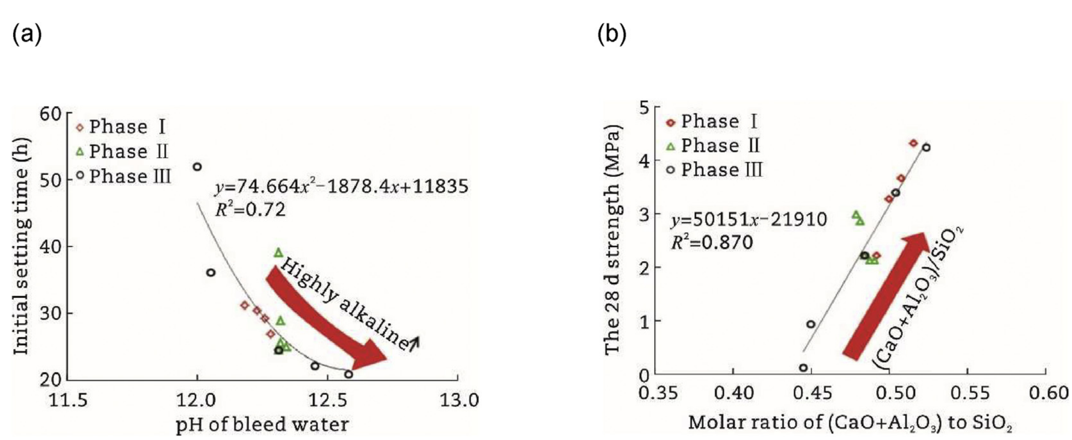


Fig. 32 – Effects of pH and proportion of active components on hydration process. (a) Relationship between initial setting time and pH of bleed water. (b) Relationship between strength and the molar ratio of (CaO+Al_2O_3) to SiO_2 (Do et al., 2019).

the skeleton structure. In addition, $Ca(OH)_2$ crystal generated in an alkaline environment can promote the soil particles to form a stable structure, which can further enhance the compactness of FSFs (Cheng et al., 2014).

The stabilization/solidification processes of the FSFs are not only the process of the formation and hardening of the cementitious products, but also the process of the transformation of the water status (Zhu et al., 2013). As shown in Fig. 33, the free water and pellicular water among the particles of the solidified filler is transformed into combined water in the hydration products such as C-S-H and AFt during the hydration process. The strength of the FSFs is closely related to the amount and space structure of cementitious products. The hydration rates of different binders are quite different. The flocculating cementitious products are gradually formed at the initial stage. With the continuous hydration reaction, the hydration products gradually wrap the soil particles and gradually develop into a spatial network structure, which makes the strength of the FSFs gradually increases (Zhang et al., 2021a). When silt and sludge with high content of clay are used to prepare FSFs, because there is a thick pellicular water layer on the surface of clay particles, this kind of soils can be solidified with ionic binders. The high valence cations (such as Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{3+}) introduced by the binders can be adsorbed on the surface of the soil particles under the action of static electricity, which can reduce the charge and the thickness of the pellicular water layer, and improve the binding effect of the binders on the soil particles (Chen et al., 2020b; Li and Li, 2020; Zhu et al., 2013).

3.4.1.4. *Construction applications*. The application of FSFs in subgrade backfill can not only greatly reduce the potential settlement and deformation, but also avoid the damage of compaction construction to the existing structures. It is necessary to reasonably plan the construction organization according to the characteristics of the FSFs and the on-site mixing equipment. The pouring form and curing measures of the FSFs should be determined by the characteristics of the backfill engineering. During the construction of subgrade with FSFs, the layered and segmented construction method is often adopted. The deformation joints are generally set every 10–20 m along the longitudinal direction of the embankment. Due to the FSFs are mainly solidified with inorganic binders, the FSFs have the hydration exothermic process after the layered pouring construction. If the pouring time of different layers is too short or the curing time is not appropriate, the thermal stress concentration phenomenon can be formed. In severe cases, the "hot channel" and burst phenomenon can be induced. Therefore, for the FSFs with obvious hydration exothermic phenomenon, the superstructure construction should be carried out after the pouring heat release reaches the maximum value.

The ball drop method can be used to determine the follow-up construction time in the construction of subgrade with FSFs. When the diameter of ball drop indentation is less than 7.6 cm, it indicates that the filling body of FSFs has sufficient bearing capacity to ensure that the next construction can be carried out (ACI, 2013; Huang et al., 2016b). Some scholars have put forward preventive measures for the deformation cracks and exothermic damage in the construction of subgrade filled with FSFs. In terms of controlling deformation cracks, the measures mainly include laying steel mesh and reinforced fiber, setting deformation joints and moisture conservation (Xu et al., 2020c). The elimination of exothermic damage is mainly by controlling the pouring volume and pouring time. Generally, the thickness of single layer should be controlled within 0.3–1.0 m. In addition, heat dissipation within 5–19 h after pouring can effectively reduce the risk of hydration heat cracking (Xie et al., 2021).

3.4.1.5. *Environmental impact assessment*. As more and more waste materials containing heavy metal ions are used in the preparation of FSFs, the environmental impact assessment of FSFs becomes more and more important. At present, the environmental impact assessment of FSFs mainly includes pH and leaching behavior of heavy metal ions. Generally, the pH value of the FSFs is controlled between 2.5 and 12.5 to meet the

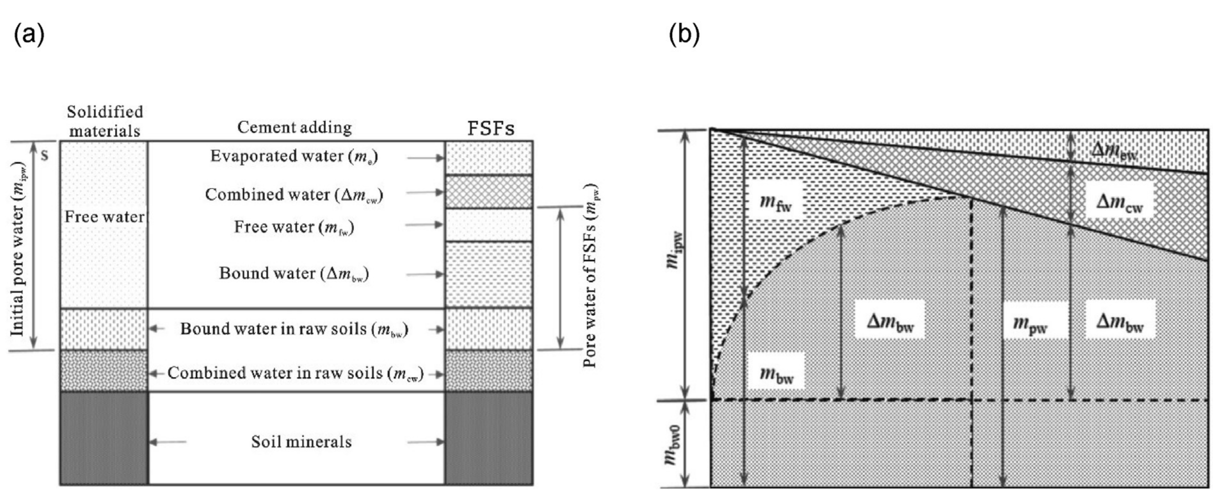


Fig. 33 – Transformation of water status in FSFS. (a) Change of water status after mixing. (b) Effect of binder on water status (Zhu et al., 2013).

requirements of corrosion resistance (Kim et al., 2016). The amount of heavy metal ions in leachate of FSFs prepared with industrial waste slags was basically below than the regulatory levels of heavy metal ions in groundwater in previous studies.

At present, scholars concluded that the stabilization of heavy metal ions by FSFs mainly includes the following reasons. (1) Heavy metal ions form carbonate or hydroxide precipitation in alkaline environment, which reduces the mobility of heavy metals (Huang and Li, 2017). (2) The dissolved heavy metal ions replace the existing Ca^{2+}, Al^{3+} and are encapsulated in AFt and other related crystals during the reaction (Suo et al., 2021; Zhen et al., 2012). (3) The pore structure of the FSF gradually becomes dense, and its permeability is significantly reduced after hydration reaction, which makes it more difficult for heavy metal ions to migrate and precipitate compared with that before solidification (Bouzalakos et al., 2016). When using different contaminated soils to prepare FSFs, appropriate binders should be selected according to the types of pollution sources to effectively change the occurrence forms of heavy metal ions in the soil and reduce the migration characteristics and bioavailability, thereby realizing the stability of the pollution source.

3.4.1.6. Development prospects and challenges. In summary, the promotion and application of FSFs in highway and urban road subgrade backfills have broad prospects. With the continuous implementation of the concept of green development, more and more waste materials will be used in the subgrade construction with FSFs. The composition design based on the types of solidified materials, application scenes, and the type of bulk waste materials will continue to be the mainstream idea in the future. However, how to realize the resource utilization, harmless and large-scale application of waste materials on the basis of ensuring the adjustable and controllable engineering properties of FSFs is still facing great challenges. The use of soil, mud, and slag containing pollution sources in the preparation of FSFs is undoubtedly an important direction for the solidification and resource utilization of contaminated soils in the future, but the law of form transformation and adsorption of heavy metal ions in FSFs is still unclear. There is still a lack of systematic research on the long-term effectiveness of heavy metal ion stabilization in subgrade backfill with FSFs. It is urgent to build a unified theoretical and technical system for the FSFs to meet the practical needs of its large-scale development. In addition, there is no unified evaluation method for the engineering quality control and environmental impact assessment of the subgrade filled with FSFs, which also restricts the development and application process of the FSFs technology in the subgrade backfill.

3.4.2. *Stabilization materials for problematic soil subgrades*

Subgrades that consist of problematic soils (e.g., loess, expansive soils, saline soils, and soft soils) may lead to uneven settlement, slope failure, frost heave, and accelerated distresses of pavement systems. Problematic soils are widely spread in most parts of the world. Traditional methods to improve the engineering properties of the subgrade have included the total or partial replacement of problematic soils with good quality fills and the use of various stabilization materials (lime, cement, bitumen, etc.) to improve the in-situ soil. However, the cost effectiveness and environmental concerns have long been researched with those approaches.

3.4.2.1. Stabilization materials for loess. Loess refers to silt sediments carried by wind in the Quaternary period, which are mainly distributed in the arid and semi-arid areas. According to Wang (2013), 9.3% of the world is covered by loess, the area covered by loess in Europe accounts for 7%, North America accounts for 5%, South America accounts for 10%, and Asia accounts for 3%. Except for South America and New Zealand, there is very little loess in other regions of the southern hemisphere. Most loess has strong collapsibility, water sensitivity and high compressibility. When loess used as subgrade, after being soaked by water and under self-weight and traffic loads, the soil structure may collapse, leading to a serious impact on the stability of subgrade.

Stabilization materials that have been proven to be effective in improving the engineering properties of loess mainly include inorganic binding materials, organic polymer materials, and biological enzymes as listed in Fig. 34.

Traditional stabilization materials have insufficient performance in improving engineering properties of loess. For example, lime stabilized loess has relatively low strength and poor water resistance. Cement stabilized loess has high strength and good water resistance, but with large shrinkage and cracking (Wang and Gao, 2012). The cost of cement slurry and water glass are high, and the red mud is easy to cause environmental pollution (Hou et al., 2019). The combination of one or more stabilization materials can complement the disadvantages of a single material. For example, cement stabilized loess with active magnesium oxide has a higher degree of hydration and better pore distribution than only using Portland cement (Wang et al., 2019d). The strength of red mud stabilized loess mixed with calcium oxide or cement is four times more than that only using cement (Chen and Song, 2020; Chen et al., 2019b).

Nano-silica is an amorphous nanomaterial, which has flocculent structure and insoluble in water. It has small-size effect and surface effect (Bu, 2016). High surface free energy and chemical activity make nano-silica highly absorbable, easily fill large voids and cement coarse particles, and thus changing the physical and mechanical properties of loess (Kong et al., 2018; Lv et al., 2018). In addition, some researchers have used nano-clay and nano-calcium carbonate to stabilize loess and found that nano-calcium carbonate has the best effect (Haeri and Valishzadeh, 2021).

Compared with inorganic stabilization materials, organic stabilization materials have been more studied by researchers in the recent years. As a natural organic polymer, lignin is a major by-product of cellulose industry. When mixed with loess, a filamentous film can be formed to cement soil particles, thus enhancing particle bond, reducing void ratio, increasing shear strength and improving water erosion resistance of loess (He et al., 2017a). However, only calcium lignosulfonate showed a good stabilization effect for loess in the cold regions (Haeri and Valishzadeh, 2021; Xu et al.,

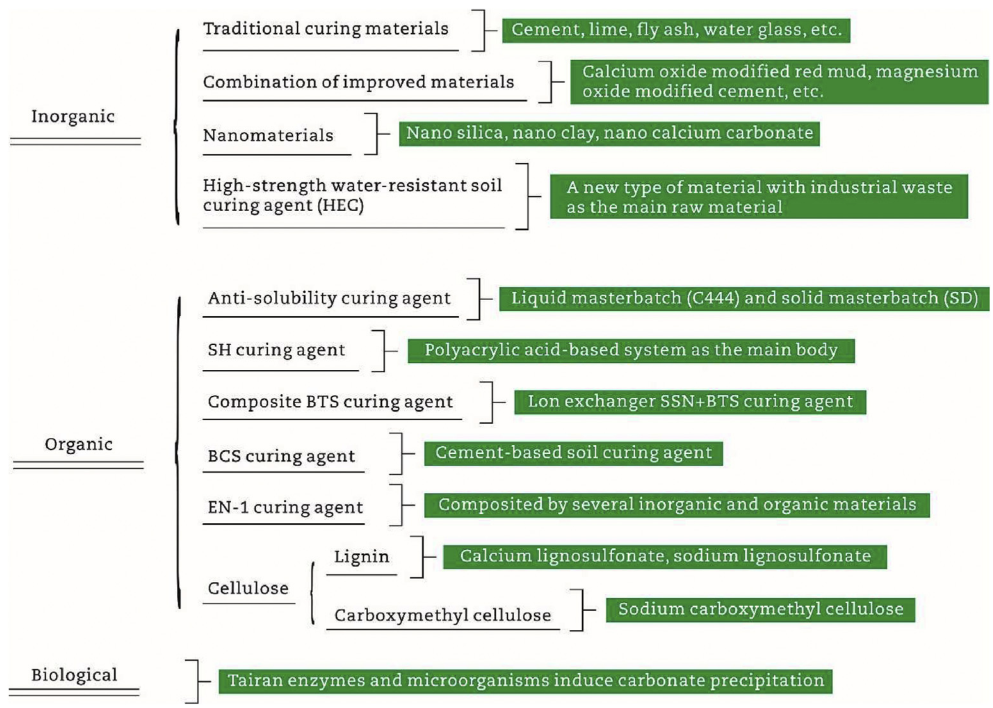


Fig. 34 – Various stabilization materials for loess.

2011), while sodium lignosulfonate could not effectively improve the mechanical properties of loess, but also lead to the intensification of loess salinization (Zhang et al., 2009b).

For biostabilization of loess, Tairan enzyme is a liquid compound enzyme produced by the fermentation of plants, which can speed up the weak chemical reaction rate between minerals and form a waterproof barrier on the surface of the soil. Then under the action of mechanical compaction, a cohesive organic film is formed between soil particles, and the compactness of the soil is increased, thereby improving the strength and stability of the soil (Hou et al., 2019), but Tairan enzyme requires the content of particles below 0.075 mm in the reinforced soil to be between 20% and 50%, while the content of fine grains in loess usually can reach to 90%. Microbial induced carbonate precipitation (MICP) refers to the use of specific bacteria such as bacillus (Liu et al., 2021b), polysaccharide mucilage bacteria and urease-producing bacteria (Naveed et al., 2020). Carbonate generated by bacterial reacts with calcium ions in the soil to form calcium carbonate with cementing function, which fills the pores in the soil, thereby increasing the strength of the soil, reducing the permeability coefficient, and improving the engineering properties.

3.4.2.2. *Stabilization materials for expansive soil*. Expansive soils are a kind of high liquid limit cohesive soil, which volume expands and contracts greatly with changes in water content. The main soil minerals of expansive soils are illite and montmorillonite with strong hydrophilic characteristics. When used as subgrade, expansive soils can cause cracks, frost heaving, frost boiling, and other distresses under repeated deformation. Researchers have well studied the engineering properties of expansive soils and found that using stabilization materials is the most cost-effective method (Zheng and Zhang, 2015).

In the recent years, researchers had further studied stabilization effects, durability, and mix-design of the traditional stabilization materials including cement (Li et al., 2018d), lime, fly ash (Al-Taie et al., 2018; Islam et al., 2019; Sivakumar et al., 2020), bottom ash (Galvin et al., 2021), industrial waste dust (Sudhakar et al., 2021), waste glass powder (Blayi et al., 2020), and red mud (Parik and Patra, 2020). Some researchers have also developed or evaluated relatively new stabilization materials including enzyme-based stabilizer (Parik and Patra, 2020), alkali-based stabilizer (Miao et al., 2017), ionic soil stabilizer (ISS) (He et al., 2018), liquid ionic soil stabilizer (LISS) (Kaneza et al., 2020), polymer reagents (Mousavi et al., 2021) and microbial induced calcite precipitation (MICP) (Tiwari et al., 2021) to control swelling shrinkage behavior of expansive soils. To combine the different stabilization effects, researchers also developed various composite stabilization materials, which mainly combine lime with biomass ash, including rice husk ash (Onyelowe et al., 2021), bamboo ash (Nwonu and Ikeagwuani, 2019), sugarcane ash (Hasan et al., 2018) and coir pith (Narendra et al., 2018). The stabilized expansive soil used for subgrade must meet requirements of mechanical properties. Therefore, most of the previous studies on effect evaluations of solidified expansive soils mainly focused on geotechnical and mechanical indexes (Al Hattamleh et al., 2020; Al-Taie et al., 2018; Blayi et al., 2020; Goud et al., 2017; Hasan et al., 2018; He et al., 2018; Liu et al., 2019c; Miao et al., 2017; Pooni et al., 2019; Rabab'ah et al., 2021; Sudhakar et al., 2021; Wu et al., 2020a).

3.4.2.3. Stabilization materials for saline soils. Saline soils are a kind of soils with soluble salt content greater than 0.3%, which are widely distributed in arid and semi-arid areas. Saline soils are distributing in more than 100 countries and regions in Aisa, Europe, Africa and North America, which accounts for 6.5% of the earth's land area. When used as subgrade, under the environmental and traffic loads, the salt expansion, dissolution collapse, and corrosion of saline soils can cause significant damage to pavement systems.

In the recent years, researches on the stabilization of saline soils are mainly focused on evaluations of the performance and their optimal mixing content of traditional stabilization materials. Traditional inorganic materials include cement, lime, fly ash, silica fume, industrial waste residue (Liu et al., 2015), magnesium slag (He et al., 2015), composite cementing materials (Dai et al., 2021; He et al., 2015; Liu et al., 2015a; Zhang et al., 2020a), and traditional organic materials include rice husk ash (Dai et al., 2021), polypropylene fiber, polyacrylamide (Liao et al., 2015c; Liu et al., 2015a), and new hydrophilic acrylate copolymer emulsion (Zhu et al., 2020d). Stabilization effects of composite materials with different components and dosage could be significantly different (Bai et al., 2020a; Hou et al., 2021; Li et al., 2018c; Liu et al., 2015a). For example, researchers found that there is a threshold mixing ratio for fly ash stabilized saline soil, and the optimal mix ratio of fly ash in chlorine-saline soil is 15%, and that in sulfate soil is 20% (Zhou et al., 2017). Some researchers also found that the stabilization effect of the same material varies with the salt content of soils (Yu et al., 2018). For soils with a large amount of sulfate ions, it can actively react with $Ca(OH)_2$ in the cement to form ettringite, so some researchers studied the salt-swelling curing agent such as rice husk ash fiber and cement. The test found that the curing agent could effectively improve the swelling resistance of the stabilized soils, reduce the strength loss rate and improve the engineering properties of cemented soils (Dai et al., 2021; Zhang et al., 2018j).

Aiming at the improvement of salt swelling and melting of salted soil, the most commonly used curing materials are inorganic materials and organic materials, while the inorganic curing method may cause environmental pollutions, while the organic curing method may become a development direction for stabilizing saline soils (Wan, 2019).

3.4.2.4. Stabilization materials for soft soils. Soft soils are a kind of soils that sediment in floodplains, deltas, and coastal areas. They are generally composed of clayey, silty or organic particles. When used as subgrade, their inherent high water content, high compressibility, and poor bearing capacity can cause severe damage to pavement systems. The poor permeability of soft soils also causes detrimental long-term consolidation settlements resulting in slow strength development. To address these issues, in the recent years, the emphasis was taken on evaluating non-traditional stabilization materials, mostly the industrial by-products. Depending on the engineering performance, relatively new stabilization materials (organic, inorganic and bio-enzyme, or polymers) evaluated in the recent years can be categorized into those which can perform individually and those which work in combination with another material. The types of stabilizers are summarized in Table 19.

The mechanical performance of soft clayey subgrade stabilized with calcium carbide residue (CCR), an industrial by-product of acetylene gas production, has been found superior compared to quick lime by both laboratory tests (Jiang et al., 2016) and field validations (Du et al., 2016). The particles of CCR are finer with higher specific area and higher pH than those of quick lime, which makes the CCR produce faster flocculation and agglomeration of clay particles and thus produce high CBR, high resilient modulus and lower values of resilient deflection and dynamic cone penetration index. The study conducted on soft soils mixed with coir wastes (0–3% coir pith and 0–1% coir fibre) has shown that the compaction, elastic modulus, and strength properties were significantly improved (Peter et al., 2016). This could be attributed to the coir pith and coir fibre of low specific gravity and high water absorption capacity. More inorganic materials have been used for soft soil improvement such as the non-biodegradable waste rubber powder to increase the strength characteristics (Farooq and Mir, 2020).

The combination of more than one stabilization materials has also proven to improve the drawbacks of some traditional stabilizers. The combined effect of enzymatic lime has proven to improve strength more than using lime alone (Eujine et al., 2017). The chemical reaction stimulation property of the enzymes on lime causes low water absorption of the clay particles leading to an accelerated strength gain and stronger soil mix thereafter (Eujine et al., 2017). With the rapid increase in use of glass materials in recent years, the glass waste has caused an environmental concern which prompted extensive studies on ways to recycle or reuse glass wastes. The recent study on the addition of nano-clays along with glass fiber to soft clays has shown that the stabilized soil produced a shearing strength increase up to 84% and a considerable improvement in unconfined compressive strength (Changizi and Haddad, 2017). When used with bentonite, the nano-clay has proven to improve the strength characteristics of soft soil by 14% increase in CBR. On the other hand, the permeability of the soft soil has decreased (Idrus et al., 2016).

Table 19 – Summary of subgrade soft soils chemical stabilizers.

Name	Type	Mode of use
Calcium carbide residue (CCR)	Inorganic	Individually
Waste rubber powder	Inorganic	Individually
Waste paper sludge ash (WPSA)	Inorganic	Individually
Coir waste (coir pith and coir fibre)	Organic/fibre	Individually
Enzyme, lime	Inorganic	Combined
Nano-clay, glass fibre	Inorganic	Combined
MgO, CO_2	Inorganic	Combined
Nano-clay, bentonite	Inorganic	Combined

3.4.3. *Geogrids in base course reinforcement*

A typical flexible pavement is usually composed of three distinct layers: asphalt mixture surface course, granular base course, and soil subgrade. The results of AASHO road test show that in the flexible pavement, the permanent deformation caused by the asphalt mixture surface course, granular base course (including subbase course), and subgrade accounts for 32%, 59%, and 9% of the total permanent deformation of the entire pavement, respectively (Vesic and Domaschuk, 1964). It is found that the permanent deformation generated by the granular base course contributes more than half of that of the entire pavement system (Ma, 2015). A high-quality granular base course can effectively dissipate the stresses imposed by vehicles to the underlying subgrade (Appea and Al-Qadi, 2000). Therefore, limiting the permanent deformation of the granular base course is particularly important for controlling the permanent deformation of flexible pavements. The granular base usually composed of unbound granular materials (UGMs). UGMs usually have enough shear strength to resist deformation, but not tensile strength. Therefore, granular particles at the bottom of the base layer could move laterally under repetitive traffic loading, weakening the base-subgrade interface and resulting in the gradual deterioration of pavement system (Giroud et al., 1984; Han et al., 2018). The deterioration is largely due to the migration of fine particles from subgrade to the base layer and the penetration of base course materials into subgrade (Al-Qadi and Bhutta, 1999; Al-Qadi, 2002). To improve the tensile performance of granular base course, geosynthetic materials with good tensile properties are introduced into the tensile deformation zone of the base course to restrict the lateral movement of UGMs and increase the stability of the granular base course. Therefore, reinforcing the granular base course by geosynthetics is considered an effective way to improve the performance of pavement.

Generally, geosynthetic products are divided into eight categories, including geotextiles, geogrids, geonets, geomembranes, geosynthetic clay liners, geopipes, geofoams, and geocomposites (Koerner, 2012). Each product is designed to solve specific civil engineering problems. Geogrid is one of the most commonly used geosynthetic product in pavement engineering. Compared with other types of geosynthetic products, geogrid has larger tensile strength and stiffness, and can withstand more tensile stresses. Since 1970s, geogrid has been widely used for subgrade stabilization and base reinforcement in flexible pavements. Numerous laboratory and field tests have confirmed the benefits of using geogrid as reinforcement in pavement systems, including decreasing rutting deformations, reducing base-soil contamination, improving the stress distribution of the base course, increasing pavement-bearing capacity, lowering the design thickness of the base course, controlling crack propagation, and prolonging pavement service life (Berg et al., 2000; Chen et al., 2009b; Ghosh and Dey, 2009; Huntington and Ksaibati, 2000; Kinney et al., 1998; Loulizi et al., 1999; Moghaddas-Nejad and Small, 1996; Palomino et al., 2010; Wu et al., 2011).

3.4.3.1. *Assessment methods for evaluating geogrid reinforcement in flexible pavements*. Geogrids are believed to realize benefits in reinforcing pavements through three main mechanisms: lateral restraint, increased bearing capacity, and tensioned membrane effect (Giroud and Noiray, 1981; Holz et al., 1998; Zornberg, 2015). In the past four decades, lots of researchers utilized different test methods to evaluate the geogrid-aggregate interaction, and these methods are mainly divided into material tests for reinforced granular material and structural tests for reinforced granular base course according to the research object.

(1) Reinforced granular material

Recently, several test methods have been proposed to quantify the geogrid-aggregate interaction governing the performance of geogrid-reinforced aggregate. These tests mainly include cyclic triaxial test, monotonic pullout test, direct shear test, bending stiffness test, push test, bender element test, modified loaded wheel test.

The cyclic triaxial test is a commonly used approach to characterize the geogrid-aggregate interaction under cyclic loading. Yang and Han (2012) believe that geogrids can provide additional lateral restraint stress on aggregates, which can limit the lateral movement of aggregates and improve the resilient modulus of aggregates to reduce the permanent deformation of aggregates. Rahman et al. (2013) and Gu et al. (2016) confirmed this conclusion in their cyclic triaxial tests on construction and demolition materials. However, the results of several other researchers showed that the permanent deformation of reinforced aggregates is significantly lower than that of unreinforced aggregates, but the resilient modulus does not increase significantly (Han et al., 2019b; Moghaddas-Nejad and Small, 2003; Nazzal et al., 2007; Wayne et al., 2011), as shown in Fig. 35. Therefore, it is controversial to use the cyclic triaxial test to evaluate the effect of geogrids in reinforcing base course.

Under repeated traffic loads, geogrids and surrounding granular materials usually experience a certain relative displacement, resulting in shear resistance at the geogrid-aggregate interface. This shear resistance can limit the lateral movement of aggregates to form an effective interlocking in geogrid apertures, thereby strengthening the whole pavement system. Pullout and direct shear tests are the other two common methods to measure this shear resistance (Alfaro et al., 1995; Ferreira et al., 2015; Kwan, 2006; Lopes and Ladeira, 1996; Wang et al., 2016c). Besides, Han et al. (2018) developed a large-scale cyclic shear test to investigate the geogrid-aggregate interface interaction in a cyclic shear load mode instead of traditional monotonic shear load. Sprague et al. (2004) employed a bending stiffness test to quantify the reinforcement effect of geogrids. The results show that the bending stiffness of reinforced aggregate is higher than that of unreinforced aggregate, and the increase percentage has a good correlation with the traffic benefit ratio (TBR) measured by the field geogrid-reinforced flexible pavement. Matys and Baslik (2004) proposed a push test to evaluate the interlocking effect of geogrids on the aggregates, and the push force was recorded for the reinforcement effect comparison. Byun and Tutumluer (2017) used a bender element to measure the shear modulus around the geogrid in a cyclic triaxial test. Results show that the shear modulus of reinforced aggregate near the geogrid is significantly larger than that of unreinforced aggregate, and the calculated shear modulus can effectively quantify the interaction between geogrids and aggregates.

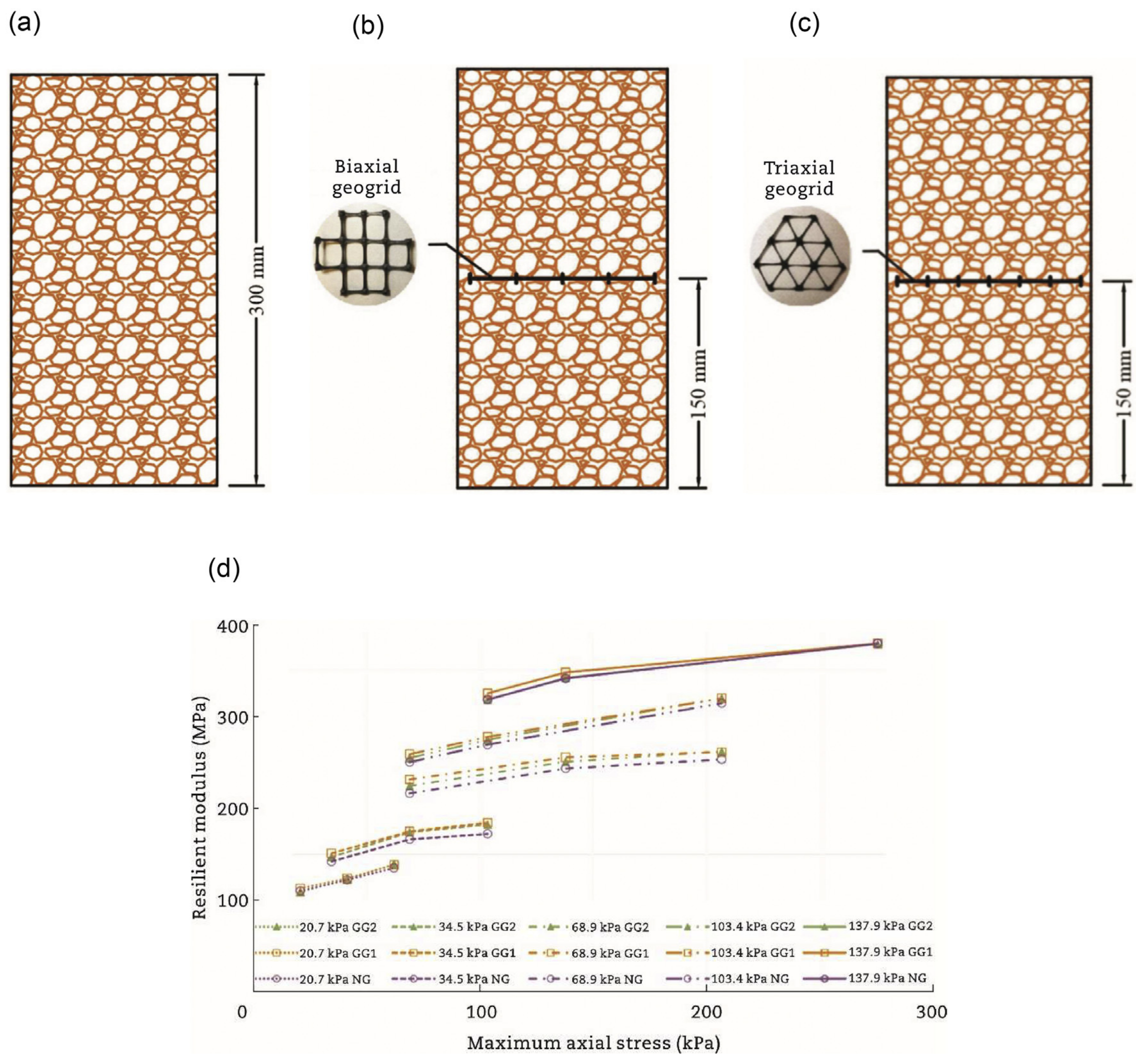


Fig. 35 – Unreinforced/reinforced specimen and test results. (a) Unreinforced case. (b) GG1 reinforced case. (c) GG2 reinforced case. (d) Resilient moduli of unreinforced and reinforced specimen (Han et al., 2019b).

(2) Reinforced granular base course

The overall strength and stability of the reinforced granular base course in the flexible pavement will be improved because of the addition of geogrids in granular materials. Due to the interaction between geogrids and aggregate, the mechanical behavior of the reinforced granular base course is greatly different from that of the conventional unreinforced granular base course. Unlike reinforced granular materials, researchers often employ large-scaled test methods to investigate the reinforcement effect of geogrids in the flexible pavement system, including cyclic plate loading test, field tracking test, accelerated pavement testing (APT), and falling weight deflectometer (FWD) test.

Cyclic plate loading test is a common method to evaluate the reinforcement effects of geogrids in base course. Halim et al. (1983) conducted a group of cyclic plate loading tests and found that the reinforced pavement structure can withstand more loadings when the pavement achieved a pre-determined rut depth of 20 mm. Based on Halim's results, Carroll et al. (1987) and Webster (1993) further improved the test, and proposed an equivalent thickness conversion diagram of the reinforced aggregate base course and the unreinforced aggregate base course as shown in Fig. 36. The inflection point represents the minimum thickness required for the reinforced aggregate base.

To better understand the geogrid reinforcement mechanisms, Haas et al. (1988) built a reinforced and unreinforced pavement structure in a large-scale tank. The test results show that reinforced base course can significantly reduce the surface permanent deformation, and the base course thickness could be reduced by 25%–50%. When the permanent deformation is large, the reinforcement is mainly strengthened by the tensioned membrane effect, while when the permanent deformation is small, the reinforcement is realized by the lateral constraint effect. Chen et al. (2009b) also employed the cyclic plate loading test to evaluate the reinforcement effect of the indoor test sections and analyzed the mechanical response of reinforced sections including stress and strain under the

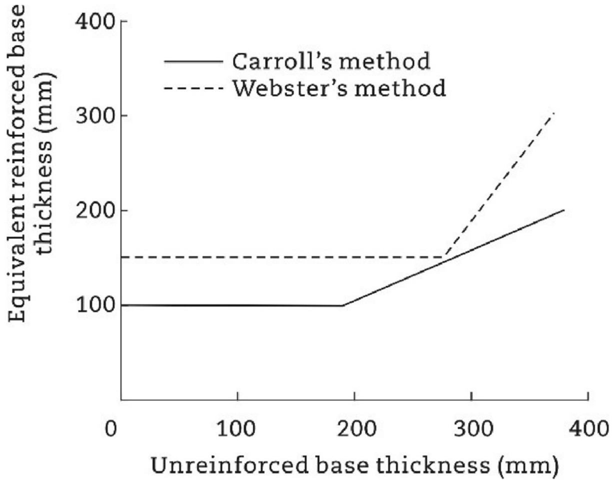


Fig. 36 – Design chart for base course thickness proposed by Carroll et al. (1987) and Webster (1993).

cyclic loadings. The result show that the bearing capacity, rigidity and rutting resistance of the reinforced sections are significantly improved compared with the control unreinforced sections. The installation of geogrids in the base course can transfer the stress to a wider area within base course and subgrade, so that the permanent deformation of the base course and subgrade in the reinforced section accounts for a lower proportion of the permanent deformation of the entire pavement structure than that in an unreinforced section.

Unlike the cyclic loading test, the accelerated pavement testing (APT) can more accurately simulate the wheel load applied on the pavement structure. Han et al. (2020) built a full-scale reinforced flexible pavement and tested the reinforcement effect of geogrid by APT, as shown in Fig. 37. Tang (2011) used a small-scaled APT facility, MMLS3, to evaluate the ability of different geogrid products to improve the rutting resistance of the flexible pavement structure. The test results show that the existence of the geogrid can improve the stress distribution in the base course, and decrease the stress applying on the top surface of the subgrade.

Field trafficking test is another excellent method for evaluating benefits of the reinforced aggregate base course. In order to study the reinforcement effect of geosynthetics in the base course, Chan et al. (1989) paved 12 different reinforced thin flexible pavements and utilized uniaxial and multi-axial APT facility to load the pavements. The results showed that the reinforcement effect depends largely on the thickness of the base course, aggregate quality, and the placement position of the reinforcement. If a pre-rutting could be made on the reinforced granular base just after the base course construction, the rutting resistance of the reinforced structure could be further improved. However, the pre-tensioning of the geosynthetics in the pavement construction does not significantly improve the long-term performance of the reinforced flexible pavement.

FWD test is also employed to test the performance of the reinforced pavement. Collins et al. (2005) conducted a 12-year FWD tracking test on one reinforced road. They found that some longitudinal cracks appeared in the unreinforced section, but no obvious cracks and ruts were found in the reinforced section, indicating that the reinforced base could improve the fatigue life of the pavement. Cox et al. (2010) conducted on-site cyclic plate loading tests on 16 completed reinforced and unreinforced actual road sections in Arkansas. FWD test were also conducted after cyclic plate loading test. They concluded that when the surface permanent deformation is small, the geogrids will not activate the reinforcement. They further speculated that geogrids be mobilized only when geogrids experience a large strain in the geogrids, but this statement has not been confirmed by field measurements.

3.4.3.2. Summary. Through the summary of the existing research methods, it is found that the interaction between geogrids and aggregate plays a significant role in the base reinforcement. The interaction could affect the mechanical behavior of the reinforced unbound granular materials (UGMs), which in turn affects the corresponding mechanical behaviors of the flexible pavement with the reinforced granular base course. Researchers have used different methods to study the mechanical properties and behavior of reinforced UGMs and reinforced granular base. These methods are summarized in Table 20.

Among these test methods, the direct shear, pullout, repeated load triaxial test are employed to characterize the mechanical behavior of the reinforced UGMs and analyze the interaction mechanisms between geogrids and aggregate. These test methods are efficient, cost-effective, time-saving, and repeatable. However, the sizes of the equipment used in these studies are small, so the number of geogrid grids contained in the specimens limited, which cannot simulate the actual interaction between geogrids and aggregate. In addition, the loads applied to the specimen are quite different to the loads applied to pavements, so the mechanical response of the specimens in these tests are different from that of actual road. In terms of cyclic plate loading test, field trafficking test and accelerated pavement testing, although these tests can better simulate the actual loading condition for the geogrid-reinforce pavement, these methods are not widely used as routine test approaches since they are time-consuming, labor-consuming, and costly. Therefore, a more convenient and practical test method should be proposed to evaluate the interaction between geogrids and aggregates. This method can effectively quantify the influence factors, select appropriate geogrids for different base, analyze the reinforcement mechanisms, evaluate the reinforcement effect of geogrids on pavements, and provide theoretical guidance for the design of the geogrid-reinforced flexible pavement.

3.4.4. *Summary and outlook*

The application of different types of reinforcement geo-materials for the road base/subgrade has a positive role in improving the stress distribution of structural layer, enhancing the anti-deformation ability, and optimizing the

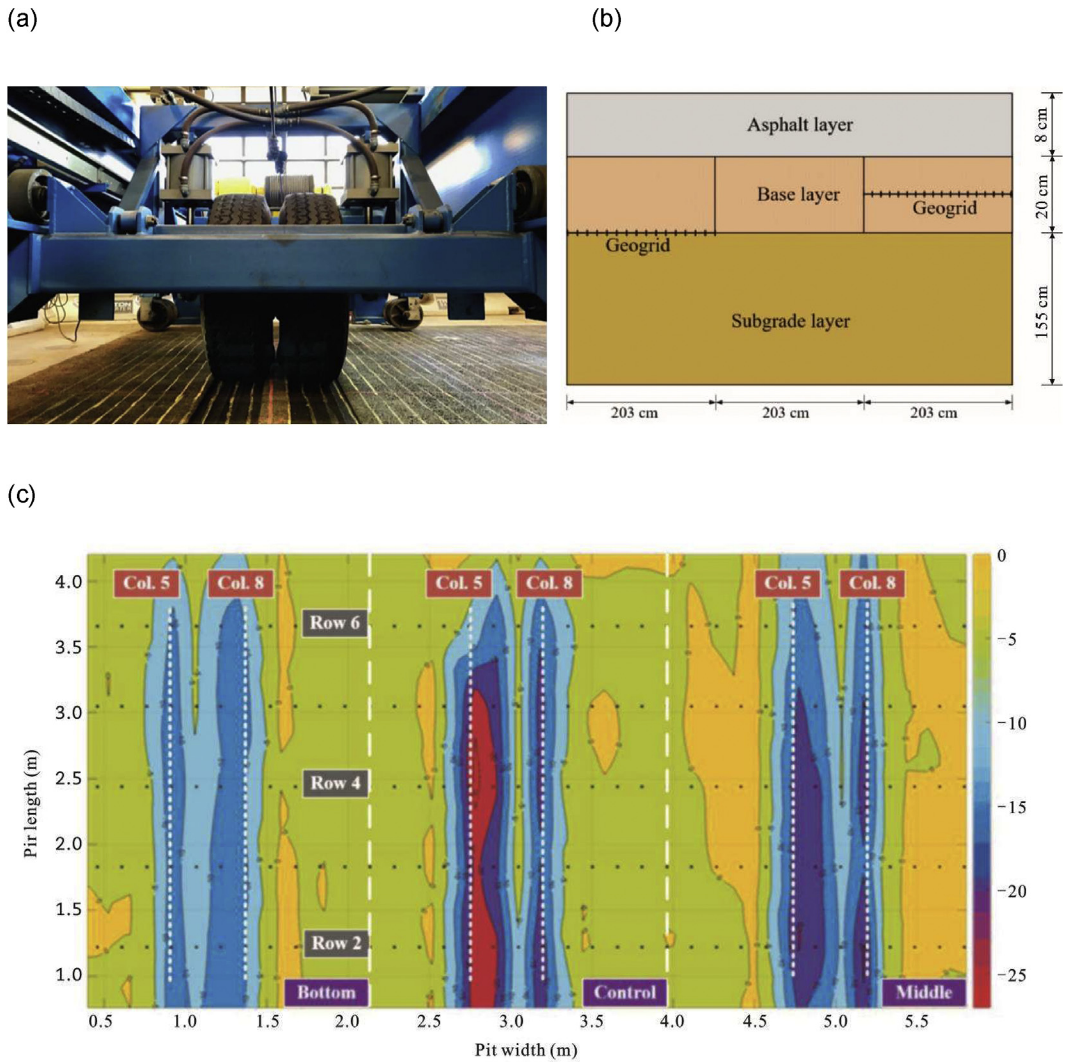


Fig. 37 – APT device, pavement structure and permanent deformation after APT. (a) Accelerated pavement loading system. (b) Schematic diagram of pavement structure. (c) Distribution of accumulated surface permanent deformation (Han et al, 2020).

pavement structure. The effective reinforcement of subgrade and base is an important premise to promote the construction of long-life asphalt pavement. With the continuous improvement of green development requirements, more and more environmentally friendly reinforcement technologies and geo-materials will continue to be used in base and subgrade reinforcement engineering. Based on the summary of the previous studies of flowable solidified fill, stabilization materials for problematic soil, and geogrids for base/subgrade reinforcement, the following prospects are put forward for the development and technical innovation of road subgrade and base reinforcement geo-materials.

(1) With the continuous progress of highway construction in special areas, special soil subgrade reinforcement projects will also increase sharply. Suitable and economical reinforcement geo-materials and technologies should be developed based on the engineering characteristics and the instability mechanism of special soil to promote the construction and development of long-life pavements in special areas.
(2) While promoting the durability of new subgrade and base engineering, it is equally important to strengthen the maintenance, detection, and reinforcement of the existing highway subgrade and base. It is urgent to form a systematic and efficient disease diagnosis and prevention technology system of road base and subgrade to improve the intelligent level of road subgrade and base reinforcement.
(3) At present, the problem of global environmental damage and climate change has become increasingly prominent, and green sustainable development has gradually become the development concept of the engineering construction. Some progress has been made

Table 20 – Summary of test methods on geogrid-reinforced flexible pavements.

Subject	Method	Load type	Test performance	Characterized mechanical behavior
Reinforced UGMs	Direct shear	Monotonic	Interaction degree between geogrids and aggregate	Interfacial shear behavior at aggregate-geogrid interface
	Pullout	Monotonic	Interaction degree between geogrids and aggregate	Interfacial shear behavior at aggregate-geogrid interface
	Triaxial shear	Monotonic	Shear capacity	Shear behavior of reinforced UGMs
	Repeated load triaxial	Cyclic	Resilient modulus, rut depth	Resilient and permanent deformation behavior of reinforced UGMs
Reinforced granular base	Field trafficking	Traffic	Long-term performance	Permanent deformation behavior of reinforced granular base
	APT	Traffic	Overall structural performance	Permanent deformation behavior of reinforced granular base
	FWD	Dynamic	Resilient modulus	Resilient deformation behavior of reinforced granular base
	Cyclic plate loading	Static/cyclic	Mechanical response	Resilient and permanent deformation behavior of reinforced granular base

in recycling of waste materials in the construction of highways and other projects, but it is still necessary to continue to explore and develop the green highway subgrade and base reinforcement technologies and form the corresponding environmental impact assessment methods.

4. Multi-scale mechanics

4.1. *Interface*

The cracking resistance of asphalt mixture is closely related to the interface characteristics between asphalt and aggregate. The research shows that the interface is often the weak link in asphalt mixture, and the resistance of interface cracking directly affects the strength and durability of asphalt mixture. However, the interfacial zone in asphalt mixture is very thin, only on the scale of micron, and it is often difficult to quantitatively evaluate the influence of interface on the macro performance of asphalt mixture by conventional methods. The best way to understand the deformation and failure of asphalt mixture under the influence of interface is to use multi-scale analysis method. Since the interface effect has multi-scale internal characteristics, the damage and fracture shown by its macro is not achieved suddenly, but a bottom-up and progressive process, involving the linkage between nano, micro, meso, macro, structure and other scales. Only by mastering the material characteristics at different scales and their influence mechanism on the next scale can it be promoted layer by layer, so as to explore the source of material deformation and damage.

4.1.1. *Multi-scale evaluation method of interfacial interaction between asphalt binder and mineral aggregate*

4.1.1.1. Molecular dynamics simulation of asphalt adsorption behavior on mineral aggregate surface. At present, in the field of road engineering, molecular simulation technology is mostly used by researchers to study asphalt and other materials. While domestic researchers use molecular simulation technology to simulate asphalt materials, the models they built are relatively simple, and usually represent asphalt materials with a typical molecule, which is different from the actual complex molecular composition of asphalt materials. For instance, Zhang et al. (2010b) studied the interaction mechanism between aging asphalt and rejuvenators by using molecular simulation technology. Tang et al. (2013) who used molecular dynamics simulation method to analyze the change characteristics of asphalt molecule aggregation state found that there is layered accumulation among asphaltene molecules, but this situation will be destroyed by the influence of temperature rise. And the asphalt colloidal structure model was verified by Ding (2013) and Tang et al. (2013). Xu (2013) used molecular simulation to simulate the interface strength between a single asphaltene molecule and different metal oxides, and studied the effects of water and temperature through thermodynamic analysis. In the above study, it was found that the interaction abilities of the four oxides with asphaltene were as follows: MgO > CaO > Al_2O_3 > SiO_2, and the water damage mechanism of asphalt pavement is proposed by Xu (2013). In the United States, Jennings et al. (1993) proposed typical molecular structures that can represent complex components of asphalt in the Strategic Highway Research Program (SHRP). Pauli et al. (2003) verified the rationality of the typical molecular structures by atomic force microscope. Subsequently, Zhang and Greenfield (2007b, 2007c, 2008) simplified the composition of asphalt materials and proposed several representative molecular models that could represent the similar chemical components in asphalt materials: asphaltene, colloid, naphthenic aromatic constituents and polar aromatic constituents, which were simulated by molecular simulation technology. In addition, they investigated the effect of the addition of polystyrene chains on properties of asphalt, such as thermal expansion coefficient, volume modulus, etc., and analyzed the temperature dependence of the viscosity through the relaxation time and diffusion coefficient of each component (Zhang and Greenfield, 2007b, 2007c, 2008). In addition to the simulation study of the all-round properties of asphalt materials, molecular dynamics stimulation has also been applied to the deicing mechanism of asphalt pavement, the composite modification of asphalt materials, and the degradation of material property under light-oxygen conditions.

4.1.1.2. *Experimental study on absorption behavior of asphalt on aggregate surface*. Experimental studies on the interaction mechanism between asphalt and mineral are mostly carried out from the perspective of adsorption and desorption of mineral to asphalt components and the component migration of asphalt is characterized by X-ray photoelectron spectroscopy and infrared spectroscopy. The results of Curtis et al. (1993), Scott (1978), Fritschy and Papirer (1978) showed that the polar components (such as asphaltene) were more easily adsorbed on the surface of mineral, and Curtis et al. (1993) found that sulfoxide, carboxylic acid, pyridine and phenols in polar components were the most easily adsorbed components.

Ardebrant and Pugh (1991) found that Langmuir isotherm and Freundlich isotherm could be used to describe the adsorption of asphalt on aggregate surface and different functional groups in asphalt performed different adsorption degree on the surface of mineral. The study of Gonzalez and Middea (1987) showed that the adsorption of asphalt on aggregate surface can be described by Langmuir isotherm, which corresponds to the monolayer adsorption hypothesis. The research of Acevedo et al. (1995, 1998) had proved that asphalt was adsorbed on the aggregate surface in the form of multi-molecular layer adsorption, which was suitable for Freundlich isotherm. Subsequent studies refined this conclusion and found that adsorption type of asphaltenes with weak aromatics was monolayer adsorption, while that of asphaltenes with strong aromatics was multi-molecular layer adsorption (Acevedo et al., 1995, 1998). Recent studies by Abudu and Goual (2009) found that Langmuir isotherm was more suitable for minerals containing silica or alumina, while Freundlich isotherm was more suitable for minerals containing dolomite and calcite, and it was found that asphaltene was the main component adsorbed on the surface of minerals, and the thickness of adsorption layer was between 2 and 3 nm.

With the development of science and technology, more valuable conclusions can be obtained through advanced characterization techniques combined with adsorption and desorption experiments. Balabin and Syunyaev (2008) studied the adsorption of petroleum asphaltenes and resins on different aggregate surfaces by near infrared reflectance (NIR). They found that the adsorption rate depended on the type of matrix, the adsorption rate was higher than the desorption rate, and the adsorption rate of resin was higher than that of asphaltene, which proved that NIR was a good evaluation technology (Balabin and Syunyaev, 2008; Syunyaev et al., 2009). Labrador measured the adsorption of asphaltene on the glass surface by using the ellipsometry. It was found that the thickness of the asphalt film was between 20 and 300 nm. The thickness of the asphalt film increased with the increase of the concentration of asphaltene-toluene solution. The author believed that the adsorption between asphaltene and glass surface was physical because there were no covalent and ionic bonds between the components (Labrador et al., 2007). Turgman-Cohen et al. (2009) also used this technology to measure the thickness of the self-assembly monolayers, and found that the interaction between asphaltene and the polar silica substrate was stronger, but the interaction between asphaltene and self-assembly monolayer components was not obvious. Saraji et al. (2010) measured the adsorption of asphaltenes in porous media by UV-vis spectrophotometer and found that the adsorption was affected by the type of mineral materials. The adsorption capacity of calcite was higher than that of quartz and dolomite, and the thickness of adsorption layer was between 1.6 and 3.9 nm.

4.1.1.3. *Research on evaluation method of interaction between asphalt and mineral powder*.

(1) Rheological mechanical method

It is extremely difficult to directly measure the adhesion strength between asphalt and mineral powder from the mechanical point of view because of the extremely small mineral powder particles. Therefore, researchers often study the interface behavior between asphalt and mineral powder indirectly by measuring the mechanical properties of asphalt slurry under different powder to binder ratios (Choi et al., 2020).

In 1971, Anderson (1971) systematically studied the mechanical properties of asphalt mortar, and the results showed that the interface behavior between asphalt and mineral powder had a significant impact on the mechanical behavior of asphalt mortar. In 2009, Wu (2009) from Harbin Institute of Technology found that temperature, type of asphalt, acid and base of mineral powder, and particle size of mineral powder all had significant influences on the interaction ability. In 2012, Guo (2012) from Harbin Institute of Technology studied the phase behavior of asphalt mortar through dynamic mechanical analysis, and analyzed the interface structure and properties of virgin asphalt mortar and modified asphalt mortar respectively, and found that the lithology and particle size of stone powder had an important influence on the interface structure and properties.

(2) Microscopic test

Shao et al. (2003) from Harbin Institute of Technology were the first to study the micro-interface of asphalt mortar through scanning electron microscopy (SEM), and the micromorphology of asphalt mortar interface is shown in Fig. 38.

Guo (2012) from Harbin Institute of Technology studied the interface behavior through atomic force microscope and infrared spectrum, and obtained the influence of different aggregate surface states and asphalt grades on adhesion force. Sha and Wang (2008) studied the interface microstructure of cement emulsified asphalt, and concluded that the interface microstructure affected the overall performance of concrete, and cement could significantly improve the interface microstructure.

Khattak et al. (2007) studied the adhesion of different asphalts to aggregates at low temperatures through overlapping shear experiments and scanning electron microscopy, and the results showed that the loss of adhesion strength at low temperatures was the main cause of the failure of asphalt mixtures. Huang et al. (2005b) used

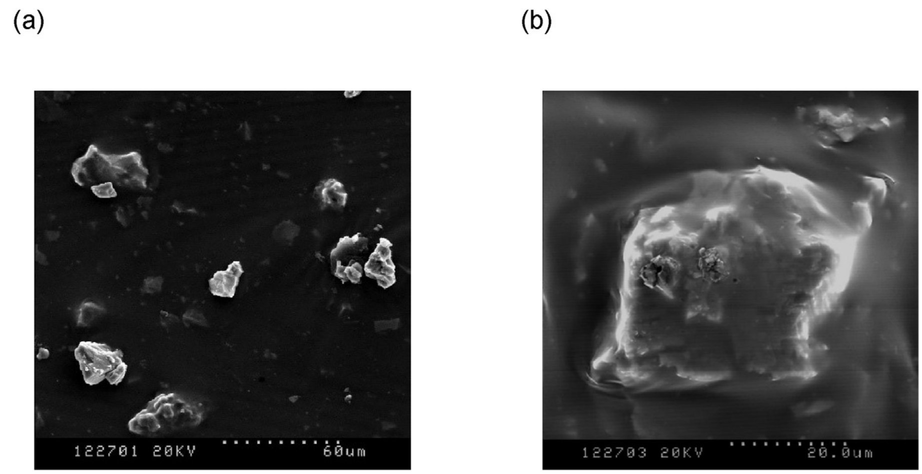


Fig. 38 – Micromorphology of interface of asphalt mastics. (a) Micro morphology of asphalt mastics. (b) Partial enlarged view of mineral filler (Shao et al., 2003).

differential scanning calorimeters and other equipment to measure the adhesion between asphalt and mineral powder, and obtained the structural characteristics of the interface between asphalt and mineral.

4.1.1.4. Study on evaluation method of interaction between asphalt and aggregate. At present, most of the studies on the asphalt-aggregate interface in asphalt mixtures focus on the cohesive and adhesive properties of asphalt and aggregates (Fig. 39). When the adhesion performance between them is poor, the impact of water and temperature is greater, coupled with the role of traffic load, eventually resulting in aggregate's spalling, mixture performance declined. On the one hand, the pavement tends to produce new diseases, such as pockmarked, loose, etc. On the other hand, the pavement will intensify the original disease, such as potholes, congestion package, nudge, etc. Therefore, it is of great significance to study the interface behavior between asphalt and aggregate.

Currently, most of the studies on the interfacial behavior between asphalt and aggregate have been conducted from the perspective of adhesion and cohesion properties, which are evaluated qualitatively by the degree of wrap integrity or quantitatively by macroscopic mechanical tests. The method of testing the adhesion is mainly to wrap the asphalt on the surface of the mineral material, immerse the mineral material in water, and determine the adhesion of the asphalt by analyzing the amount of asphalt peeling. Common test methods include boiling method, water immersion method, shear adhesion test, peeling test, and surface energy method.

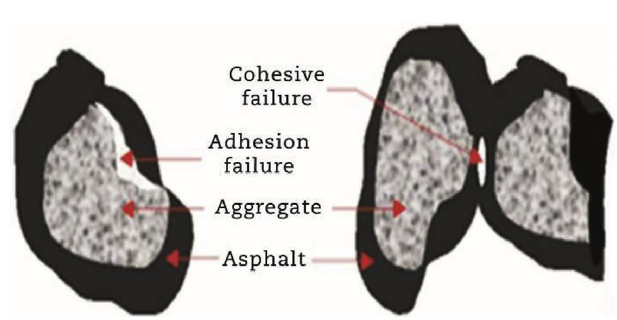


Fig. 39 – Damage types of interface between asphalt and aggregate (Guo, 2016).

In addition to the above-mentioned experimental methods, researchers have also explored numerical simulations to investigate the behavior of the asphalt-aggregate interface. For example, Gong (2012) from Harbin Institute of Technology established a microstructure model for asphalt mixtures and considered the interface strength to study the effect of fine microstructure on the interface and mortar crack resistance.

Conventional research has considered the adhesion between asphalt and aggregate to be most closely related to the water damage resistance of asphalt mixtures, and less research has been done on the relationship between interfacial behavior and other aspects of performance. Ribeiro et al. (2009) found that the interaction between asphalt and aggregate affects the mechanical properties of asphalt mixtures, with the degree of influence varying depending on the composition of the aggregates.

Warm mix combined recycling technology is becoming a hot topic of research for road workers due to its significant economic advantages and environmental benefits. Some researchers believe that warm mix technology can achieve similar pavement performance as hot mix technology when paving recycled asphalt pavements (Mallick et al., 2008b; Shu et al., 2012). However, more researchers have found that water damage, rutting, and temperature cracking can occur when paving recycled asphalt pavements using warm mix technology (Canestravi and Ingrassia, 2020; Guo et al., 2014; Hill et al., 2013; Zhang, 2020; Zhao et al., 2013). Although researchers have done a lot of research in this area, none of them have been able to clarify the mechanism of this performance difference. Mohajeride et al. (2014) characterized the interfacial transition region between recycled and new asphalt in recycled asphalt mixtures by using a combination of nanoindentation, nanocomputed tomography, and optical microscopy techniques and concluded that this region affects the overall mechanical properties. It can be seen that studying the interfacial properties between asphalt and recycled aggregates can provide a theoretical basis for improving the warm mix-recycling technology.

4.1.2. *Multi-scale numerical simulation method considering interface effect*

4.1.2.1. *Multi-scale effect of interface*. The overall mechanical properties of asphalt mixtures, especially their resistance to damage and cracking, are not only related to the mechanical properties of their constituent phases, but also closely related to the interfacial properties and interactions between asphalt and aggregate. Existing studies have shown that the non-polar and polar substances in asphalt materials will produce physical adsorption and chemical adsorption with different sizes, degrees and properties with the surface of rough aggregate, which leads to that the bonding material is not an ideal surface in the bonding area, but a spatial area with the scale of several microns to tens of microns. Therefore, there must be a transition region from asphalt to aggregate between asphalt and aggregate, which is called the interface region. In such a space, the material presents non-uniform and anisotropic distribution characteristics. The material properties and microstructure in the interface zone are necessarily related to but different from asphalt and aggregates, showing unique characteristics (structural characteristics, chemical and mechanical properties, etc.).

The macro damage and fracture of pavement materials do not happen at one go, but in a bottom-up, layer by layer progressive process, involving the interaction among multiple scales such as nano, micro and macro. Therefore, in order to deeply understand the deformation and damage of materials, we should not only stay at the macro scale that gives the representation, but fully carry out multi-scale analysis, integrating the perspectives of multiple disciplines such as engineering, materials, chemistry and physics, so as to combine the macro, micro scale and even nano scale analysis to find out the root and mechanism of material deformation and destruction at a deeper level.

In this part, the previous multi-scale numerical simulation methods considering interface effects are reviewed strictly, which can provide methods and basis for material selection, modification, material composition and structural design.

4.1.2.2. *Study on performance of asphalt mixture based on micro nano scale testing technology*. Interfacial problems need to be analyzed effectively and accurately on a discrete nano scale. With the development of experimental interface mechanics, the characterization methods of the microstructure of the interface region of composite materials are becoming more and more perfect.

In terms of interface micromechanical properties, traditional test methods include single fiber pull-out test, single fiber pull-out test, bending test, shear test, and pull-out test, etc. In recent years, nanoindentaiton (NI), MRS, fluorescence spectroscopy (FS) have been developed, by combining with the traditional interface micromechanics test, formed a new, richer and more perfect experimental technology and data analysis method. Nanoindentation technology, which emerged in the mid-1980s, provides an effective method for in-situ testing of mechanical properties of composites, and can measure various mechanical properties of materials on micro and nano scales, such as load-displacement curve, elastic modulus, hardness, fracture toughness, viscoelasticity, etc. (Ling, 2011). At present, this technique has been widely used in testing the mechanical behavior of interfacial transition zone of composite materials. MRS and FS are two kinds of spectroscopic analysis techniques. In the past 20 years, these two technologies have made rapid development in the field of interface research, and have made great contributions to the exploration of interface behavior of composite materials, especially the micromechanics of interface.

Nahar et al. (2013) determined that the miscibility region of old and new asphalt was between 160 nm and 2.07 μm by applying AFM. Yang et al. (2014a) used AFM to study the relationship between microstructure and self-healing properties of asphalt under different aging degrees. Rinaldini et al. (2014) used micro-CT, environment scanning electron microscope (ESEM) and energy dispersive X-ray spectrometer to observe the spatial structure and microcracks in the old and new miscible zone of recycled asphalt mixture. Dourado et al. (2012) studied the mechanical properties of honeybee structures using nanoindentation technology. Shen et al. (2014) studied the diffusion law of modified regenerators in aging asphalt by using gel permeation chromatography (Fig. 40). Jahangir et al. (2015) used AFM to get the bee structure of asphalt, and based on this, established a 2D finite element model to analyze the bee structure changes under the action of tensile stress. Jäger et al. (2007) adopted NI and inverse algorithm to obtain the micro nano creep behavior of asphalt. Tarefder et al. (2010) used NI to study the elastic modulus and hardness of asphalt at micro nano scale. Katsuki and Gutierrez (2014) used NI to measure the hardness and rheological behavior of asphalt mixture at micro nano scale.

4.1.2.3. *Study on the interface between asphalt and aggregate based on molecular dynamics*. Molecular dynamics simulation (MD), with its high accuracy, can help people understand the basic characteristics of matter from the perspective of atomic and nanoview. With the continuous development of computer technology and the recognition of molecular simulation results, there have been many applications in the field of road materials research in recent years. Some scholars have studied the adhesion characteristics of asphalt-aggregate interface at the micro scale with the help of MD simulation.

From the aspect of microscopic characteristics, the research process of asphalt aggregate interface with MD simulation method is shown in Table 21. As early as the 1990s, Murgich et al. (1998) used molecular simulation to study the adsorption behavior of asphaltene and colloid on Kaolin crystal surface. In recent years, Xu (2013) and Li et al. (2016a) used MD to study the interaction between asphalt and aggregate. Asphaltene molecules were selected to represent asphalt, six major chemical components (SiO_2, CaO, MgO,

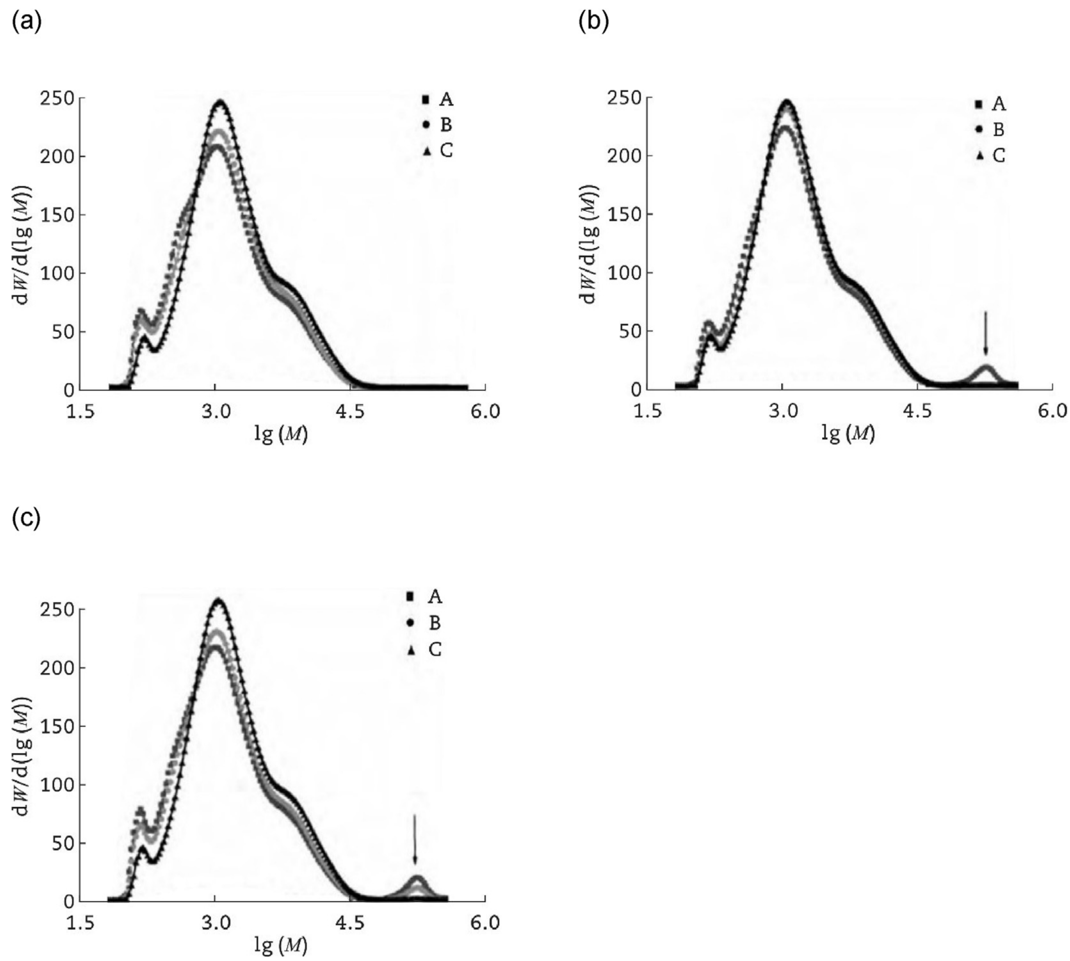


Fig. 40 – Molecular weight distribution curves of asphalt binder in different diffusion position. (a) R-1 regenerating agent. (b) R-2 regenerating agent. (c) R-3 regenerating agent (Shen et al., 2014).

Al_2O_3, Na_2O and K_2O) in conventional aggregate were selected to represent aggregate, and the interface model of asphaltene/oxide molecules was established. The molecular interface energies of asphaltene/oxide and the cohesive energies of asphaltene at different temperatures were calculated. Yu et al. (2012) studied the adsorption behavior of asphaltene on quartz surface, observed the adsorption conformation of asphaltene on quartz surface in different solvents, and calculated the interaction between asphaltene and quartz interface and solvent. Xu and Wang (2016b) selected the asphalt molecular model of Zhang and Greenfield (2007a) and collected materials with SiO_2 and $CaCO_3$ crystal models. The interaction energy and adhesion work of asphalt-aggregate were calculated by MD simulation method. It is found that for the same aggregate, the difference of adhesion work between two kinds of asphalt to aggregate is small, but the difference between the same asphalt and different aggregates is large. In addition, the study found that the interaction between asphalt and mineral aggregate is dominated by van der Waals forces. Wu et al. (2013, 2015b) studied the adsorption capacity of four components of asphalt on quartz interface by using interaction energy as the main evaluation index. Guo et al. (2017c) studied the diffusion characteristics of four components of asphalt on the surface of SiO_2, Al_2O_3, CaO, MgO and Fe_2O_3, and characterized the movement characteristics of each component of asphalt by means of the mean azimuthous displacement and diffusion coefficient.

The bond strength of asphalt-aggregate interface has always been the focus of attention, and many new testing methods have been applied to evaluate the bond strength of asphalt-aggregate interface. Xu et al. (2016c) took silicate minerals represented by silicon cells as AFM tips, and established matrix, short-term aging and long-term aging asphalt molecular models respectively by using the twelfth fractional and four-component model proposed by Li and Greenfield (2014a). The AFM force curve scanning test was simulated with MD to obtain the force displacement curves of three kinds of asphalt materials with different aging degrees, and the maximum gravity was used as the adhesion force to calculate the bond strength. The calculated results show that the short-term aging asphalt has the largest bond strength with aggregate, followed by the long-term aging asphalt. Based on the simulation

Table 21 – Research process of microstructure characteristics of asphalt-aggregate interface.

Researcher	Year	Research progress
Murgich et al.	1998	The adsorption behavior of asphaltene and gum on kaolin crystal surface was studied.
Yu et al.	2012	The adsorption behavior of asphaltene on quartz surface was studied, and the interaction between asphaltene and quartz interface and solvent was calculated.
Wu et al.	2013, 2015b	The adsorption capacity of four components of asphalt on quartz interface was studied.
Xu	2013	The interaction between asphalt and aggregate was studied.
Li et al.	2016a	The interface model of asphaltene/oxide molecule was established, and the interface energy and cohesive energy were calculated.
Xu et al.	2016c	The molecular models of matrix, short-term aging and long-term aging asphalt were established.
Xu and Wang	2016c	The interaction energy and adhesion work of asphalt aggregate are calculated.
Guo et al.	2017c	Characterization of movement characteristics of asphalt components
Du and Zhu	2019	A 12-component AAA-1 asphalt model and five oxide models were generated.
Zhu et al.	2020a	The effect of mineral filler on the structural, thermodynamic and mechanical properties of asphalt mastic were explored.
Du et al.	2021d	The diffusion and structural properties of moisture (water molecules) in both neat asphalt binder and asphalt mastic were characterized.

calculation and experimental results, Xu et al. (2016c) proposed an asphalt-aggregate interface interaction model, which considered that the asphalt surface was uneven due to the colloidal structure of the asphalt material. When asphalt and aggregate are in contact with each other, there is a balance between repulsion and gravity. The aggregate first touches the bulging part of asphalt material. With the approach of aggregate, the bulging part begins to deform until the balance between gravity and repulsion is reached between asphalt and aggregate. The model can explain how the surface structure of asphalt material affects its adhesion to aggregate. Xu and Wang (2016b) established the asphalt aggregate interface model. After the model was fully relaxed, the MD simulation method was used to simulate the pull-off test, and the force-displacement curve was obtained. The force-displacement curve was fitted by the cohesive zone model (CZM) and the maximum adhesive force σ_c was used to calculate the interfacial bond strength. Du and Zhu (2019) analyzed the adhesion and diffusion of asphalt binder on mineral surfaces at a nano scale based on molecular dynamics simulation. A 12-component AAA-1 asphalt model and five oxide models were generated to represent asphalt binder and mineral aggregates, respectively (Fig. 41). To fully understand the filler reinforcement mechanism in asphalt mastic, Zhu et al. (2020a) adopted molecular dynamic (MD) simulation to explore the effect of mineral filler on the structural, thermodynamic and mechanical properties of asphalt mastic. Zhu et al. (2020a) and Du et al. (2021d) also adopted the molecular dynamics simulation technique to characterize the diffusion and structural properties of moisture (water molecules) in both neat asphalt binder and asphalt mastic.

4.1.2.4. *Study on performance of asphalt mixture based on meso-mechanics*. Different sizes of aggregates and binders in asphalt mixture will affect the overall performance of asphalt pavement. The meso-mechanical model can take into account the role played by all basic materials in the composite in the overall structure. In recent years, more and more researchers began to investigate the mechanical behavior of asphalt mixture from the perspective of meso-mechanics of composite materials. Anderson and Goetz (1973) used the mesoscopic model to study asphalt mixtures earlier and believed that the macro-performance of asphalt mixtures was closely related to particle size, the interaction between asphalt slurry and particles, and temperature. Lytton (1990) proposed a three-phase meso-prediction model, assuming that asphalt mixture is composed of aggregate, binder and void. Buttlar and Roque (1996) evaluated the applicability of four kinds of micromechanical models to the prediction of elastic modulus of asphalt mixture through elastic modulus test of asphalt mixture at low temperature, and believed that the prediction value of elastic modulus of asphalt mixture by the existing two-phase spherical inclusion model would be low. They point out that many of the current micromechanical models may be applicable only to typical suspended asphalt mixtures because the coarse particles are not in direct contact with each other, but are suspended from each other between smaller particles and asphalt mortar, so that there is no obvious interaction between aggregate and aggregate. Li et al. (1999) buried the circular aggregate wrapped in asphalt film into the equivalent asphalt mixture medium to form a two-layer embedded meso-model, and derived the expression of the two-dimensional effective elastic modulus, but this expression is related to another elastic constant of asphalt mixture, Poisson's ratio, which is still determined by empirical formula when used. Using this model, they only studied asphalt horseshoe grease gravel (SMA), and did not carry out the relevant test validation. Shu and Huang (2008a) used the same mesoscopic model as Li et al. (1999) to derive the expression of the three-dimensional effective elastic modulus of hot trip asphalt mixture, but the empirical formula was still used for Poisson's ratio. Krishnan and Rao (2000) applied a relatively simple mixing criterion to study the effect of voidage in asphalt mixtures, that is, weighted average of various inclusion phases according to their

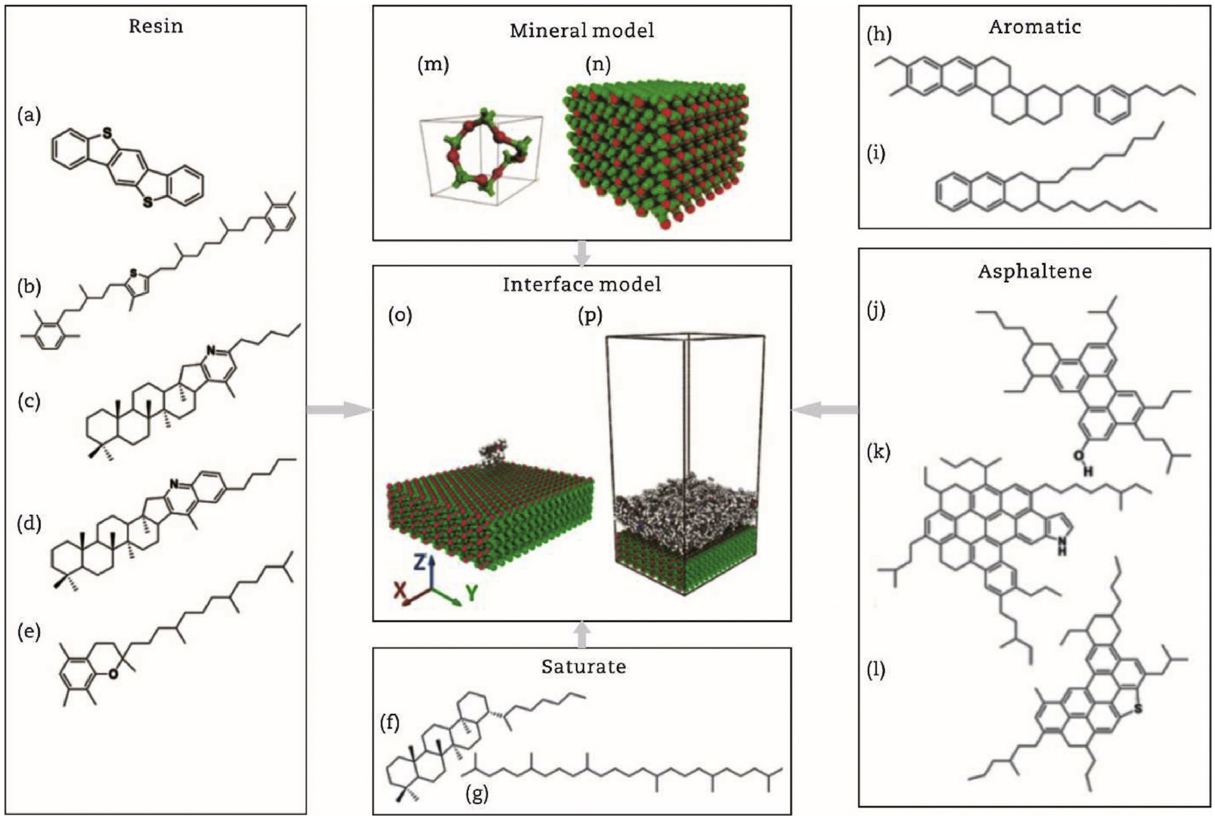


Fig. 41 – Components of asphalt-aggregate interface model. (a) Benzobisbenzothiophene. (b) Thio-isorenieratane. (c) Pyridinohopane. (d) Quinolinohopane. (e) Trimethylbenzene-oxane. (f) Hopane. (g) Squalane. (h) PHPN. (i) DOCHN. (j) Asphaltene-phenol. (k) Asphaltene-pyrrole. (l) Asphaltene-thiophene. (m) Unit cell of quartz. (n) Bulk surface model of quartz (with atoms Si and O in green and red respectively). (o) Asphalt component molecule and quartz mineral. (p) AAA-1 asphalt binder and quartz mineral (Du and Zhu, 2019).

volume ratio to obtain the overall macroscopic equivalent mechanical properties. Huang et al. (2003) used Cox shear theory and mixing criterion to study the tensile strength of asphalt mixture at low temperature, taking into account the bond between asphalt slurry and particles and asphalt aging problems, and verified them through experiments. Shashidhar and Shenoy (2002) simplified the generalized self-consistent theory by using the order of magnitude simplified analysis method and permeability theory to discuss the dynamic mechanical behavior of asphalt mixtures. Li and Metcalf (2005) simulated the asphalt mixture into a two-phase meso-mechanical model and used a two-step method to predict the modulus of asphalt mixture. The first step is to simulate the asphalt mixture into a two-phase medium, including circular fine aggregate-binder and circular coarse aggregate; the second step is to simulate the circular fine aggregate-binder with a two-phase model, including circular fine aggregate-binder and asphalt binder. They recommend that tests be carried out on different asphalt mix designs to validate existing methods. Guo and Zhao (2007) proposed the equivalent modulus calculation formula of fiber-reinforced composite materials on the basis of Eschelby-Mori-Tanaka theory, and assumed that the asphalt mixture was composed of matrix and cylindrical fibers uniformly distributed in any direction, so as to predict the elastic modulus of fiber-reinforced asphalt mixture.

Previous studies on viscoelastic behavior of asphalt mixtures have assumed a constitutive model that can describe viscoelastic properties of asphalt mixtures, such as Burgers model and four-element and five-parameter model, which are generally considered in engineering to better reflect relaxation and creep properties of asphalt mixtures. Then, various parameters of the model were calibrated by creep tests (trabecular bending creep test or uniaxial static compression creep test, etc.). This research method belongs to the semi-empirical and semi-theoretical method, and is limited by the experimental conditions, so it is difficult to reflect the effect of aggregates, voids, asphalt mortar and other components and meso-structure in the whole. At present, domestic and foreign researchers have done some researches and discussions on the viscoelastic meso-mechanics of asphalt mixture. Shashidhar and Romero (1998) used the generalized Nielsen model to conduct a series of discussions on the creep compliance of asphalt mixture. The influences of various particle sizes, gradations, aggregate shapes and aggregate distribution on asphalt mixtures are summarized by generalized Einstein coefficient and filler packing fraction. Guo et al. (Guo et al., 2007, 2008b; Guo and Zhao, 2007) have also done a lot of work in this field. Their main idea is to combine the equivalent modulus calculation formula of particle reinforced composites proposed on the basis of Eschelby-Mori-Tanaka theory with the four-element and five-parameter model, and then carry out Laplace transform. Then the parameters of the model were calibrated according to the test and used for viscoelastic analysis of asphalt mixture. Kim and Little (2004) respectively use the three expressions about effective shear modulus given by Hashin, GSCM and Nielsen (based on rheology), and use the Schapery direct transformation method, that is, when the inverse transformation is carried out in the Laplace domain, the Laplace variable is directly replaced by the time variable 0.56/t, so as to obtain the effective relaxation modulus expression of linear viscoelasticity of asphalt mixture, the results of dynamic shear rheometer test show that the existing model is in good agreement with the test only at low volume fraction. Shu and Huang (2008a, b) used a two-layer embedded model to derive an expression for the effective relaxation modulus of viscoelasticity of three-dimensional asphalt mixture lines. The expression takes into account the effects of voidage and maximum particle size, and can reflect the general trend of dynamic modulus, but its predicted value is lower than the experimental data.

4.1.2.5. *Mesoscopic numerical simulation test of asphalt mixture*. The numerical simulation method can be used to study the damage and cracking mechanism of asphalt mixture, which can provide a theoretical basis for the micro-structure design of asphalt mixture and the optimization of mechanical properties of materials. As shown in Table 22, it is the progress of numerical simulation experiment.

In 2005, Kim et al. (2005) established a two-dimensional finite element model of asphalt mixture to analyze the damage mechanical response of asphalt mixture. By introducing a micro-mechanical nonlinear viscoelastic bonding zone model (cohesive zone constitutive model) into the interface of the model, the propagation and damage evolution of interface cracks were analyzed. The research results show that the basic properties and fracture characteristics of raw materials have an important influence on the fracture mechanical properties of asphalt mixture (Kim et al., 2005). In 2011, Aragão et al. (2011) combined finite element method and cohesive zone fracture model to study the damage and fracture process of asphalt mixture, and carried out parameter analysis on fracture performance. The measured results verified the applicability of the model. Dai (2011a) proposed a three-dimensional meso-finite element mesh model to predict the elastic damage behavior of stone-based materials such as asphalt mixture, and introduced the bilinear damage law. Through indirect tensile and uniaxial compression simulation tests, the meso-damage distribution and the overall fracture behavior inside the sample were analyzed. By comparing with the measured results, it is found that the three-dimensional finite element model established can better predict the typical damage behavior of rock-based materials under the action of load (Dai, 2011a). From 2012 to 2013, You et al. (You, 2013; You et al., 2012) reconstructed the three-dimensional numerical model of asphalt mixture including aggregate and asphalt mortar by using CT scanning images, introduced the thermo viscoelastic, thermo viscoplastic and thermo visco damage constitutive models, and studied the stress-strain behavior of materials, damage evolution process, recoverable and nonrecoverable strain at different temperatures through the virtual simulation tests of uniaxial compression, uniaxial tension and virtual simulation test of repeated creep recovery. The results show that the three-dimensional microstructure model and constitutive model can effectively predict the thermal-mechanical response of asphalt mixture (You, 2012; You et al., 2012). In 2013, Wang et al. (2013b) used CT image and digital image processing technology to establish two-dimensional finite element numerical model of heterogeneous porous epoxy asphalt mixture, by splitting the simulation test the damage evolution process of crack initiation extension is analyzed, the results show that the distribution of the mesoscopic structure is affected the distribution of stress and strain response of asphalt mixture and its factors. In 2016, Onifid et al. (2016) proposed a viscoelastic damage constitutive model of asphalt mixtures on the basis of continuous damage mechanics and thermodynamics, and analyzed the effectiveness of dissipative creep strain energy index in evaluating the damage and cracking performance of asphalt mixtures through Superpave indirect tensile test simulation (Onifade, 2017). In 2019, in order to control the degradation of asphalt pavement and improve the durability of asphalt mixture, Kollmann et al. (2019) used CT and digital image processing technology to reconstruct the two-dimensional finite element numerical model of asphalt mixture. On this basis, indirect tensile virtual tests were carried out to study the

Table 22 – Research progress of numerical simulation method

Researcher	year	Established model
Kim et al.	2005	Two-dimensional finite element model of asphalt mixture
Aragão et al.	2011	Finite element method and cohesive zone fracture model
Dai	2011	Three-dimensional meso-finite element mesh model
You et al.	2012; 2013	Three-dimensional microstructure model and constitutive model
Wang et al.	2013b	The finite-element model including the aggregate, sand mastic and air voids
Onifade et al.	2016	Viscoelastic damage constitutive model of asphalt mixture
Kollmann et al.	2019	Reconstruction of two-dimensional finite element numerical model of asphalt mixture

effects of temperature and porosity on micro-crack initiation and propagation of asphalt mixture.

4.1.3. *Multi-scale investigation on interface deterioration*

The property of aggregate-binder interface is a key factor affecting the strength formation of asphalt mixture. As a result, the deterioration of aggregate-binder interface has a great influence on the distress of asphalt pavement. Modeling and evaluating the deterioration of adhesive bond between aggregate and binder from the micro or meso scope become critical for revealing the mechanism of asphalt pavement deterioration. Recent studies on the deterioration of aggregate-binder interface in the last decade show that the adhesive bond at the interface is affected by various factors such as moisture, aging, deicing salt solution infiltration, and freeze-thaw cycle, as shown in the Fig. 42.

The macroscopic manifestation of moisture damage mainly includes stripping and ravelling, which is closely related to the aggregate-binder/mastic interface. Experiments have shown that the deterioration of aggregate-binder bonds correlate well with the moisture uptake, and the moisture diffusion also affects the interfacial retained tensile strength (Zhang et al., 2017a), Currently, CZM model, surface free energy theory, and molecular dynamics are widely used to investigate the deterioration of aggregate-binder/mastic interface (Omar et al., 2020).

CZM model is usually embedded in finite element analysis to investigate the influence of water or moisture on the aggregate-binder interface. Some studies based on CZM are summaried in Table 23. The mechanical properties of the material could be considered as a function of the moisture concentration (Caro et al., 2010b; Hu and Qian, 2013). Studies based on CZM model have shown that the presence of water reduces contact stress, reduces the load of interfacial failure, and accelerates the fracture development at the interface (Caro et al., 2010b; Hossain and Tarefder, 2014). It was observed in some studies that the damage starts at the same place regardless of the amount of water, but the subsequent development is different (Hu and Qian, 2013). Current studies based on CZM models could effectively introduce the change in interface properties, thus characterize the deterioration of asphalt mixture. However, the simulation results are highly dependent on the constitutive model and the values of key parameters, which are difficult to be determine.

Surface energy theory uses the classical wetting theory to analyze the process of water damage to the interface. According to surface energy theory, water has high surface energy, which prevents the effective bonding between asphalt and aggregate (Ji et al., 2017; Wang, 2010). When water intrudes into the asphalt-binder interface, the interfacial tension between binder and aggregate is greater than that between water and aggregate, resulting in easy falling off of the asphalt (Liu et al., 2010a). The presence of water makes the surface energy reduction at the asphalt-aggregate interface change from negative to positive (Han et al., 2010). By measuring the surface free energy of different binder and aggregate, the work of adhesion with and without the presence of water could be calculated, making it feasible to analyze the adhesion between binder and aggregate with the surface energy theory (Cheng, 2002). These studies proved that the presence of water has an important effect on interface deterioration, but the specific deterioration principle needs to be further studied. A relatively simple way is to compare the change of surface free energy of binder-aggregate interface with and without water. However, the presence of water may lead to some chemical and physical changes at the interface, so it is necessary to combine chemical thermodynamics theory with surface energy and introduce the three-phase interface equation (Xiao et al., 2012a, b). From the perspective of energy, surface energy can fully reflect the change of interfacial molecular tension, but it is difficult to reflect the influence on the motion of water molecules. Therefore, molecular dynamic (MD) simulation was further studied.

Molecular dynamics (MD) is to establish molecular models at the atomic level to simulate the behavior of water molecules at the interface. MD studies have shown that the presence of moisture decreased the total interaction energy between aggregate and binder, thus reduces the interface adhesion strength (Gao et al., 2018a; Lu and Wang, 2017; Wang et al., 2017c). The dissolution of polar molecular into

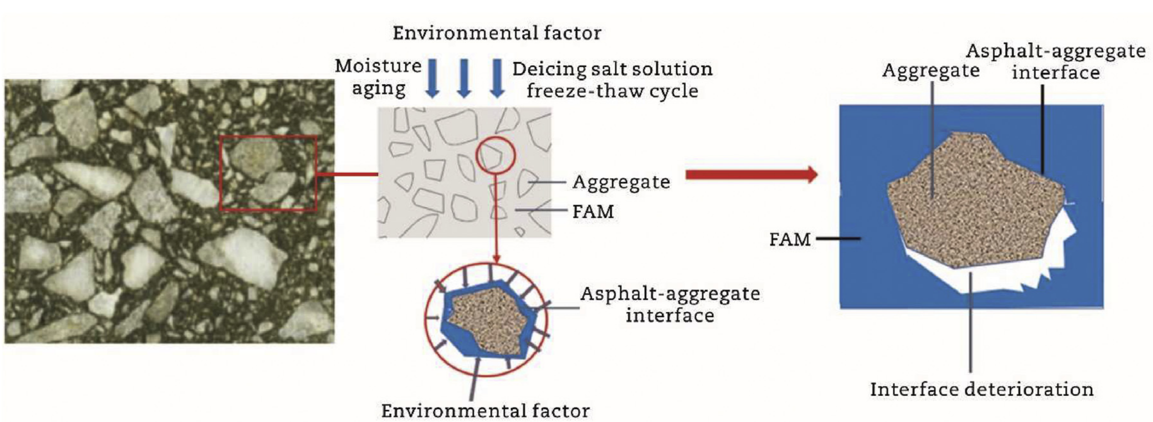


Fig. 42 – Schematic diagram for interface degradation.

Table 23 – Summary of interface deterioration analysis based on CZM.

Reference	Material parameter	Moisture transport mechanism	Theoretical damage model	Damage model parameter
Hossain and Tarefder, 2014	Dynamic elastic modulus of dry and wet conditions	–	Traction-separation damage law	Interface stiffness
Caro et al., 2010b	Function of moisture concentration	Fick's second law	Fracture mechanics and thermodynamics principle	Crack correlation parameter
Hu and Qian, 2013	Linearly changes with water content	Forchheimer's law	Traction-separation law	Bonding failure
Bozorgzad et al., 2018	Function of moisture content	Fick's second law	Traction-separation law	Fracture energy

Note: "–" means the data is not provided.

water induces the nanostructure collapse, and further leads to the asphalt-aggregate interface debonding (Dong et al., 2017). The immersion of the water solution can reduce the concentration of the asphalt molecules on the surface, thus weakening the physical adsorption effect between the asphalt and silica aggregate surface (Long et al., 2020). External moisture that intruded into the interface of the aggregate-binder system reduced the adhesion works of the aggregate-binder interface, and declined the water damage resistance of asphalt mixture (Cui et al., 2020b, c). The water adsorbed on the surface of weakly alkaline aggregates significantly decreased the aggregation concentrations of resin and asphaltene and made the distributions of SARA components near the calcite surface more uniform (Fig. 43), which seriously affected adhesion energy between asphalt and calcite (Cui et al., 2020b, c). The model established based on the intermolecular bond energy/force and the mechanisms of cohesive and adhesive failures also confirmed that the increase of water vapor concentration at the interface would lead to the decrease of tensile bonding strength (Nobakht et al., 2020). Due to the anisotropic mineral surfaces, water has different degradation effects on the interface, making the degree of interface degradation distinct for different aggregates (Luo et al., 2020a).

Another important cause of interface deterioration is aging. Studies show that the aging could lead to decrease of fracture energy at asphalt-aggregate interface, and reduce interfacial adhesion (Yuan et al., 2020b; Zhang et al., 2020c). The attenuation of micro-surface energy caused by aging is the main factor to reduce the value of macro-bonding, further indicating that the main reason for the bonding failure of aged asphalt with aggregate is the weakening of interface chemisorption (Ji et al., 2020). However, for different mineral composition, the impact of aging on the interface is different. In detail, aging can degrade the interfacial adhesion of binder-acidic minerals. In comparison, the interfacial adhesion of binder-strong alkali minerals does not deteriorate or even increase (Gao et al., 2019).

Salt and freeze-thaw cycles can also degrade the interface (Feng et al., 2010; Guo et al., 2019b). These factors usually appear in road deicing. The higher the concentration of deicing salt, the stronger the erosion effect on the interface,

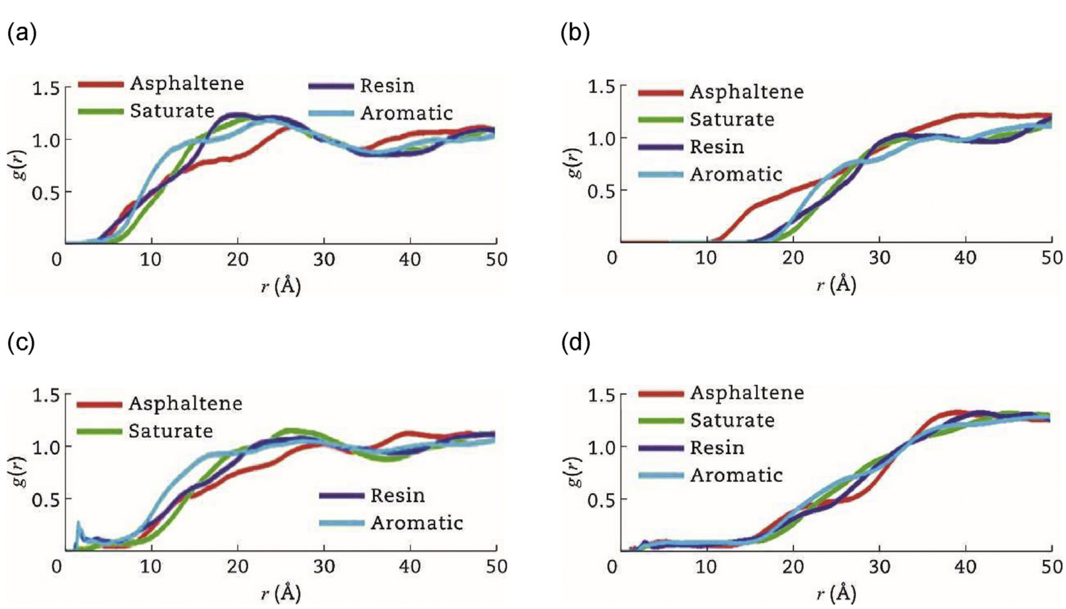


Fig. 43 – Asphalt-aggregate interface radial distribution function (RDF) curve. (a) Asphalt-calcite under dry condition. (b) Asphalt-water-calcite under wet condition. (c) Asphalt-calcite-HS under dry condition. (d) Asphalt-water-calcite-HS under wet condition (Cui et al., 2020c).

and the invasion of salt will lead to the change of interface energy (Xiao et al., 2012a, b). Test results show that microcracks could be observed at the binder-aggregate interface after cyclic freeze-thaw exposure, indicating the loss of adhesion bonds (Xu et al., 2020d). The coupling actions of salt immersion and F-T cycles would change in interface deterioration patterns (Guo et al., 2019b).

Asphalt pavement is often subjected to temperature changes in practice. Temperature variation also affects the performance of the asphalt-aggregate interface (Xu and Wang, 2016a). In order to explore the damage and deterioration of the asphalt-aggregate interface caused by temperature, scholars have studied it from multiple scales. Based on the contact-slip test, it is observed that temperature can affect the bonding/lubrication transformation behavior of the aggregate-asphalt system (Su et al., 2020a). Although it can be seen from the test that temperature does have an important influence on the interface damage, microscopic numerical simulation is still needed to study the specific interface condition. One of the possible reasons for temperature deterioration of the interface is differential thermal contraction at the interface between mastic and aggregates (Bekele et al., 2021). Another reason is the change of interface composition caused by the change of temperature (Guo et al., 2017c, 2018b; Guo and Tan, 2021). It causes changes in intermolecular forces. In particular, high temperature leads to deterioration of interface adhesion (Wang and Zheng, 2021).

4.1.4. Summary and outlook

The interface transition zone in asphalt mixture is very thin, only micro nano size, and the material structure distribution is complex, showing a non-uniform and heterogeneous state. It is almost impossible to quantitatively evaluate the properties of the interface zone. However, if the interface layer is simplified to a surface without thickness according to the conventional engineering treatment method, the influence of the microstructure and evolution of the interface phase on the interface strength and crack initiation at the interface cannot be studied. With the development of multi-scale analysis method, it is possible to accurately evaluate the characteristics of the interface region and explore the crack initiation and crack propagation in the interface region caused by the evolution of the properties of the interface region. However, limited by the current test methods, at present, it is still difficult to accurately determine the physical and mechanical indexes such as interface thickness, modulus, ultimate tensile strength and fracture energy, which makes it difficult to accurately predict the impact of interface performance degradation on the performance degradation of asphalt mixture. In the future, the feasible way is to fit the mechanical parameters of the interface by testing more samples and combining with the multi-scale mechanical analysis model, and then use the fitted interface parameter values to establish the database of interface properties of asphalt mixtures with different meso structures.

The deterioration of binder-aggregate interface is a complex phenomenon involving chemical, physical, and mechanical processes. Studies have been conducted to reveal the mechanism of interface deterioration from different perspectives and scopes. However, there are still some challenges in this field.

(1) Present studies are mainly based on simulation, while the simulation results highly depend on the constitutive model and parameters. In practice, accurately determine these parameters is not an easy task, which limits the applicability of the results. This problem may be solved by conducting systematic studies on determination of key parameters.
(2) The deterioration of binder-aggregate interface involves chemical, physical, and mechanical effects. These effects are not independent of each other, but coupled with each other. This coupled effect is usually ignored in present studies. Further studies may establish the relationship between the chemical, physical, and mechanical effects.

4.2. *Multi-scales and numerical methods in pavement engineering*

Pavement is a highway infrastructure composed of various layers which are built with different mixtures, while mixtures are made of different source materials which have different chemical constituents. Evidently, a pavement geometry is a multi-scale system and the interactional effects among different scales should be seriously considered for achieving a better engineering design. In the past few decades, with the rapid development of modern computational technologies plenty of research efforts have been made for dealing with the multi-scale system of pavement. In order to improve the fundamental understanding of the multi-scale system, literatures of the three aspects below are searched and analyzed in this section.

- Asphalt pavement multiscale system
- Multiscale modeling methods
- Cross-scale modeling methods

4.2.1. *Asphalt pavement multi-scale system*

Since pavement is a multi-scale system where various factors impact its performance in very complex ways, it is challenging to predict pavement performance with a single-scale model. As a result, the traditional pavement design is done with the empirical methods based on observations and historical performance from the previously built pavements. With the rapid development of computer technologies, multi-scale analysis methods have been developed and applied for dealing pavement or mixture performances at different length scales. In a multi-scale analysis method, different length scales are linked with each other through homogenization: the lower scale is homogenized and transferred to the next higher scale and the macro scale properties can be predicted from the lower scale properties (Allen et al., 2017a, b, c; Arshadi, 2015; Ling, 2016). On the contrary, the mechanical behavior on the higher scale will further change the material parameters on the lower scale. The scales are therefore entangled with each other. There are various multi-scaling approaches, which include upscaling, expanding multi-scaling, contracting multi-scaling, two-way coupled multi-scaling approach, and so on. Before introducing the scaling approaches, multiple length scales within an asphalt pavement structure are discussed in this section.

4.2.1.1. Multi-scale definitions from literatures. Researchers have developed different ways for their own research objectives and there are different definitions of multi-scales as demonstrated in the literatures. Representative multi-scales are plotted in the Fig. 44 and the corresponding literatures are introduced as follows.

Research effort was made to develop a multi-scaling method as a primary means of pavement design (Allen et al., 2017a). This research considers a pavement construction material as a result of adding multi-scale particles to asphalt binder. As shown in Fig. 44(a), the binder-scale is referred to asphalt mastic which is constructed by adding microscopic particles such as mineral fillers or limes into the asphalt binder; the fines-scale is referred to asphalt sand mastic which is formed by adding fines or sands into asphalt mastic; and the aggregates-scale is referred to asphalt mixture which is constructed by adding aggregates into asphalt sand mastic. The minimum scale is the molecule-scale which is asphalt binder in fact and cannot be solved with the traditional continuum mechanics; while the maximum scale is the roadway-scale which is usually difficult to be measured through lab tests.

Research effort was made to develop a two-way coupled multi-scale algorithm where global, local, and micro scales are included as shown in Fig. 44(b) (Allen et al., 2017c; You et al., 2018b). The global length scale is referred to a roadway section, the local length scale is referred to the aggregates-scale which is a local unit or core-sample in the roadway section, while the micro scale is referred to the key components in the aggregates-scale.

Fig. 44(c) shows another research about the multi-scales in asphalt mixtures, which include bitumen-scale, mastic-scale, mortar-scale, asphalt-scale, and macro scale (Arshadi, 2015).

Research efforts (Sun and Wang, 2009) was made to define scales based on the physical length as shown in Fig. 44(d), where the micro scale is referred to the scale less than nanometer, the meso scale is referred to the scale between 10 nm and 1.0 mm, and the macro scale is the stable larger than 1.0 m. In asphalt pavement engineering, asphalt binder's chemical constituents can be considered in the micro scale, the asphalt mixture components are in the meso scale, and the asphalt mixture is macro scale as the key component of an asphalt pavement.

In modeling of asphalt mixtures, many researchers built their microstructures of mixtures without considering its constituents less than nano scale (Dai et al., 2006; Kim and Buttlar, 2009; You and Buttlar, 2006). In their research, particles larger than 1.18 or 2.36 mm were used to build the micro scale models. Therefore, another definition of microscale is the length scale around 1.0 mm and the corresponding macro scale is the length scale larger than 10 cm as shown in Fig. 44(e).

4.2.1.2. A newly-proposed Asphalt Pavement Multi-scale System. As demonstrated in Fig. 44, various definitions and notational purposes have been developed. In addition to the literatures mentioned above, there are many other research efforts whose objectives are to develop or utilize multi-scale concepts of asphalt pavements (Amiri, 2004; Chen, 2015; Chen and Huang, 2012; Dai et al., 2020; Espinosa et al., 2021; Ji et al., 2020; Ling, 2016). Through comparing multi-scales from the existing literatures, an asphalt pavement multi-scale system is newly proposed herein. As shown in Fig. 45, an asphalt pavement system is divided into three length

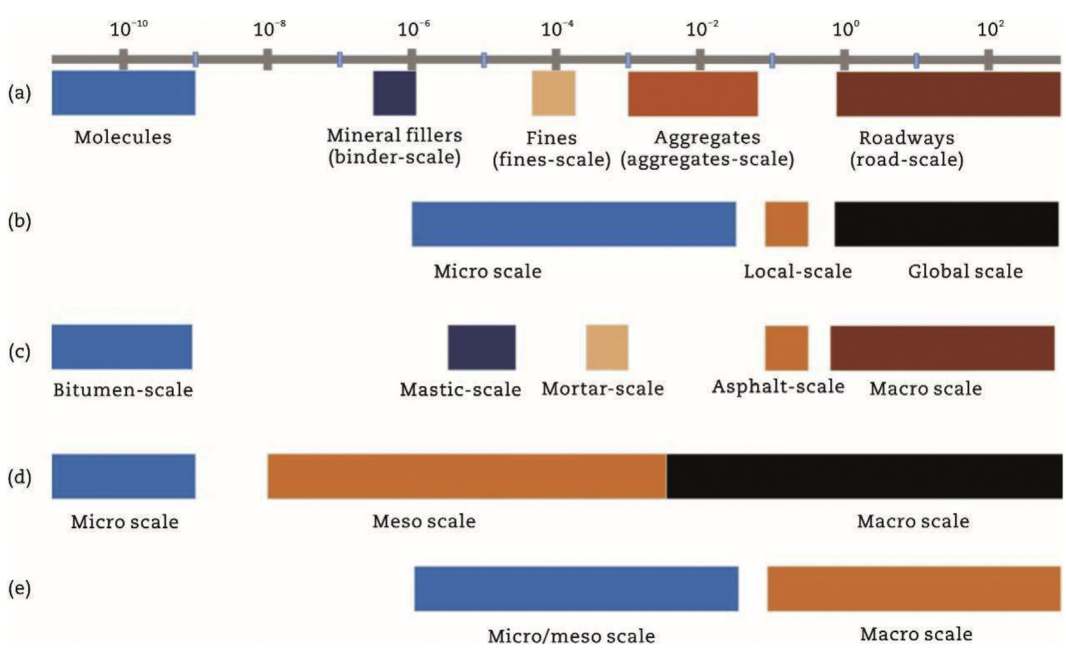


Fig. 44 – Multi-scales in asphalt pavement engineering. (a) Data from Allen et al. (2017a). (b) Data from Allen et al. (2017c) and You et al. (2018b). (c) Data from Arshadi (2015). (d) Data from Sun and Wang (2009) (e) Data from Dai et al. (2006), Kim and Buttlar (2009) and You and Buttlar (2006).

scales, namely structure-scale, mixture-scale, and molecular-scale in terms of compositions, or macro scale, meso scale, and micro scale in terms of physical lengths, or field-scale, lab-scale, and chemical-scale in terms of measurement methods.

(1) Structure-scale

A pavement is composed of various layers which play different roles and influence the overall performance in different manners. Fig. 46 shows the multi-scale moduli which include surface modulus, layer modulus, and element modulus. The surface modulus is a result of the combined effects of the layer moduli, while the element moduli may influence the layer moduli. For instance, the pavement modulus of surface course is the combined effect of the surface layer modulus, base/subbase layer modulus, and subgrade surface modulus, while each layer modulus is the combined effect of the corresponding element moduli which may be various at different locations.

Under this background, an asphalt pavement structure-scale can be further divided into three sub-scales, namely structure-scale, layer-scale, and element-scale as shown in Fig. 45. At the structure-scale, attentions should be paid on the overall pavement performance which is measured or evaluated with less considerations on the structural components. At the layer scale, the layer performance or layer effects should be considered in the pavement performance analysis, while at the element scale,

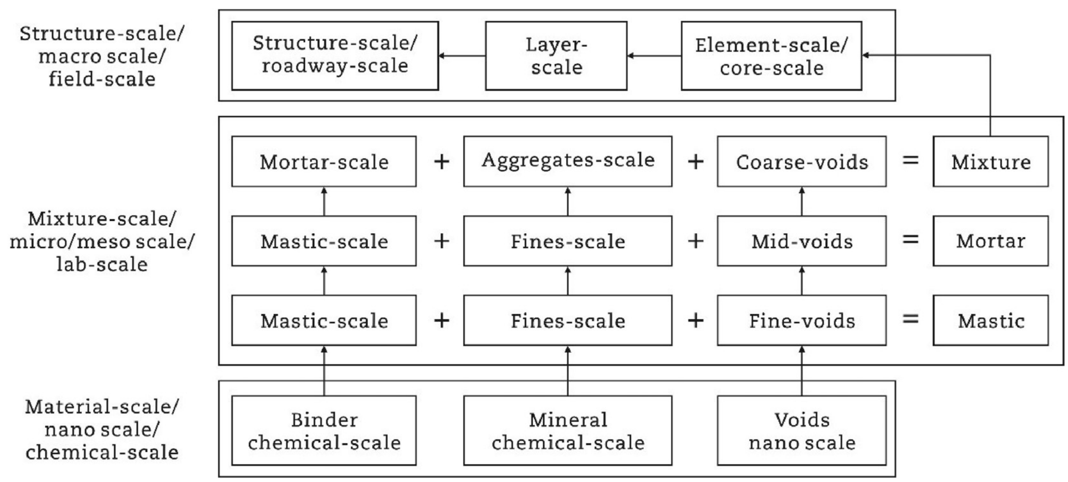


Fig. 45 – A newly-proposed asphalt pavement multi-scale system.

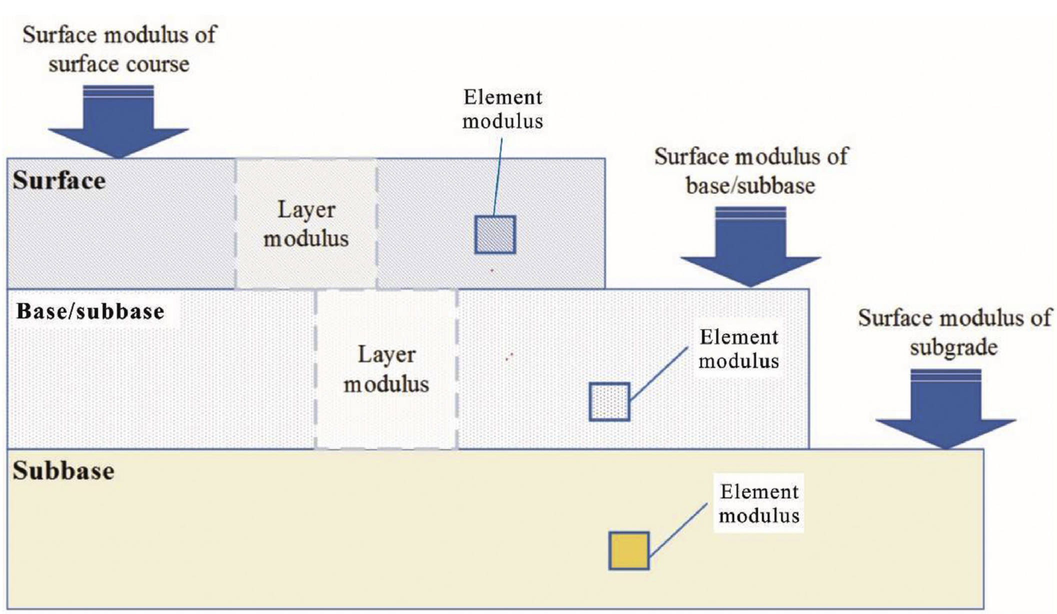


Fig. 46 – Sub-divisions of the structure-scale in the asphalt pavement multi-scale system.

performance variance of different elements should be evaluated and considered.

(2) Mixture-scale

Pavement is built with mixtures which may be asphalt-bound mixtures, hydraulically-bound mixtures, unbound mixtures, and Portland cement concrete. In the three scales above, mixtures are considered homogenous materials without considering their internal compositions. Obviously, compositions directly influence mixture performance. Therefore, the mixture-scale should be further divided into sub-scales. In this research, a mixture is a three phase composite, namely bounding phase, particle phase, and air void phase. The bounding phase has three scales, namely binder-scale, mastic-scale, and mortar-scale; the particle phase has three scales, namely filler-scale, fines-scale, and aggregates-scale; and the air void phase also has three scales, namely coarse-void, mid-void, and fine-void. The relations among the sub-scales are shown in Fig. 45.

(3) Material-scale

The last scale is the molecular scale, where chemical compositions should be considered for improving understanding of the source materials and air voids. This scale is critical to make innovative design of pavement materials.

4.2.1.3. *Research Ideas in the newly-proposed multi-scale system*. Thousands of literatures about multi-scale research or practices have been available in pavement engineering. Of course, it is impossible to discuss all those literatures. This section herein mainly introduces and analyzes some of the selected literatures for supporting the following viewpoints.

First of all, at the structure-scale, the pavement overall performance is usually measured by field testing, which includes falling weight deflectometer (FWD) (Abe et al., 1993; Hachiya and Sato, 1990; Rabbi and Mishra, 2021), Benkelman beam testing (Cox, 1976; Serrano, 2008; Ueshita et al., 1973), plate load testing (ASTM International, 2016; McCartney et al., 2013; Ping et al., 1995; Wayne et al., 2014), accelerated load testing (Anon, 1985; Chen et al., 2007b; Garg et al., 2019; Sharp, 1991), and so on. Therefore, the structure-scale is also called field-scale or macro-scale. The structure-scale has been successfully used in practice. For instance, in AASHTO pavement design guide (AASHTO, 1993), the structure-scale performance is indicated by structural number (SN), while SN is determined by the layer coefficients which are further related to mixture-scale properties. In Chinese design specifications (Ministry of Transport of the People's Republic of China, 2006, 2011, 2017), the pavement structural performance is predicted by inputting layer moduli and the layer material design is also specified.

Secondly, the mixture-scale is usually measured in the laboratory and the results are used as inputs for the structure-scale. This scale has not only been studied by researchers but also used in practices. Researchers developed micro-structural models to find correlations between asphalt mixtures' sub-scales (Buttlar and You, 2001; Chen and Wong, 2017; Dai and You, 2006; Huang et al., 2016c; Kim et al., 2008; Liu et al., 2009; Schuler et al., 2016), while plenty of design and construction specifications include mixture-scale testing methods (AASHTO, 1993; Ministry of Transport of the People's Republic of China, 2006, 2011a, 2011b).

Thirdly, at the material-scale, plenty of research works have been published for studying asphalt binder properties at the nano scale, while few research works have been conducted on mineral fillers' chemical properties and nano scale voids.

4.2.2. *Multi-scale modeling methods*

Due to the multi-scale nature of asphalt pavement system shown in Fig. 45, it's challenging to understand and predict the macroscopic performance of asphalt pavement. The structure-scale behaviors are always dominated by the material-scale properties. To characterize the multi-scale system, multiscale modeling methods are developed to predict the macroscopic performance using information or models from different scales. In general, the hierarchy of multi-scale modeling involves the following scales, namely: the nano scale, the micro/meso scale and the macro scale. On each specific length scale, particular methods are used for addressing the concerned phenomenon. This section is mainly focused on the latest advances in multiscale modeling methods at the nano scale and the micro/meso scale for asphalt pavement materials shown in Fig. 47.

Atomistic and molecular modeling is particularly important for materials science since it is an effective way to interpret the material properties and mechanical behaviors from fundamental molecular processes. Some important simulation approaches have been developed at the nano scale, due to recent advances in the high-performance computation which make it possible to perform complex physical phenomena modeling and simulation in materials. Among these approaches, the density functional theory (DFT) calculation and molecular dynamics (MD) simulation are two key methods and have been preliminarily applied to investigate chemical structure and property characterization of asphalt materials. At the micro/meso scale, micromechanical modeling plays an important role in the performance prediction of asphalt materials, which can characterize the overall (or effective) mechanical behaviors using the volume fractions and properties of individual constituents in the materials. The micromechanical models can be divided into two major categories: the composite micromechanics and numerical modeling methods (e.g., FEM, DEM, etc.).

4.2.2.1. *Density functional theory (DFT) calculations*. Density functional theory (DFT) is a quantum mechanical modeling method to compute the interactions between molecules using the functions of electron density of molecules. The DFT method from quantum mechanics has been employed to investigate the molecular models and intermolecular interactions of asphalt components at the atomistic scale. Combined with Clar sextet theory, Martín-Martínez et al. (2015) used DFT calculations to propose molecular asphaltene models. The chemical structures of the new models were more stable than the asphaltene molecules used in previous asphalt models. These isomers including a more representative arrangement of the π electrons were

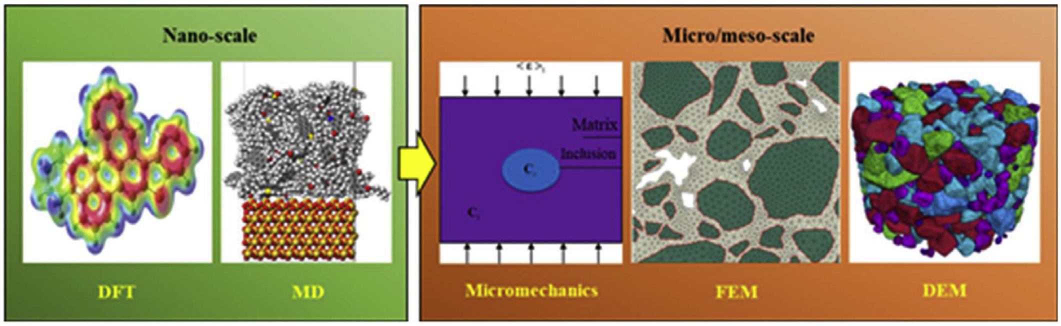


Fig. 47 — Multi-scale modeling methods for asphalt pavement materials.

critical for further description of the formation of nanoaggregates and the molecular interactions. Mousavi et al. (2016a) performed DFT calculations with B97-D/6-31G* basis set to evaluate the effect of the interactions between asphaltene and resin molecules on the colloidal stability of crude oil. They used binding energy to establish the correlation between the final stability of the asphaltene-resin system and the number of asphaltene sheets. It was found that the colloidal behavior of crude oil was better described by asphaltene-asphaltene associations. The molecular interactions between asphaltene and resin were preferred over asphaltene-asphaltene interactions only when the number of resin molecules per micelle was greater than that of asphaltene. Mousavi et al. (2016b) also investigated the intermolecular interactions between asphaltene and amide using DFT calculations. The results showed that two main factors, the orientation of the amide functional group and the part of the amide frame exposed to the aromatic zone of the asphaltene, had an important effect on the stability of the asphaltene-amide complex, which were supported by MD simulations and a series of experiments using X-ray powder diffraction and high-resolution transmission electron microscopy.

The DFT has also been applied to study the synergistic effects of intermolecular interactions between asphalt modifiers and the molecular packing in asphalt during rejuvenation. Mousavi et al. (2019) employed DFT calculations to investigate the synergistic and antagonistic interactions between polyphosphoric acid (PPA) and nanosilica. The DFT results indicated that the silica surface could set up an efficient interaction with PPA via noncovalent interactions, resulting in PPA asphalt interactions. Researchers also used DFT calculations to evaluate the synergistic effects of intermolecular interactions to synthesize hybrid rejuvenators for aged asphalt (Pahlavan et al., 2018, 2019, 2020). It was found that the bio-rejuvenation process involved: a) the bio-rejuvenators increased the intersheet spacing through the interactions with the polar chemical groups of the asphaltene nanoaggregates in aged asphalt, and b) the bio-rejuvenators intercalated into the intersheet spacing within the asphaltene stacks to reduce the size of oxidized asphaltene nanoaggregates, leading to restoration of the thermo-mechanical properties of aged asphalt.

These preliminary studies above show that the DFT calculations can provide a good understanding of the molecular structure and intermolecular interactions of different components in unmodified and/or modified asphalt. Two key conclusions can be drawn from the DFT studies: (1) the properties based on the electronic structure and visualizations of quantum chemistry results support the molecular models of asphalt materials; and (2) the intermolecular interactions that are consistent with force field calculations support the appropriate use of force fields in molecular simulations of asphalt materials.

4.2.2.2. Molecular dynamics (MD) simulations. Molecular dynamics (MD) based on classical Newtonian and statistical mechanics is a technique to analyze the fundamental properties of the materials through elucidating the molecular mechanisms which control deformation and failure of interactions at the molecular scale. The MD method has been widely used for the molecular modeling and simulations of asphalt materials, which is well summarized and presented in Section 2.2.2. This section is mainly focused on the applications of MD simulations in multiscale modeling and characterization of pavement materials.

Shen et al. (2016) applied MD simulations with a reactive force field to characterize the influence of crack with on healing property of asphalt. The healing in asphalt was found to be triggered by the molecular diffusion. Higher temperature would lead to higher molecule diffusivity and thus higher healing rate. Researchers from Aston University employed MD simulations to investigate the molecular mechanisms of the interfacial adhesion between asphalt and aggregate in asphalt materials with the effects of aggregate mineralogical composition, water and asphalt oxidative aging (Gao, 2020b; Gao et al., 2018a, 2019), as shown in Fig. 48. The simulation results indicated that the alkali minerals (e.g., calcite, albite and microcline) had a stronger adhesion with asphalt than the acidic minerals (e.g., quartz) due to the larger electrostatic interaction. To evaluate the synergistic and antagonistic interactions between asphalt modifiers, Mousavi et al. (2019) used MD simulations to study the interaction of PPA and silica. The simulation results showed blocking the active sites of PPA by wax prevented PPA from effective interaction with asphalt

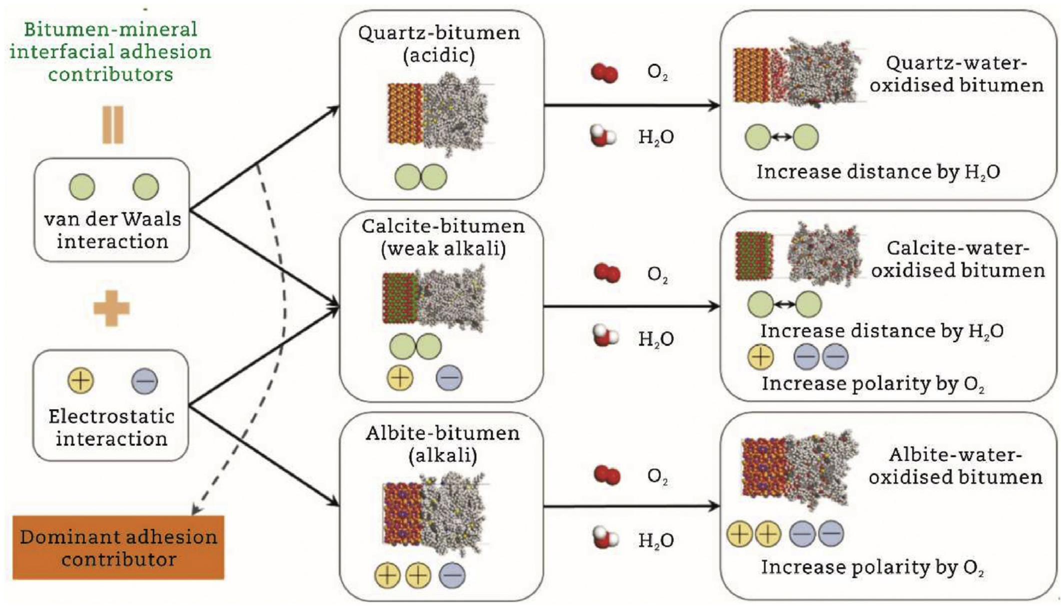


Fig. 48 – MD simulation for asphalt-mineral interfacial interaction in asphalt materials (Gao et al., 2019).

components. Ren et al. (2021b) employed MD simulations to explore the effects of lignin on the thermodynamics characteristics of asphalt. It was found that the lignin increased the cohesive energy density and adhesion of asphalt but weakened the diffusion and self-healing properties of asphalt. Hou et al. (2017) used MD simulations to investigate the mechanical behaviors of ettringite, a hydration product of cement paste, at the molecular level. By coupling the MD simulations and phase-field theory (PFT) model at the crack tip, a two-way multiscale modeling approach was developed to simulate Mode I cracking in the ettringite.

These studies above indicate that MD simulations can be used to predict the thermodynamics properties and molecular behaviors of asphalt materials. To improve the accuracy of MD simulation and extend its application, more efforts are needed to develop a reliable molecular model of aggregates and an appropriate force field for pavement materials.

4.2.2.3. *Composite micromechanics methods*. A number of researchers have used the composite micromechanics methods to predict the mechanical properties of asphalt mixtures. Based on the equivalent medium theorem reported by Eshelby (1957), asphalt mixtures were considered as particulate-filled composite materials. Lytton (1990) proposed a three-phase (asphalt, aggregates, and air voids) model to predict the modulus of asphalt mixtures. Shu and Huang (2008a, b) developed a viscoelastic micromechanical model to evaluate the dynamic modulus of hot-mix asphalt mixtures. Both aggregate gradation and air void size distribution were considered in the proposed model. Luo and Lytton (2011) and Alam and Hammoum (2015) used micromechanical self-consistent model to study the viscoelastic properties of asphalt mixtures, e.g., the relationship between individual material properties, and the complex modulus and phase angle of asphalt mixtures. Wang et al. (2020h) predicted the complex shear modulus of crumb rubber modified asphalt using four micromechanical models, i.e., the dilute model, the Mori-Tanaka model, the self-consistent model, and the generalized self-consistent model.

To account for the interface between asphalt and aggregates, researchers have incorporated interfacial bonding into the micromechanical model. Zhu et al. (2014b) employed a Kelvin-Voigt type viscoelastic interface in the proposed micromechanical creep models to simulate the asphalt-aggregate imperfect interface in asphalt mixtures. Gao et al. (2015) and Dong et al. (2016) introduced a linear spring layer model into a modified Mori-Tanaka method to develop new micromechanical models. The developed model had the capability of taking into account to the interface effect on the creep characteristics and dynamic modulus of asphalt concrete. Fan et al. (2020a) incorporated a bilinear cohesive zone model (CZM) into the Mori-Tanaka model to predict the constitutive behavior of asphalt mixtures. It was found that the interfacial debonding between asphalt and aggregate exhibited a significant dependency on aggregate size. Wang et al. (2021h) improved the modulus prediction accuracy for crumb rubber modified asphalt using the micromechanical models modified by considering the interparticle interactions. Table 24 shows a summary of micromechanical models that are commonly used for asphalt materials. A comprehensive review of micromechanical models has been reported by Zhang et al. (2020a).

4.2.2.4. *Finite element method (FEM) simulations*. Numerical micromechanical models including finite element method (FEM) and discrete element method (DEM) have also been widely applied to characterize the mechanical behaviors of

Table 24 – A summary of micromechanical models commonly used for asphalt materials

Model	Reference
Eshelby-based model	Wang et al., 2020a
Self-consistent model	Alam and Hammoum, 2015; Luo and Lytton, 2011; Wang et al., 2020h
Generalized self-consistent model	Pichler et al., 2012; Shu and Huang, 2008a; Wang et al., 2020h
Mori-Tanaka model	Dong et al., 2016; Fan et al., 2020c; Gao et al., 2015; Wang et al., 2020h

asphalt mixtures. Combined with digital image processing and X-ray computerized tomography (CT) used to obtain the internal structure of asphalt mixtures, the numerical simulations are performed using the FEM or DEM on the basis of reconstruction digital specimen.

The FEM allows to accurately predict the overall properties of asphalt mixtures by incorporating the constitutive behaviors and microstructure geometries of aggregate and mastic. The constitutive behavior of asphalt mixtures was simulated using the FEM method (Dai, 2010; Dai and You, 2008). The three-dimensional (3D) FEM was developed to predict the global material properties of asphalt mixtures including dynamic modulus and phase angle (Dai, 2011b; Tehrani et al., 2013).

The FEM was also used to characterize the microstructure (Salemi and Wang, 2018) and the thermal properties (Mirzanamadi et al., 2018) of asphalt mixtures. Castillo et al. (2015) presented a FE model to investigate the role of certain microstructural properties on the mechanical performance of asphalt mixtures. Du et al. (2021a) used a locally homogeneous FE model to account for the internal structures of asphalt mixtures. Chen et al. (2015b) generated the 3D microstructure of asphalt concrete with three phases and simulated the steady heat transfer to predict the thermal conductivity of asphalt concrete. Chu et al. (2020) introduced a regular row-column FE model to compute the thermal conductivity of asphalt mixture. Hajikarimi et al. (2021) developed a biphasic heterogeneous viscoelastic FE model of the BBR test for bituminous composites containing taconite or crumb rubber to predict the effect of modifiers as the compositional factors on the thermal cracking.

Recently, the fracture performance of asphalt mixtures (Kollmann et al., 2019; Wang et al., 2018f; Yin et al., 2011, 2013) was also investigated using the FEM.

4.2.2.5. *Discrete element method (DEM) simulations*. The DEM uses Newton's second law with appropriate inter-particle contact forces to analyze particulate systems by modeling the translational and rotational behaviors of each particle. Researches were conducted to predict the viscoelastic behaviors of asphalt mixtures using the DEM (Liu and You, 2011; Liu et al., 2009). The 3D DE model was generated from the X-ray CT and has been employed to characterize the creep compliance and complex modulus of asphalt mixtures (You et al., 2011a; Yu and Shen, 2013; Zhang et al., 2019a, b).

DE models of asphalt mixture were also established using the PFC2D software to predict the stress-strain characteristics of the coarse aggregate (Ding et al., 2017a; Ma et al., 2016a, 2018c). The particle shape (Liu et al., 2017d; Zhou et al., 2018, 2019b, 2019c) and grain size (Garcia-Hernandez et al., 2021; Liu et al., 2019d) of aggregates in asphalt mixtures have been characterized using the DEM method. Barrasso et al. (2015) introduced a mechanistic model for a wet granulation process, combining the techniques of population balance modeling and DEM to predict the porosity and size distribution of the granule.

Researchers also developed user-defined algorithms for generating air-void structures in an idealized asphalt mixture and evaluated the influence of air-void structures on modulus prediction and rutting test of asphalt mixtures (Zhang et al., 2018h, i). The rutting deformation of the asphalt mixture was also simulated using the 3D DE model (Ding et al., 2019b; Gong et al., 2018b, c; Ma et al., 2016a, b). The DEM was recently employed to investigate the force chains of cement emulsified asphalt mixture (Wang et al., 2021c), the mechanical behavior of uncompacted asphalt mixture (Chen et al., 2019c) and the asphalt-screed interaction during pavement pre-compaction (Wang et al., 2021e).

In conclusion, these micromechanical methods (i.e., micromechanics, FEM and DEM) mentioned above provide an effective tool to predict the mechanical properties of asphalt materials at the micro/meso scale. However, some key parameters in the micromechanical models are generally assumed and/or estimated according to the macroscopic laboratory tests, which does not consider the size effect of materials. Therefore, more fundamental studies are needed to explore how to accurately determine and validate the micromechanical model parameters from the microscopic scale.

4.2.3. *Cross-scale modeling methods*

In the past ten years, researchers have done a lot of research and discussion in multi-scale numerical simulations for asphalt mixture and pavement, as introduced in Section 4.2.2, which mainly focus on how to utilize appropriate modeling methods at each scale, such as DFT, MD, composite micromechanics, DEM, FEM, etc., to up-scale and thus reflect the higher-level mechanical behavior. In theory, all higher-level problems can be simulated and solved through a single method on a low-level scale, even across several scales. For example, there is no problem that using the asphalt and aggregate models established by MD (material-scale) to construct the asphalt mixture (mixture-scale), and further to build the pavement structure (structure-scale).

However, this may be a fantasy, because this single-mode modeling method is difficult to achieve in practice, and its calculation scale will greatly exceed our imagination. For example, a simple pavement structure containing 2 billion particles (approximately 2 m $\times$ 2 m $\times$ 1 m in size), if it is simulated by DEM on an ordinary personal computer, it will take about eighty years. Therefore, it is necessary to find other ways to solve large-scale numerical calculation problems. One way is cross-scale calculation, and the other is parallel calculation. This section mainly discusses the former.

For clarity of presentation, multi-scale calculation methods will be divided into two categories here, simple multi-scale methods and cross-scale methods (Fig. 49). It is defined that only one method is used to form a macroscopic representation from the micro-structure as a simple multi-scale method. The content reviewed in the previous Section 4.2.2 basically falls into this category. Obviously, the model established by this method is generally small, and most of them do not exceed the size of the specimen. A cross-scale method is defined as that using an appropriate method to mesh one scale, and the meshes established on different scales are connected through a coupling mechanism to achieve the upscaling and downscaling operations between different meshes. The same or different modeling method can be used on different scales.

Considering there are still many limitations and deficiencies in the cross-scale theory, the application of new methods, and the efficiency of the solution, this section will also introduce the current research status of methods that are applied in other fields and are expected to be applied in the analysis of pavement material mechanics.

4.2.3.1. *Mechanism of cross-scale calculation*. The cross-scale method is a coupling technology to analyze the characteristics of materials at different scale levels. It is essentially a combination of micro-material properties and macro-mechanical behavior through a certain mathematical algorithm, with strong multi-disciplinary features. Asphalt concrete materials have inherently complex components, complex material interface connections and strong particle-particle contact. It is suitable to use the multi-scale/cross-scale method to study the large deformation, damage, cracking and phase change behavior of asphalt concrete.

Cross-scale methods can be divided into multiple categories according to their mechanical mechanism. Geers et al. (2010) defines the multiscale (also cross-scale) scheme as a computational homogenization method, and divides it into the first-order computational homogenization method and the second-order computational homogenization method. In fact, the first-order and second-order multi-scale methods are derived from the asymptotic expansion principle of the mechanical analysis of inhomogeneous materials, which can be explained in detail from the mechanics of composite materials.

The first-order method was first addressed by Renard and Marmonier (1987). And a number of contributions make major developments for this method (Guedes and Kikuchi, 1990; Miehe and Bayreuther, 2007; Smit et al., 1998; Terada and Kikuchi, 2001). To improve accuracy of a first-order method, a full second-order extension has been developed by following scholars (Geers et al., 2003, 2009; Kaczmarczyk et al., 2007). For the first-order cross-scale method, a representative volume element (RVE) is imagined to replace a solution point and the RVE behavior offers the constitution relationship for the material of the solution domain. The behavior of this RVE only reflects the force under microscopic deformation. When this RVE includes both microscopic variables and macroscopic variables, that is, it can reflect both lower-scale behavior and higher-scale behavior, then it becomes a high-order cross-scale method. An overview of the multi-scale methods used in composite materials is provided by Kanouté et al. (2009).

Here some cross-scale methods that can be applied to asphalt pavement, such as multi-scale FEM, FEM-DEM coupling method and numerical manifold method will be reviewed.

4.2.3.2. *Multi-scale FEM method*. The idea of multi-scale finite elemem method (MsFEM) can be traced back to the work of Babuska and Osborn (1983) and Babuska et al. (1994). Hou and Wu (1997) and Hou et al. (1999) successfully extended this idea and applied it to the simulation of flow field with continuously changing parameters. In this method, the domain is meshed by two sets of grids-coarse grids and fine grids. Fine grids are used to mesh micro scale material but the coarse grids to the macro structure. The core idea of this method is to construct the basis functions of coarse grid through numerical methods, and use these basis functions to bring the micro-heterogeneity information on the fine grids to the coarse grids, so that the original problem only needs to be solved on the coarse grid and calculation time is significantly reduced.

Zhang et al. (2009a) proposed a multi-scale finite element method for coupling in a vector field and later, Zhang et al. (2010b) proposed an extended multi-scale finite element method by considering the Poisson effect of heterogeneous materials in different directions in order to improve the

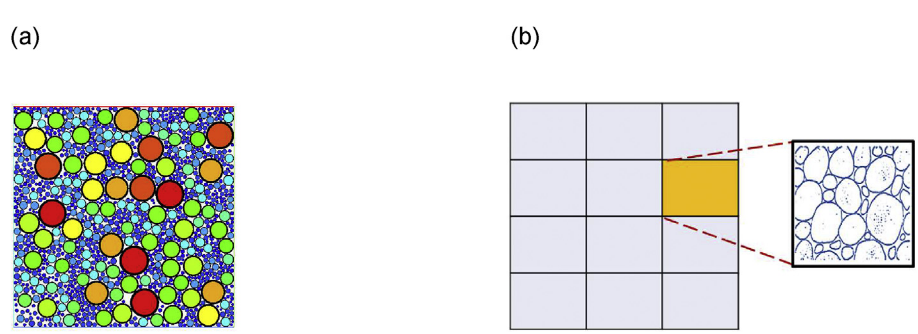


Fig. 49 – Two categories of different concepts. (a) Simple multi-scale modeling method. (b) Cross-scale modeling method.

ability of numerical basis functions to capture the heterogeneous information inside the coarse grid. Conceptually, this method changes the boundary conditions for constructing multi-scale basis functions, and introduces an additional coupling term in it to improve the accuracy of the entire algorithm. This method has wide applicability. Based on the extended multi-scale finite element method, researchers extended the method to dynamic analysis (Zhang et al., 2013), elastic-plastic analysis of heterogeneous materials (Zhang et al., 2015a), adaptive analysis of periodic truss materials (Liu and Lv, 2017; Liu and Zhang, 2013) and so on.

In view of the actual situation of asphalt concrete, we suggest the following two multi-scale finite element schemes (Fig. 50) can be used. One is based on regular grids, which need homogenize the material parameters for each fine grid. The other one is to use non-uniform grids according to the material interface. When attention needs to be paid to the treatment of the transition zone of the material interface. In addition, it is also a big challenge to develop a viscoelastic-based multi-scale finite element method.

4.2.3.3. *FEM-DEM coupling method*. Although finite element method (FEM) is one of the most successful numerical methods in mechanics, for asphalt concrete and other complex granular materials, the lack of suitable constitutive relations makes the application of FEM facing great difficulties. Similarly, the great success of the discrete element method (DEM) in understanding the complex behaviors of granular material at the micro-level causes it facing huge computational time-consuming when simulating large-scale pavement structures. How to make use of the advantages of FEM and DEM while voiding their defects or shortcomings is the main motivation to realize FEM-DEM coupling calculation, which is an inevitable choice to develop the pavement numerical methods.

FEM and DEM coupling calculation methods generally include three types (Fig. 51). This section only considers the third type, namely DEM-in-FEM multi-scale method.

Terada and Kikuchi (2001) have originally proposed the consistent two-scale modeling for nonlinear problems by using the generalized convergence theorems in the nonlinear homogenization theory and developed the two-scale or global-local analysis method. From then on, the multi-scale idea based on the FEM-DEM coupling algorithm was used to analyze the deformation and failure mechanisms of biaxial test (Kaneko et al., 2003; Meier et al., 2009; Nguyen et al., 2013; Nitka and Tejchman, 2011). This method is classified into first-order computational homogenization as definition of Geers et al. (2010).

Guo and Zhao (2014, 2016a, 2016b) simulated the influence of material mechanical properties on a macro scale by adjusting the arrangement of DEM elements on the meso scale, and also simulated the deformation of three-dimensional specimen.

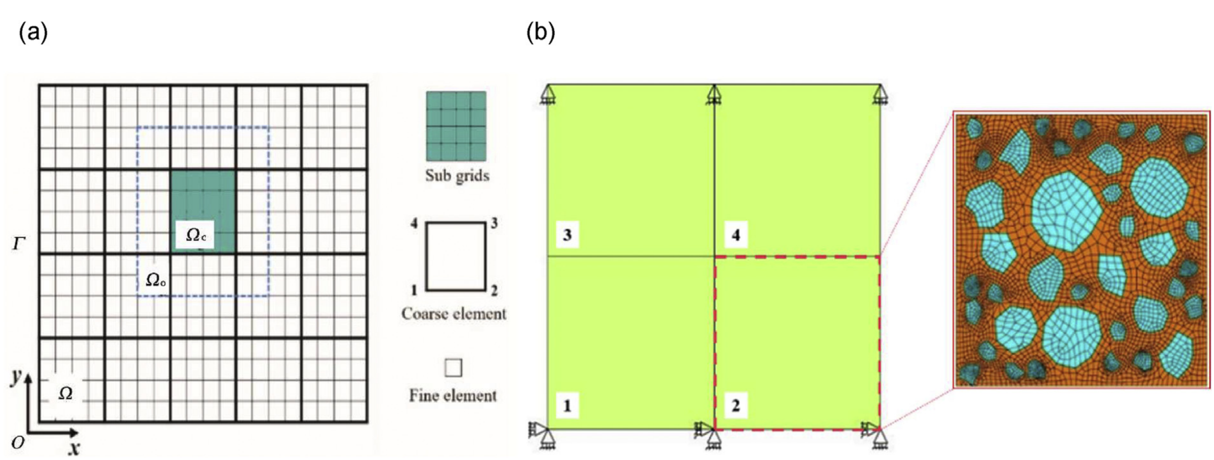


Fig. 50 – Different multi-scale FEM model. (a) Multis-cale FEM (mode I). (b) Multi-scale FEM (mode II).

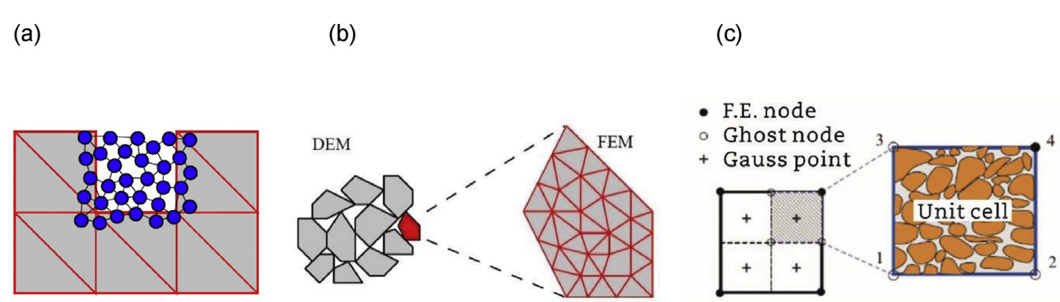


Fig. 51 – FEM-DEM coupling types. (a) Concurrent multi-scale method. (b) FEM-DEM multi-scale method. (c) DEM-in-FEM multi-scale method.

Zhou et al. (2021b) introduced the algorithm of the coupled multiscale framework based on FEM-DEM and a coupling simulator (CoSim) with GPU acceleration is developed for the acceleration of the coupling process.

However, this coupling scheme still needs great improvement in terms of solving efficiency, because these solutions are usually solved separately in FEM software and DEM software, and then call each other's data to realize the coupled calculation. There is still a long way to go to the real coupling solution under one system, and it is hoped that further research can make important progress in this area.

4.2.3.4. NMM family methods. Numerical manifold method (NMM) is a new numerical method initially established by Shi (1991) using the finite coverage technique of manifold analysis in mathematical science. In essence, NMM is a highly unified numerical method, which core idea is to use two finite coverage systems to integrate continuous and discontinuous deformation. NMM can easily deal with the large deformation (Fig. 52), crack development, dynamic response, and coupling calculation of multi-phase materials including stone, cement, pore water and air. In theory, it is a master of other methods since it can derive other methods (FEM, DEM/DDA, Meshless methods, etc.) (Fig. 53) through degradation. In this view, NMM is also a good framework for multi-field coupling calculation when several different methods are co-used for one problem. Lin (1997) and Lu (2002) also made many contribution to the NMM. Zhou et al. (2009a, b) developed the application of this method in the discontinuous numerical calculation of asphalt mixtures. Some Kernel principles such as linkage of asphalt mastic and searching mechanism for support nodes are discussed in their papers.

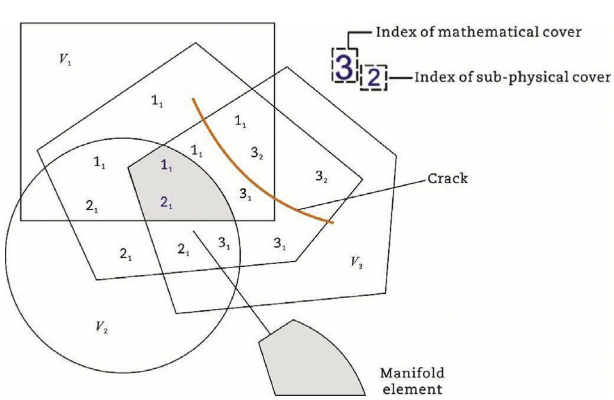


Fig. 52 – Manifold covering system (Zhou, 2009).

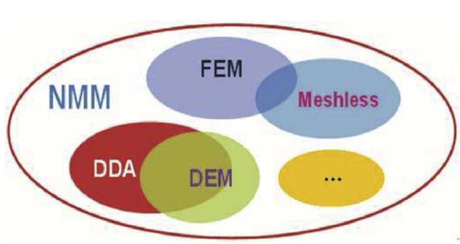


Fig. 53 – The logical relationship between NMM and other methods.

Jia et al. (2007) applied the element free Galerkin method (EFGM) to the mechanical analysis for asphalt pavement structure. The results of EFGM were compared with that of FEM. Luo et al. (2010) used the coupling element free Galerkin and finite element method to simulate top-down crack propagation in asphalt pavement based on the fracture mechanics. Li et al. (2012d) studied the depth of rutting of asphalt concrete pavement using the element free Galerkin method and the influences of different types of structure, load, module and thickness of the middle course on anti-rutting performance of the pavement are analyzed.

Up to now, most of the methods of the NMM family have not been well developed and applied to the numerical simulation of asphalt mixtures. In the development of highly coupled methods, such as FEM-DEM, DEM-MD, or meshless-DEM, NMM should be the simplest way to reflect the coupling effect.

4.2.4. *Summary and outlook*

This review is focused on concepts and research approaches of asphalt pavement multi-scales. The first part of this section is about asphalt pavement multi-scale. Based on the existing literatures and asphalt pavement engineering principles, an asphalt pavement multi-scale system was newly proposed, where asphalt pavement is divided into structure-scale, mixture-scale, and material-scale. Those three major scales are further divided into sub-scales as demonstrated in Fig. 45. At the structure-scale, the pavement overall performance is usually measured by field testing and the outputs are usually considered as the macroscopic properties. Therefore, the structure-scale is also called macro scale or field-scale. The mixture-scale is usually measured in the laboratory and lengths of its sub-scales (binder-scale, mastic-scale, mortar-scale, fillers, fines, aggregates, and voids) are usually considered in the meso scale range. The mixture-scale is also called meso scale or lab-scale. This scale has not only been studied by researchers but also used in practices. At the material-scale, plenty of research works have been published for studying asphalt binder properties at the nano scale, while few research works have been conducted on mineral fillers' chemical properties and nano scale voids.

In the second part of this review, the latest advances in multi-scale modeling methods for asphalt pavement materials were reviewed, including the DFT, MD, micromechanics, FEM and DEM. The multiscale modeling methods provide the fundamental understanding of material properties or structural behaviors of asphalt pavement materials at each individual scale (nano scale or micro/meso scale). It is still extremely challenging to achieve the cross-scale performance characterization of a large asphalt pavement system using the simple multi-scale modeling methods due to the limitation of computation time. Future work must ultimately address the following problems: (1) size effect mechanism; (2) cross-scale constitutive modeling; and (3) structure-property relations across multiple scales. With the further development of high-performance computation, it is believed that the updated multi-scale modeling methods will significantly improve the accuracy and reliability of the multi-scale modeling and performance prediction of asphalt pavement materials.

The cross-scale methods and applications to calculate the performance of asphalt pavement materials was mainly reviewed in the third part of this review. The multi-scale methods can be divided into two categories according to the modeling mode from micro-level and macro-level. They are the simple multi-scale methods and the cross-scale methods. The simple multi-scale methods basically describe the entire macroscopic specimen by stacking a large number of FEM elements or DEM particles. Affected by the performance of the computer, the size of the research object is generally not large. How to reduce the number of particles is currently an important bottleneck of this type. The cross-scale methods adopted FEM or NMM methods at the macro level, and uses DEM/DDA or Meshless to describe the microstructure. The coupled solution is realized by transferring information between the two levels. The low transfer efficiency between scales is a big problem at present. There is still a long way to go for the real cross-scale simulation. As a promising method, NMM have not been well developed and applied to the numerical simulation of asphalt mixtures. It may play an important role in developing new cross-scale methods.

It is hoped that further research can make important progress in multi-scale simulation, not only to develop more effective multi-scale computing methods, or to modify the efficiency of the cross-scale algorithm, but also in how to accelerate the computing speed of multi-scale methods, such as to use multi-GPU and multi-threaded parallel computing or to adopt large-scale computers faced by current researchers of this field.

4.3. *Pavement mechanics and analysis*

The efficient characterization of pavement mechanics analysis and its parameter inversion that develops in pavements is important to pavement performance. Although pavement mechanics and analysis have gradually evolved from an art to science, empiricism still plays a critical role even up to the present date. As the experience of pavement design and analysis was gained throughout the decades, various approaches were developed by different agencies and scholars for evaluating the pavement mechanics and its parameter inversion. Some of the key technical items will be summary in this section of the literature review.

4.3.1. *Constructive methods to pavement response analysis*

The general objective of this part is to provide the engineers and researchers with fundamental mechanical models and efficient to comprehensively summary the mechanical behaviors of asphalt pavement. Commonly, the asphalt mixture exhibits significantly complicated behaviors when it is under a compressive load. The asphalt pavement damage such as permanent deformation and cracking could be avoided, and the asphalt mixtures can be considered to be an anisotropic viscoelastic solid when the compressive load is sufficiently tiny (Levenberg and Uzan, 2004). However, with the compressive load increases, in asphalt pavement, the stress and strain have a nonlinear relationship that may be caused by stress-induced damage and material relaxation-the stress-induced damage major consists of viscoplastic deformation and viscofracture cracking, such as a time-dependent fracture. Meanwhile, the pavement engineers have been greatly interested in layered under vehicle loading conditions mainly because asphalt pavements are composed of horizontal layers of road materials. Conventionally, although asphalt mixtures are generally considered typical viscoelastic materials, the asphalt pavement is regarded as a layered structure for response analysis. It would be more reasonable to combine material properties and pavement structure in asphalt pavement structural design and response analysis.

4.3.1.1. *Viscoelastic constructive models*. Asphalt mixtures are typical time and temperature-dependent materials; the viscoelastic properties are customarily characterized with creep compliance, relaxation modulus, dynamic modulus, and phase angle based on the viscoelastic theory. These properties provide a basis for quantifying how far the plasticity and fracture depart from the undamaged elastic state. To describe the viscoelastic response of asphalt pavement (asphalt mixtures), the researchers generally adopt integral and differential (derivative) constitutive relations. A single integral constitutive model is often used to analyze its integral constitutive model, including the Boltzmann superposition principle to express the linear viscoelastic behavior of asphalt mixtures, and the time reduction model modified Boltzmann superposition principle to represent the nonlinear viscoelastic behavior of asphalt mixtures. In the research of derivative constitutive models, classical constitutive relations such as the Kelvin model, Maxwell model, and Burgers model generally use the series or parallel combination of Newtonian viscous pots and springs (Jazouli et al., 2006; Montonna, 1947). Depart from the viscoelastic properties of asphalt mixtures when the load is sufficiently small, with the load increases, the asphalt mixtures represent significant viscoplastic deformation and viscofracture cracking. Zheng et al. (2008) coupled the Burgers model and the continuous damage factor model to construct a viscoelastic damage model for asphalt mixtures. Ye et al. (2009) proposed a mechanical model that connected elastoplastic, viscoelastic, and viscoplastic elements in series, which could better describe the nonlinear creep deformation of asphalt mixture. For the nonlinear characteristics of asphalt mixtures, based on continuous damage mechanics, Zeng et al. (2013) modified the traditional Burgers model and proposed a viscous, elastic, plastic, and creep constitutive damage model, which could better reflect the nonlinear characteristics of accelerated creep of asphalt mixtures. The classical derivative constitutive model theory is intuitive and easy to understand, of which the physical concept is straightforward.

However, the order of these types of classical model is an integer, and the differential operator is local, which cannot accurately describe the mechanical behavior of materials under complex loading conditions such as the wide frequency range. The fractional derivative model, retaining the advantages of the classic model, has developed rapidly and is widely used in the response analysis of viscoelastic materials. The included fractional differential operator and it could describe the mechanical properties of viscoelastic materials such as asphalt mixtures in a wide frequency range. There are some researchers who did some useful trying, for example, Baglieri et al. (2017) analyzed the creep and creep recovery shear test data of asphalt and used the fractional Maxwell model to express the rheological properties of asphalt; by composing the improved fractional Kelvin model and fractional Maxwell model, Lagos-Varas et al. (2019) reported a fractional viscoelastic model in accurately describing the viscoelastic properties of asphalt mixtures; Celauro et al. (2012) used the fractional Burgers model to represent the viscoelastic behaviors of asphalt mixture by analyzing the test data of creep and creep recovery performance. They concluded that the fractional derivative model shows significant advantages over the classical viscoelastic model.

In addition, the Sigmoid function is an empirical model that extends dynamic viscoelastic parameters to a broader frequency domain and temperature domain. The model builds master curves such as dynamic modulus based on the principle of time-temperature equivalence, while this model has certain limitations. In order to overcome these deficiencies, the recent studies reported a generalized Sigmoid function to describe the asymmetric dynamic viscoelastic behavior of asphalt mixtures (Chen et al., 2017b; Forough et al., 2015). Li et al. (2016c) and Luo et al. (2020a) adopted a fractional-order viscoelastic model combined with dynamics test parameters to characterize the performance of the asphalt mixture considering the influence of load frequency and temperature. Huang et al. (2020a) further considered the impact of the loading method, and their research results showed that the dynamic modulus obtained by the bending force loading method of the asphalt mixture was the smallest while the phase angle was the largest. Based on the analysis of the fractional derivative three-element model and the finite element method, Yin and Chen (2012) successfully derived a viscoelastic structure power unit format with fractional derivative three-element constitutive relations. Moreover, the dynamic viscoelastic response analysis of asphalt pavements was carried out with the two-dimensional finite element calculation method, which confirmed the effect of this method in the dynamic viscoelastic analysis of asphalt pavements. It shall be noted that the order of the fractional derivative in the viscoelastic constitutive relationship in the above study is constant, which means that the mechanical behavior of the asphalt mixture in the creep process with time is not considered, and there is a certain difference from the actual situation. In recent decades, in describing the viscoelastic properties of asphalt mixtures, the research on variable-order integrals and variable-order derivatives derived from the (constant-order) fractional differential theory has been widely used by researchers in the modeling of viscoelastic materials and viscous fluids. Attention has become a hot spot in the field of fractional calculus. Therefore, in the study of viscoelastic properties of asphalt mixtures, to accurately describe the complete three-stage creep deformation of asphalt mixtures, it would be interesting to use variable-order fractional derivative theory to characteristics the viscoelastic properties of asphalt mixtures.

4.3.1.2. Anisotropy and its characterization. Based on the viscoelastic constructive models, Elseifi et al. (2006) used the generalized Kelvin model combined with the finite element method (FEM) to calculate and analyze the stress and strain of the asphalt pavement under vehicle load conditions. They compared the results with the experimental test data and concluded that it was essential for asphalt pavement design and analysis considered the viscoelastic properties of the asphalt mixture. Kim et al. (2009) also employed the generalized Kelvin model viscoelastic constitutive relationship to study the top-down cracking behavior and cumulative strain of asphalt pavement structures. The related research was the study of the viscoelastic properties of asphalt pavement considering the isotropy of asphalt mixtures, which reflected the mechanical behavior of asphalt pavement structure and revealed the failure mechanism. The importance of considering the viscoelasticity of asphalt mixture in asphalt pavement response were both analyzed and confirmed (Ahmed and Erlingsson, 2016; Dong and Lyu, 2011; Dong et al., 2013; Huang et al., 2006; Khavassefat et al., 2015; Li et al., 2016b; Zhao et al., 2012, 2014). Although the fractional-order viscoelastic constitutive relationship can more truly reflect the static and dynamic response of asphalt pavement, these models and methods are based on the isotropy assumption of asphalt mixture. However, in asphalt pavement response analysis and especially stress analysis, the asphalt mixture performs in anisotropic viscoelastic and the inherent anisotropy that is caused by the preferential orientation of aggregates. Aside from the nondestructive properties of asphalt mixtures, due to the different crack areas projected in different directions, the anisotropic viscoplasticity and the anisotropic viscofracture are the destructive properties of asphalt mixtures (Zhang, 2012). Therefore, during the asphalt pavement response analysis, the anisotropic properties should be considered with the viscoelastic, viscoplastic, and viscofracture properties of asphalt mixtures.

The asphalt mixtures is a bonded granular material whose internal structure is anisotropic, due to the particle orentation distribution and shape, pore structure, and anisotropic compaction in asphalt mixture (Wang et al., 2005; Yan et al., 2016). The anisotropic internal structure leads the asphalt mixtures to express significant spatial variability of parameters or random anisotropy characteristics. It would be worthwhile for the degree of anisotropy and its influence on asphalt pavement response to be investigated due the approaches for characterization and analysis of isotropic and anisotropic are quite different. Typically, during the response analysis of asphalt pavement, the anisotropic properties of asphalt mixtures can be simplified to be as transversely isotopic or cross-anisotropic, as illustrated in Fig. 54. For the mentioned simplified cases, asphalt mixture is considered to have a significant difference only in the vertical and horizontal directions because of anisotropic compaction, particle orientation, restraint conditions, and gravity direction.

Although the asphalt mixture has been recognized as an anisotropic material in asphalt pavement, the degree of anisotropy and its implications for asphalt pavement design and analysis have not been understood clearly. In recent decades, the degree of anisotropy of asphalt mixtures has been characterized by the researchers and they have some useful findings, Table 25 summarized the related works, and it

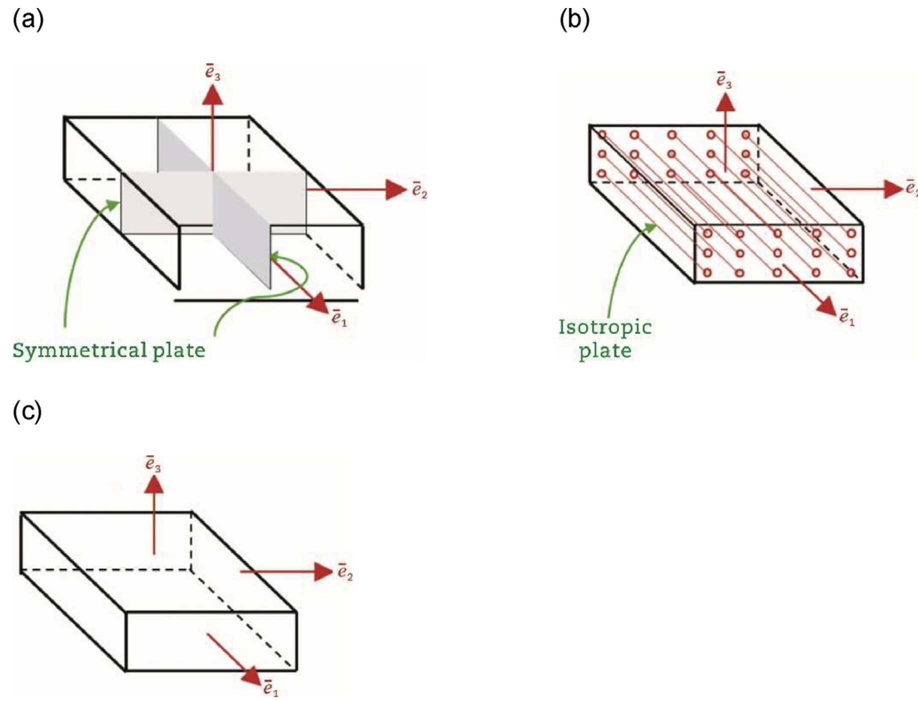


Fig. 54 – Possible existence of various planes of symmetry and orthotropy in asphalt pavements. (a) Cross-anisotropic. (b) Transversely isotropic. (c) Isotropic (University of Maryland, 2018).

presented that the asphalt mixtures have significant anisotropic properties. There are some studies have focused on the anisotropic and viscoelastic properties of asphalt mixtures in asphalt pavement structural analysis (Wang et al., 2005; You et al., 2018c; Zhang, 2012; Zhang et al., 2011). The constructive approaches are continually necessary to incorporate the inherent anisotropy into the mechanistic modeling of the asphalt mixtures so that the inherent anisotropy is accounted for in the viscoplastic and viscofracture characterization.

Through ADINA numerical simulation and field measurement, Chen et al. (2011b) and Masad et al. (2006) reported that the asphalt pavement design considering isotropic characteristics significantly underestimated the shear stress and tensile stress under vehicle loading, leading to early fatigue cracking and permanent deformation of the asphalt pavement. From the experimental and theoretical perspectives, Zhang et al. (2011) found that asphalt mixture was not only a viscoelastic material but also had obvious anisotropic properties in its spatial structure. Yan et al. (2016) and You et al. (2018c) used numerical simulation and analytical methods to conduct preliminary research on the mechanical behavior of asphalt pavement, considering the viscoelasticity and transverse isotropy of the asphalt mixture. They reported that the anisotropic characteristics of the asphalt mixture had a more significant impact on the asphalt pavement's static and dynamic responses. Considering the viscoelastic properties of asphalt mixtures, the mechanical behavior of asphalt pavements could be more accurately described. Ahmed et al. (2015) used numerical simulation to study the stress response of orthotropic asphalt pavement based on the generalized Maxwell viscoelastic model and found that horizontal tensile strain was significantly affected by the anisotropy of asphalt mixtures, especially for the fatigue cracking and permanent deformation (rutting). To sum up, in the design and analysis of asphalt pavements, it is possible to more accurately study the mechanic behavior of asphalt pavements under vehicle and environment conditions, considering anisotropy (transversly isotropic, cross-anisotropic, or isotropic) and viscoelastic properties of asphalt mixtures.

4.3.1.3. *Mathematical methods to asphalt pavement response*. The increasing use of sandwich panels (multi-layered medium) demands a better understanding of the response of multi-layered asphalt pavement structures. A typical pavement structure as shown in Fig. 55, consists of surface layer, base layer, and soil foundation. It is obvious that a precise study of the response of asphalt pavement under vehicle loads could be examined in detail via numerical simulation, mathematical modeling, and in-situ testing. However, the cost of in-situ testing of any real asphalt pavement structure is still far too high for practical design and analysis; a much more realistic option but still quite costly is multi-scale numerical simulation such as FEM and district element method (DEM).

The mathematical methods are usually constructed to appropriate mathematical and mechanical theories in asphalt pavement response analysis, where it is assumed that the asphalt pavement is made up of a certain number of layers, which are supposed to be full-bonded or gradual bonded together. As an economical computing method, the mathematical methods have developed into multi-branch situations, which consist of precise integration algorithm, transfer matrix method, spectral element method, Green's function

Table 25 – Characterization of anisotropic properties of asphatl mixtures.

Reference	Description	Characterization	Key finding
Sui et al. (2020)	The custom-made permeameter was used to measure the horizontal and vertical hydraulic conductivities of hollow Marshall specimen with gradient porosity.	Horizontal and vertical hydraulic conductivities	(1) Transversely isotropic permeability was commonly existing in both types of asphalt mixture; (2) permeability reveals fiercer transverse isotropy in asphalt concrete.
Zhang et al. (2012a)	The uniaxial compressive creep test, uniaxial tensile creep test, and indirect tensile creep test were used to determine the tensile and compressive properties at each temperature and then to construct the master curve of each property.	(1) Magnitude and phase angle of the compressive complex modulus in the vertical direction; (2) magnitude and phase angle of the tensile complex modulus; (3) magnitude and phase angle of the compressive complex modulus in the horizontal plane.	(1) Asphalt mixtures have significantly different tensile properties from compressive properties; (2) magnitude of the compressive modulus in the vertical direction is approximately 1.2 to 2 times of the magnitude of the compressive modulus in the horizontal plane.
Motola and Uzan (2007)	Asphalt mixture slabs were uniaxially compressed in three directions at 40 °C.	Dynamic modulus in the three principal directions	(1) Asphalt mixtures compacted in the field is initially not isotropy, but rather cross-anisotropy; (2) the degree of cross-anisotropy is about 0.7 (the ratio between vertical to horizontal moduli is about 1.4).
Uzan (2020)	Prismatic field specimens were tested in a triaxial cell with controllable vertical stress and confining pressure.	Dynamic modulus and creep compliance	Prismatic specimens are preferred in the case of cross-anisotropy.
Levenberg and Uzan (2007)	Asphalt mixture cylindrical specimen compacted with vibratory shaker under confining pressure was tested in creep and recovery cycles under uniaxial and isotropic stress conditions.	Applied stress, radial strain, and lateral strain	(1) The asphalt mixture is not isotropic; (2) one unique creep-compliance function could be used to describe the viscoelastic response of the material under multiaxial stress conditions.
Ahmed et al. (2015)	Uniaxial test and indirect tensile test were carried out to measure the vertical or axial stress by controlling strain test.	Vertical modulus, horizontal modulus, and the degree of cross-anisotropy	(1) The ratio of the horizontal to the vertical instantaneous moduli is 0.33; (2) the tensile strain at the bottom of the asphalt mixture layer decreases with the increase of the cross-anisotropy ratio toward unity.
Benedetto et al. (2016)	(1) Tension-compression complex modulus tests were performed in the horizontal and vertical directions at different strain rates; (2) sinusoidal axial loading is applied on the specimens to measure sinusoidal axial and lateral strains as well as sinusoidal axial stress.	Complex moduli, complex Poisson's ratio, phase angles, and shift factors	The degree of anisotropy depends on the load frequency.
Pham et al. (2015)	(1) Complex modulus measurements were conducted to determine linear viscoelastic behavior; (2) axial stresses and strains, radial strains were measured under sinusoidal cyclic loadings.	Complex modulus and complex Poisson's ratios	Reclaimed asphalt pavement (RAP) performs as transverse isotropy.
Underwood et al. (2005)	Gyratory asphalt mixture samples were uniaxially compressed and tensed at different strain rates at different temperatures.	Compressive strength ratio	Drastic anisotropic behavior in compression, slight effect in tension, and no effect in dynamic modulus.
Ayres Jr. and Witczak (1995)	Field-collected cores were tested from a newly constructed Maryland State Highway Administration project with indirect tension mode.	Resilient modulus	Resilient modulus of field samples did not show any anisotropy.
Masad et al. (2002)	Aggregate particle orientation was analyzed to characterize the anisotropy of asphalt concrete mixtures.	Stiffness	The aggregates orientation played a significant role in the degree of anisotropy.

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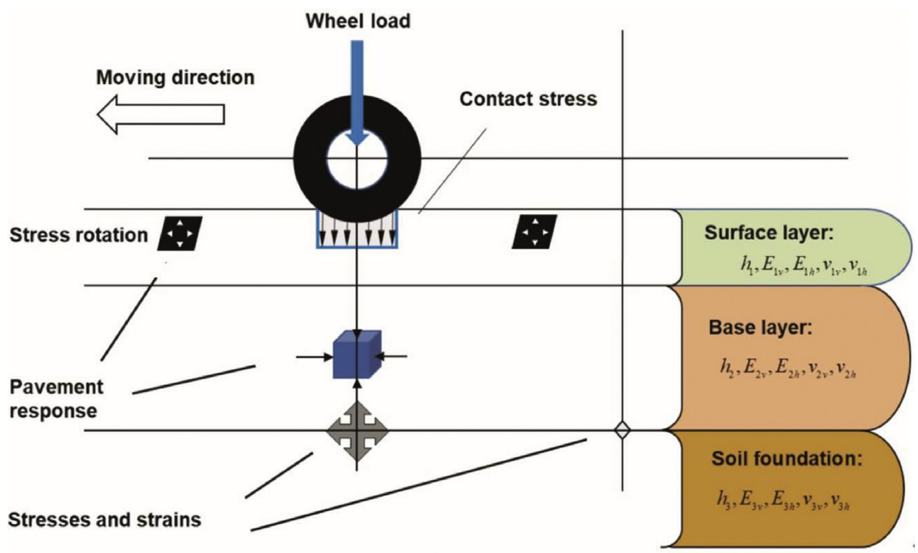


Fig. 55 – Hypothetical asphalt pavement structure (Maina et al., 2017a, b).

method, and thin-layer method, etc. Table 26 demonstrated the brief information of these mathematical methods in asphalt pavement response analysis and design.

4.3.2. *Finite element modeling for analyses of pavement mechanics*

In the past decades many computer programs have been developed and increasingly used as mechanistic model for solving the layered pavement system. Most of them are based on multilayer elastic (MLE) theory and finite element method (FEM). The MLE models are considered satisfactory for fast predicting asphalt pavement response under external wheel loads and relatively easy to operate. However, the situation of asphalt pavement in actuality may be extremely different with the assumptions in these programs based on MLE, e.g., finite geometrical scale in lateral extent, non-uniform loading condition, and inelastic material properties (Huang, 1993; Wang et al., 2020m). These differences may result in significant deviation between the calculated and the real responses of the asphalt pavement. Finite element (FE) models are also very good to predict pavement response and can consider the above-mentioned requirements. The application of FEM to simulate asphalt pavement will be particularly introduced in three aspects including simulation of asphalt pavement structure, material properties and boundary conditions. Through this review, the most important characteristics of the asphalt pavement are concluded, which are the basic for analyses of pavement mechanics and parameter inversion.

4.3.2.1. *Geometrical dimension of the FE models*. When modeling asphalt pavement systems through FEM, the first subject is the geometrical dimension. Generally, three categories are considered for FEM modeling, 2D plane-strain, axisymmetric, and full 3D modeling. The different dimensions of the model have several influences on the computation results such as accuracy and efficiency.

In the year of 1968, Duncan et al. (1968) proposed proper domain sizes for 2D axisymmetric FE modeling, which is the first major study on the effect of the geometrical size of an FEM model for the analysis of pavements. The initial and most comprehensive investigation of the effects of the dimensions of 2D plane strain, 2D axisymmetric and a 3D simulation was carried out by Cho et al. (1996). These three types of FE formulation were proposed and BISAR was used to obtain MLE results for comparison. They studied the effect of different geometrical parameters such as aspect ratio, size of element and model dimensions. The investigation showed that the 3D and the axisymmetric models yielded similar results and were capable of modeling static and non-moving traffic loads (Cho et al., 1996). The effects of the geometrical dimensions of FEM models in 3D and 2D analyses were further investigated by Myers et al. (2001). It was found that a 3D formulation could lead to more accurate results, however, the computational time was significantly increased. A modification to the 2D analysis which could enhance the accuracy of the results to an acceptable level was introduced by the authors (Myers et al., 2001). Ghadimi et al. (2013) investigated different models with 2D plane strain, 2D axisymmetric and 3D formulations. The results were compared with MLE programs CIRCLY and KENLAYER and thus the effect of each formulation on the results was discussed. According to their conclusions, the 2D axisymmetric and 3D models yielded an acceptable agreement with the analytical solution; however, the difference between the 2D plane strain results was not within the accepted range (Ghadimi et al., 2013). Recently, Liu et al. (2015b) developed the FE program named SAFEM which is based on the semi-analytical FE method. It is a 3D FE algorithm that only requires a 2D mesh by incorporating the Fourier series in the third dimension, as shown in Fig. 56. SAFEM is able to analyze static and dynamic responses of asphalt pavements under stationary or moving loads. Besides linear elasticity, a viscoelastic material model

Table 26 – Mathematical methods to asphalt pavement response.

Method	Description	Advantage
Precise integration algorithm (Han et al., 2019a; Zhong and Williams, 1994)	A high-precisioyumerical time step integratio method proposed for a linear time-invariant structural dynamic system.The reason for the high precision is the use of the 2N algorithm within the delt time step.	This method not only avoids the computer truncation errors due to meticulous dividing, but also increases the numerical solution of matrix exponential to the accuracy of the computer.
Transfer matrix method (Zhong et al., 1992; Zhong and Geng, 2009)	According to the balance equation and the physical equation of the problem, the equation expressed by the state vector is derived and then the Hankel transformation is performed to obtain the relationship between the state vector of any layer and the initial state vector. The state vector of any layer can be represented by the product of the transfer matrix of the corresponding layer and the initial state vector. The transfer matrix is only a 4th-order square matrix, and the initial state vector can be determined by the boundary conditions. After solving the state vector of any layer, the inverse Hankel transform can be used to obtain the displacement and stress solution of the layer.	Using the transfer matrix method to solve the axisymmetric problem in the elastic half-space. No matter how many levels it is, it ultimately boils down to solving a system of binary linear algebraic equations, which greatly simplifies the problem. This method also has high application value in solving dynamic problems and viscoelastic problems in this field.
Spectral element method (You et al., 2016, 2018a, 2019, 2020a, 2020c)	The analytical layer element is used to describe a single layer, then the global stiffness matrix is obtained by assembling the interrelated layer elements based on the principle of the finite element method and the boundary conditions, and the solution for the corresponding problem was obtained by solving the algebraic equations of the global stiffness matrix	It not only reduces the computational requirement dramatically but also demonstrates the numerical efficiency and stability due to the absence of positive exponential functions and evades the inconvenience of the numerical evaluation of contour integration between zero and infinity.
Green's function method (Dickhoff and Barbieri, 2004)	A mathematical physics equation expresses the relationship between a specific field and the source that produces this field. When the source is decomposed into a superposition of many point sources, if the field generated by the point source can be known, using the principle of superposition, the field of any source under the same boundary conditions can be found. This method of solving mathematical and physical equations is called Green's function method. The field generated by a point source is called Green's function.	It provides an accurate solution to the multi-field coupling problem.
Thin-layer method (De Oliveira Barbosa and Kausel, 2012)	Thin-layer method can carry out at least one of the two Fourier transforms in closed form, which will reduce the computational effort to that of a series of plane-strain problems supplemented by a numerical transform over the third spatial direction.	The three-dimensional (3D) problem is solved as an aggregate of two-dimensional (2D) problems of manageable size.

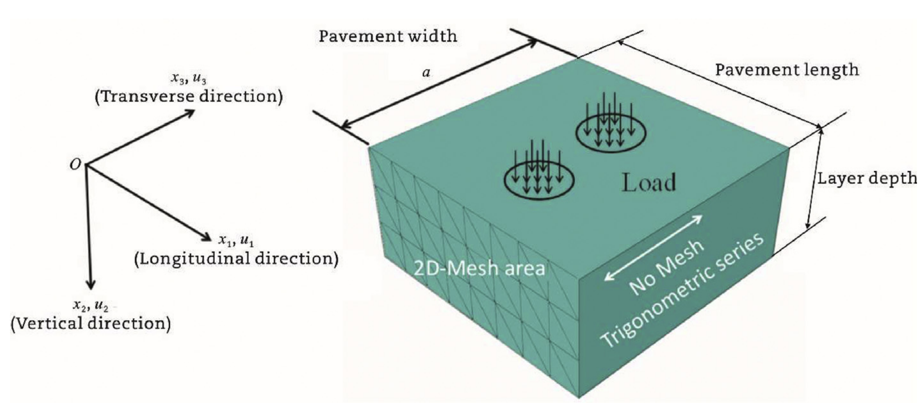


Fig. 56 – A typical SAFEM model (Liu et al., 2015).

for asphalt layers has also been integrated. Verification was carried out to prove that SAFEM is an accurate tool for the fast prediction of asphalt pavement responses (Liu et al., 2015b, 2017a, 2017b, 2017c, 2018). As above, the 3D, 2D plane strain and axisymmetric FE models offer good methods of analysis for multilayered pavement systems to some extent. They have different element formulation and consider different directional components of stresses and strains. Strictly speaking, although it consumes more computational time, only the 3D FE analysis can consider all three directional response components and should predict the most accurate pavement responses (Kim, 2007).

4.3.2.2. Constitutive models of pavement materials. The first concept used to simulate pavement material behavior is linear elasticity, in which the stress-strain relationship is assumed to be linear. This concept has been used by different researchers and has the advantage of simplicity in calculation and formulation. However, the pavement experiences not only elastic deformation but also plastic, viscous and visco-elastic deformation under cyclic traffic loading. Many investigations for pavement analysis with FE simulation have incorporated viscoelastic models for asphalt mixtures and stress-dependent elastic models for granular materials (Tang, 2011).

From the end of the last century, researchers have successfully applied linear viscoelastic theory to describe the behavior of asphalt materials in FE simulation. Elseifi et al. (2005) firstly applied the generalized Kelvin model into an FE program to simulate pavement responses and then conducted a comparative study between the elastic FE model and the linear viscoelastic FE model in a later research (Elseifi et al., 2006). The results showed that it is imperative to incorporate a viscoelastic constitutive model into pavement design methods for improved accuracy. The elastic theory grossly underestimated pavement responses, which is not conservative and may lead to the premature failure of asphalt pavements in reality. Mikhail and Mamlouk (1997) incorporated viscoelastic material parameters into an FE model to study the effect of vehicle-pavement interaction on pavement response. To help define appropriate specimen size and shape for laboratory tests and to check stress and strain distribution in laboratory test specimens, Weissman and Sackman (1997) incorporated viscoelastic constitutive models in the FEM. The results were also used to predict stresses and strains in a pavement structure loaded by the heavy vehicle simulator (HVS) in their research. The theory of viscoelastoplasticity has also been extensively used to analyze hot mix asphalt (HMA) materials recently. Chehab (2002) developed an advanced material characterization procedure including the theoretical models which encompass the elastic, viscoelastic, plastic and viscoplastic components of asphalt concrete (AC) behavior. Pirabarooban et al. (2003) successfully developed a viscoelastoplastic creep model representing the time-dependency of asphalt mixtures to evaluate their rutting potential and to identify factors of influence. The creep model parameters were derived from asphalt pavement analyzer test results. The plastic and viscoplastic behaviors have been incorporated into FE programs at the North Carolina State University of the USA in comparison with other studies where the research mainly focused on simulating linear viscoelastic behavior (Liao, 2007). Zopf et al. (2015) proposed an appropriate asphalt material model that considers elastic, viscous as well as plastic properties and that allows for large strain theory, which was then applied for the FE modeling. The comparison of experimental and numerical results showed good agreement. Tong et al. (2020a) investigated the criterion of asphalt pavement rutting using Perzyna theory. They applied the thermal-visco-elastic-plastic model in their FE models. Their analysis illustrates that the key to controlling rutting at intersections is to use better anti-rutting materials at the top layers instead of deepening the usage of modified asphalt mixture. Besides, the depth of rutting varies dramatically with axle weights (Tong et al., 2020a).

4.3.2.3. Variability of material property along with different directions. Besides the material constitutive models mentioned above, a number of studies have been performed considering pavement materials as isotropic and anisotropic to predict pavement responses. A study by Masad et al. (2006) used both isotropic and anisotropic materials to determine the pavement response. An axisymmetric FEM was developed in their study. This model was subjected to a static loading condition to simulate Benkelman beam load (Masad et al., 2006). Cross-anisotropy (transverse isotropy) was also investigated by Oh et al. (2006). A schematic representation of cross-anisotropic materials is shown in Fig. 57.

Four different cross-anisotropy material models were developed in their study based on laboratory tests. These material models were then implemented in a static FEM to determine the pavement response under falling weight deflectometer (FWD) and multi-depth deflectometer (MDD) test. In addition, this FEM was used to determine the pavement performance such as rut depth over time. Al-Qadi et al. (2010) performed a study where they considered cross-anisotropy for all the layers except HMA layer. They performed a 3D dynamic FE analysis using implicit algorithm to simulate FWD test results. Effect of cross-anisotropy was only studied for unbound layers in this research (Al-Qadi et al., 2010). Later Wang and Al-Qadi (2013) built a nonlinear anisotropic 3D FE pavement model to

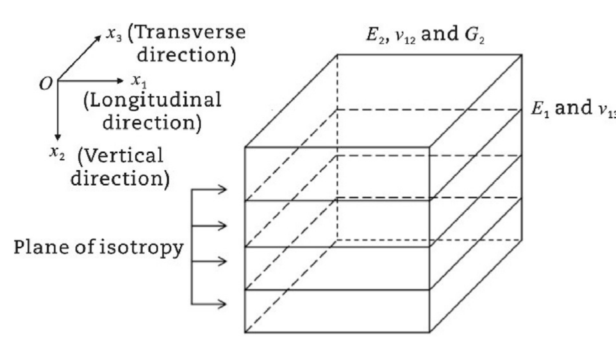


Fig. 57 – Schematic representation of cross-anisotropic materials.

simulate the granular base layer and predict viscoelastic pavement responses under moving vehicular loading. The FE model simulated the vehicular loading as a moving load with 3D contact stresses at the tire-pavement interface (Wang and Al-Qadi, 2013). Ignoring cross-anisotropy of asphalt mixtures may cause significant error in prediction of critical strains, which are related to fatigue damage or permanent deformation predictions of a pavement. To determine the pavement response under truck load, Choi et al. (2011b) developed a 3D static FEM using anisotropic behavior of HMA. Base and subgrade materials in that model were considered to be isotropic. The effect of cross-anisotropy of AC on horizontal strain and vertical stress was investigated by Ahmed et al. (2013). However, the effect of cross-anisotropy on the vertical strain was not performed by these authors. Tarefder et al. (2014) performed a 3D dynamic FE analysis of a pavement structure considering material cross-anisotropy in every pavement layer. In essence, cross-anisotropic behavior of an instrumented asphalt pavement section was studied under FWD and actual truck load. In addition, effect of cross-anisotropy was investigated on pavement damage (Tarefder et al., 2014). As subsequent research, the combined effect of AC cross-anisotropy and temperature variation on pavement stress-strain under dynamic loading was investigated (Ahmed et al., 2015). Cross-anisotropy in the model was defined as the ratio of horizontal to vertical modulus (n-value) of the AC. And then the effects of cross-anisotropy and stress-dependency of pavement layers on pavement responses under dynamic truck loading was further investigated (Tarefder et al., 2016). It was observed that the increase in horizontal modulus caused a decrease in layer strains.

4.3.2.4. *Loading patterns of FE models*. One important factor in FE modeling of asphalt pavements is the geometry of contact area between tire and pavement as well as the loading distribution. A typical measurement of wheel load is shown in Fig. 58.

Regarding the shapes of contact area, several assumptions have been proposed according to the experiments. The first one is a circular area, which has been widely used by researchers for a long time (Austroads, 2004; Harichandran et al., 1990; Raad and Figueroa, 1980). Afterwards, a rectangular shape is adopted to simulate the contact area. Huang (1993) proposed a method to set up the rectangular shape translated from the circular shape. An advantage of the rectangular shape applied in 3D FEM modeling is the convenience in mesh generation, i.e., using a circular area in full 3D modeling may cause some mesh generation difficulties especially when brick elements are used (Ghadimi, 2015). Based on experimental investigations, early studies on FE modeling of asphalt pavements were carried out (Blab and Harvey, 2002; De Beer et al., 1997; Merrill et al., 1998; Weissman and Sackman, 1997). These FEM studies indicated that the regular shape of contact area such as a rectangle with non-uniform loading distribution indeed improved prediction of the stress and strain state in the near-surface pavement section. With the development of measuring method and computer technology, the non-uniformly distributed pressure and unregular contact areas have been applied in FE modeling. Novak et al. (2003) used the FE code ADINA to model the 3D effects of measured tire contact stresses in a typical pavement configuration. The results showed that the predicted stress states and measured radial tire contact stresses were both larger in magnitude and more focused near the surface than those obtained from traditional circular uniform vertical loading conditions. In terms of effects of possible pavement damage mechanisms, predicted high near-surface shear stresses may be a part of an explanation for near-surface rutting failure modes. Wang et al. (2012) constructed a 3D tire-pavement interaction model in ABAQUS to predict the contact stress distributions for future use in the mechanistic analysis of pavement responses. The analysis results showed that the non-uniformity of vertical contact stresses decreased as the load increased, but increased as the inflation pressure increased. Bai et al. (2020b) conducted a 3D FE modeling based on non-uniform distributed tire-pavement contact pressure, full interfacial layer bonding conditions, and viscoelastic characterization of the asphalt

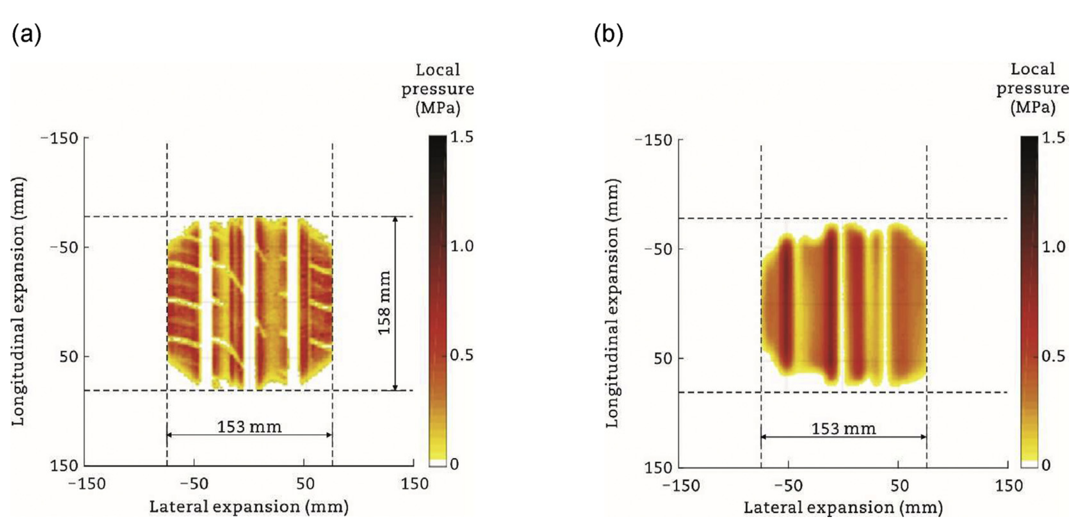


Fig. 58 – The measurement with 6000 N wheel load. (a) Static measurement. (b) Dynamic measurement (Friederichs et al., 2021).

layers. The results indicated that under elastic modeling assumptions, there is a high propensity for failure at the bottom of the asphalt and/or base layer due to high tensile stresses. With viscoelastic modeling assumption, however, the asphalt layer is more likely to suffer from surface shear failure due to high shear stresses on the surface (Bai et al., 2020b).

4.3.2.5. *Interaction between adjacent pavement layers*. Layers can be assumed to be fully attached or relative displacements between layers can be considered. Pan et al. (1994) conducted one of the very first studies on this effect in the year of 1994. The effect of the soil-pavement interaction was considered by coupling boundary element method (BEM) and FEM. The dynamic elastic and elastoplastic solutions were compared and the results showed that the dynamic analysis resulted in less deflection, and the elastic soil medium led to less deflection than the elastoplastic soil medium. With advancements in FEM software, the interface elements were applied in the modeling of layer interactions. Baek et al. (2010) studied the interaction effect in pavement layers composed of HMA laid over joint concrete pavement (JCP) by using interface elements. The constitutive model of interface elements was Mohr-Coulomb frictional behavior in their study. The effects of different interface parameters were studied regarding the developed cracks. Ozer et al. (2020) used the same frictional behavior of interface elements to study the effect of the interaction between soil and the AC layer in ABAQUS with dynamic loading. In this study, the AC layers lay on a Portland cement concrete (PCC) layer. The study concluded that a significant difference existed between the strain induced in pavement layers caused by the different definitions of the interface elements properties. Möller and Oeser (2002) proposed a numerical method for assessing the load-bearing capacity of multi-layered road pavements using FEM in combination with BEM. The schematic representation of asphalt pavement model with interface elements is shown in Fig. 59.

This method permits the separate treatment of individual layers as well as the elastic semi-infinite space. Horizontal and vertical interlayer composite action may be accounted for by means of special kinematic coupling conditions. If layers were not entirely flat over their entire surface due to temperature and humidity effects, the assigned layering conditions may also be accounted for with the aid of kinematic couplings. The couplings also permitted a consideration of the transfer of shear forces along the layer interfaces (Oeser, 2002). Wollny et al. (2016a, 2016b, 2021) proposed a theoretical-numerical asphalt pavement modeling at material and structural level, whereby the focus was on a realistic and numerically efficient computation of pavements under rolling tire load by using FEM based on an arbitrary Lagrangian Eulerian (ALE) formulation. A viscoelastic cohesive zone model was implemented into the ALE pavement formulation to describe the interaction of the single pavement layers. The viscoelastic cohesive zone model was further extended to account for the normal pressure dependent shear behavior of the bonding layer. The simulation of interfacial layers was fitted to experimental data.

4.3.3. *Pavement mechanics test and parameter inversion*

The modulus of pavement structure layer plays a very important role in road design, evaluating and service life prediction. Researchers and engineers have proposed many ways to measure the mechanical properties of pavement which mainly can be divided into destructive and nondestructive tests. The destructive tests tend to be directly measuring the mechanical properties and more accurate, however, it also has drawbacks including time-consuming, breaks the pavement structure and use the material modulus instead of structural modulus. In the last decades, with the rapid development of pavement nondestructive testing technology, the numerical inversion has attracted more and more attention. The purpose of this portion is to provide a comprehensive review on current research status, field application and development trend of asphalt pavement mechanics testing and parameter inversion, the basic principles and research progresses of asphalt pavement nondestructive modulus testing technology are summarized, and the technical characteristics of pavement structure parameter inversion methods are analyzed. Finally, the challenges and development trends of asphalt pavement mechanical test mechanics and parameter inversion in the future are analyzed and prospected.

4.3.3.1. *Nondestructive pavement modulus test*. The nondestructive modulus test is mainly applying external load to the pavement by the detection system to obtain the pavement deformation, and then calculate its modulus by mechanical model. In the early stage, researchers mainly measured the pavement rebound deflection under truck through the Beckman beam method, this method has been widely used with convenient setup, however, the quasi-static load used in this method could lead to larger measured pavement rebound deflection (Hoffman, 1983; Wang, 1985). To improve the

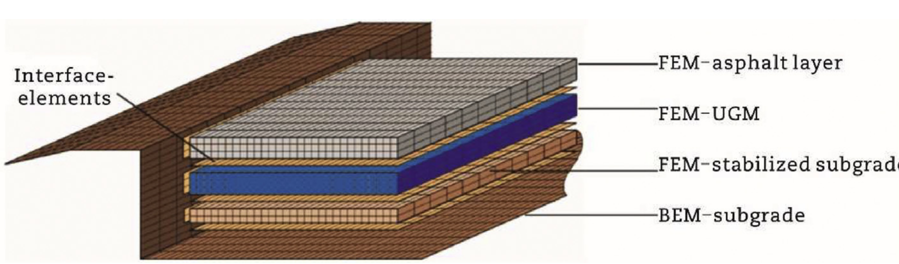


Fig. 59 – Discretization of layers and semi-infinite subgrade surface with FEM and BEM.

accuracy of pavement structure modulus test, the dynamic deflection instrument was developed based on computer and electronic sensing technology, such as the falling weight deflectometer (FWD) (Grenier and Konrad, 2009; Grenier et al., 2009; Kuo et al., 2016; Salour and Erlingsson, 2013; Yusoff et al., 2015). Based on the FWD tester, researchers could obtain reasonable dynamic modulus of pavement under dynamic loading, according to the test data, the modulus of pavement structure layer could inversely calculate by the dynamic back calculation program (El-Raof et al., 2018; Fu et al., 2019, 2020; Grenier et al., 2009; Pratelli et al., 2018; Zhang et al., 2021c). However, the FWD also have limitations for indoor test because of the large test vehicle (Wu et al., 2015a), because of this, researchers developed various indoor deformation measure method including the light deflection instrument (Senseney et al., 2013), surface wave (Yusoff et al., 2015) and geophone (Zhang et al., 2021i), and have compared it with the FWD test data, and established the relationship between the modulus measured by the light deflection instrument, surface wave, geophone and FWD. In order to further improve the accuracy of pavement modulus test, some scholars have applied the laser Doppler sensor to pavement modulus test (Gui et al., 2018; He et al., 2017b), and Ma et al. (2018a) proposed an intelligent pavement scheme with built-in sensors to monitor the pavement stress and strain response under aircraft load and established the asphalt layer modulus theoretical calculation model for pavement mechanical response of double elastic system under service load. Table 27 is the summary of nondestructive pavement modulus test method, in terms of the recent development of pavement deflection detection for FWD and LWD, the deformation of the surface of the structural layer can be detected by sensors distributed at different distances from the measuring point, and then it was recorded and transmitted to obtain the dynamic deflection and deflection basin data generated under dynamic loading, and then the pavement structure layer modulus can inversely calculate.

Although the nondestructive pavement modulus testing technology has been widely used, there are still some problems to be solved: (1) the data noise is still a problem under various test method, and more optimized noise reduction and extraction algorithms are needed to improve data accuracy; (2) to incorporate the pavement structure layer properties (layer thickness, material viscoelasticity, etc.), which including the application of self-sensing sensing technology, ground penetrating radar technology and visualization technology to increase the accuracy and speed of the pavement modulus measurement.

Table 27 – Summary of nondestructive pavement modulus test method.

Reference	Nondestructive pavement modulus test method
Grenier and Konrad (2009), Grenier et al. (2009), Kuo et al., (2016), Salour and Erlingsson (2013), Yusoff et al. (2015)	Falling weight deflectometer
Senseney et al. (2013)	Light deflection instrument
Yusoff et al. (2015)	Surface wave
He et al. (2017b), Gui et al. (2018)	Laser doppler sensor
Ma et al. (2018a)	Built-in sensors to monitor
Zhang et al. (2021i)	Geophone

4.3.3.2. Pavement structural parameters inversion method. The pavement structure parameters inversion is steps to input the measured modulus parameters of a certain layer into the given mechanical model for the back-calculation of pavement parameters. Thus, the parameter inversion accuracy was directly affected by the modulus input, inversion models and algorithms. At present, many researches were mainly focused on algorithms and parameter correction (Deng et al., 2021; Saltan et al., 2013). With the development of computer technology and numerical analysis method, the inverse program of integral transformation and finite element solution based on elastic layered system is developed. According to the measured data of FWD, the structural layer modulus and initial modulus can be obtained by finite element iterative method (Cao et al., 2019b, 2020a; Madsen and Levenberg, 2017; Qiu et al., 2011). Some researchers also used data mining (DM) method to calculate the elastic modulus and Poisson's ratio of pavement layer based on the deflection test data (Saltan et al., 2011). However, compared with the traditional finite element iterative inversion program, artificial neural network (ANN) and genetic algorithm (GA) have many advantages including no consideration of the initial modulus and complex material properties. Researchers have applied ANN and GA to the inversion of pavement structure modulus, and developed the corresponding inversion program (Li and Wang, 2017; Varma and Kutay, 2015; Wang et al., 2019e; You et al., 2020b). With the in-depth study of the pavement structure layer modulus inversion algorithm, on the basis of ANN and GA, researchers further developed firefly algorithm (Zhang et al., 2020d), constrained system identification (SID) method (Cai et al., 2015), particle swarm optimization (PSO) algorithm (Li et al., 2012b) and gene expression programming (GEP) (Hu et al., 2016) for the pavement structure layer modulus inversion. The results showed that these methods have high identification accuracy and significant calculation stability, which can effectively reduce the influence of initial trial value on the inversion results. With the continuous optimization of the pavement structure layer modulus inversion algorithm, researchers have conducted in-depth research on the uniqueness of the modulus solution after inversion and the rationality of the inversion results. By considering the parameters such as the deflection basin (Dong et al., 2011), the thickness of the pavement layer (Garbowski and Pozarycki, 2017), the best inversion section (Timm and Tutu, 2017), the best inversion point (Zhu and Sun, 2017), the pavement condition and the internal abnormal noise (Yu et al., 2018c), and the interlayer contact (Zhang et al., 2021f), etc., the inversion algorithm is further optimized to more reasonable modulus inversion value. Table 28 is the summary of pavement structural parameters inversion method, it can be seen from the research on the above modulus back-calculation method that the modulus back-calculation method needs to be further studied in the future.

With the application of artificial intelligence technology, nondestructive testing based on machine vision, and multi-source heterogeneous data fusion, the deeper network structure and more optimized identification method are expecting to further improve the speed and accuracy of calculation and inversion of pavement modulus. At present, there is still certain gaps between the machine vision and the multi-source heterogeneous data fusion method and the practical engineering application, which is mainly in the following aspects: (1) the anisotropy of engineering structure, parameters, and materials need to be further integrated to different structural types of pavements; (2) the interpretation of characteristic variables of pavement structures also needs to be further optimized.

4.3.4. *Summary and outlook*

The part of constructive methods to pavement response analysis review (Section 4.3.1) provides engineers and researchers with fundamental mechanical models and is efficient in comprehensively summary the mechanical behaviors of asphalt pavement. In the existing studies, (1) when considering the viscoelastic properties of asphalt mixtures, most of the classical viscoelastic models are based on homogenous assumptions and do not reflect the volatility and trend of asphalt pavement structural parameter, while their changes along with the structural depth; (2) when considering the anisotropic characteristics of asphalt mixtures, it is generally based on the transversely isotropic elastic theories, which cannot reflect the static and dynamic viscoelastic properties of asphalt mixture. In addition, in asphalt pavement response analysis and especially stress analysis, the asphalt mixture performs in anisotropic viscoelastic and the inherent anisotropy that is caused by the preferential orientation of aggregates. Aside from the nondestructive properties of asphalt mixtures, due to the different crack areas projected in different directions, the anisotropic viscoplasticity and anisotropic viscofracture are the destructive properties of asphalt mixtures. Therefore, it is necessary to develop the constructive models of asphalt mixtures and the respective mathematic methods to analyze the asphalt pavement response under vehicle loads with more accuracy.

Table 28 – Summary of pavement structural parameters inversion method.

Reference	Pavement structural parameters inversion method
Qiu et al. (2011), Cao et al. (2019b, 2020a), Madsen and Levenberg (2017)	Finite element iterative
Saltan et al. (2011)	Data mining (DM)
Li et al. (2012b)	Particle swarm optimization (PSO) algorithm
Li and Wang (2017), Varma and Kutay (2015), Wang et al. (2019e), You et al. (2020b)	Artificial neural network (ANN) and genetic algorithm (GA)
Cai et al. (2015)	Constrained system identification (SID)
Hu et al. (2016)	Gene expression programming (GEP)
Zhang et al. (2020b)	Firefly algorithm

The part of finite element modeling for analyses of pavement mechanics (Section 4.3.2) shows the FE models have been applied extensively to the analysis of pavement structures in the M-E design methods. The predicted pavement responses are affected by many aspects such as the geometrical dimension, material properties, and loading types. The FE algorithms currently used in asphalt pavement analysis, whether the specific developed or general-purpose, have their respective advantages and disadvantages in terms of accuracy, efficiency, and applicability. It is necessary to develop specific FE algorithms for a full 3D fast and precise modeling of asphalt pavement that can consider representative material behaviors and different loading modes. Moreover, the balance of efficiency and reliability should be addressed especially. The following recommendations can be made to point out the direction of future development. (1) Advanced constitutive material models could be implemented. (2) Special-purpose elements and methods that are designed for specific circumstances could be implemented. (3) The shape of contact areas and loading distribution could be further investigated and more configurations of them could be implemented. (4) Thermal-hydraulic-mechanical coupling analysis could be implemented, by which the asphalt pavement could be analyzed to assess the importance of thermal and hydraulic effects on the stresses, strains, and displacements in the structural behavior of asphalt pavements. (5) Multi-scale simulation should be comprehensively studied and the efficient approach of macro scale models can be combined with the high accuracy of microscale simulations.

The part of pavement mechanics test and parameter inversion (Section 4.3.3) illustrates that found that many research progresses has been made for pavement structural layer modulus backcalculation through nondestructive testing technologies. However, the non-destructive testing of pavement modulus still needs to be improved in data noise reduction and data accuracy, and the combination of pavement structural layer parameters with sensing technology can improve the speed and accuracy of pavement modulus testing. During the pavement structure parameters inversion process, the models and algorithms determine the efficiency and accuracy of parameters inversion, and the speed and accuracy of parameters inversion can be improved through nondestructive testing based on machine learning and multi-source heterogeneous data fusion. Overall, the following recommendations can be made as of future development, in the future, researches on pavement modulus acquisition and inversion still need to be further studied from the following aspects. (1) The nondestructive testing of pavement modulus is still point by point detection. How to realize the point surface, improve the detection speed, reduce the detection cost, and ensure the detection accuracy in the future is the research area that needs to be studied. (2) The meso scale aggregate contact and material properties also impact the pavement modulus parameters, there is still no simple and efficient method to characterize the pavement modulus parameters with the incorporation of meso scale properties.

5. Green and sustainable pavement

5.1. *Functional pavement*

With the continuous development and improvement of the road system, in addition to meeting the traditional requirements of safety, durability, and comfort, the pavement is gradually endowed with intelligent functions such as energy harvesting, pavement sensing, pavement adaptation, and adjustment. Energy harvesting function, mechanical energy, thermal energy, and light energy resources within the road area are converted into electricity by energy transducer devices, and the environmental energy can be collected and utilized cleanly. Road sensing function includes two aspects: roadside device perception and road ontology material perception. Sensors, lidar, video surveillance, and other peripheral equipment are used to achieve the acquisition of road traffic, load, mechanical parameters, and other information. Self-sensing of pavement temperature can be achieved by using self-regulating materials. The self-sensing of pavement stress is realized by using conductive phase materials. Through the construction of structural health monitoring system, the self-perception of pavement disease is realized. In the aspect of pavement adaptation and adjustment, by increasing the reflectivity of asphalt pavement, the radiation absorption and pavement temperature can be reduced, and the urban heat island effect can be alleviated. Photocatalytic materials are used to realize the harmless degradation of vehicle exhaust on the road. The use of self-repairing materials can achieve the active healing of micro-cracks and other damages, and prolong the service life of the pavement.

5.1.1. *Energy harvesting function*

5.1.1.1. Piezoelectric pavement. There is abundant energy in the road area. Most of the mechanical energy generated by vehicles impact and vibration dissipates in the form of road deformation. If the piezoelectric energy harvesting technology is applied to the pavement, the mechanical energy can be converted into electricity based on the piezoelectric effect, and the resources can be utilized cleanly.

When the vehicle load acts on the transducer embedded in the road, the electricity is generated and collected, and the mechanical energy is converted and utilized. The piezoelectric transducer is at the core of the piezoelectric pavement. Piezoelectric materials and the structure of the transducer influence the energy harvesting efficiency. Improving the collection efficiency of piezoelectric harvesting pavement under different conditions and increasing the electrical output power has always been a research hotspot.

$Pb(Zr_xTi_{1-x})O_3$ (PZT) is the most widely used piezoelectric material in the piezoelectric pavement, which has the advantages of high piezoelectric constant, electromechanical coupling coefficient, and strength. The maximum output can reach 1400 mW when it applies to road energy harvesting (Khalili et al., 2019). With the improvement of the preparation process, the electrical properties of polyvinylidene fluoride (PVDF), an organic piezoelectric material with superior flexibility, are gradually improved. The output power density of the PVDF piezoelectric transducer can reach 16.5 W/m^2 (Shin et al., 2018). In addition, piezoelectric material properties can be greatly improved through element doping (Li et al., 2017a), structural design (Zhao et al., 2020b), material composite (Ding et al., 2017b), and process improvement (Fei et al., 2015). However, the complex process and high cost have made most of the materials rarely used in piezoelectric harvesting pavement.

Table 29 shows the recent researches on the piezoelectric energy harvesting system. Piezoelectric transducer structures mainly include cymbal, crescent, bridge, cantilever beam, stack, hybrid, and so on. Their mechanical properties and working efficiency are different. Cymbal transducer has high energy conversion efficiency; cantilever transducer has good fatigue characteristics; and stack transducer has a large bearing capacity (Song et al., 2016; Zhao et al., 2016a). The stack array transducer can withstand a load of 150 kN. The test results of MMLS3 showed the piezoelectric transducer performance remained after 100,000 cycles of loading (Yang et al., 2017). After combining the cantilever beam transducer with a stack transducer, the working efficiency was 3.6 times higher than a single stack transducer (Dayou et al., 2015). According to the bionics principle, the butterfly transducer based on cantilever transducer can obviously improve its receiving frequency range (Wang et al., 2020k). The maximum output of the integrated system composed of two conductive asphalt layers and a piezoelectric material layer can reach 300 mW under the optimal conditions (Guo and Lu, 2017).

Piezoelectric transducer layout form has an important impact on its working state and service life. Embedding in the road surface and buried in the road are two common forms. The load can directly act on the surface of the transducer and the conversion ratio of mechanical energy is high (Yang et al., 2021d). When the transducer is embedded in the reserved groove of the pavement, the asphalt mortar is used as the cushion, which can enhance the coupling degree between the transducer and the pavement structure, and improve the integration degree (Song et al., 2019). The buried transducer is integrated with the pavement structure, and the load stress is dispersed and transmitted to the transducer surface. Through the analysis of the stress characteristics of the transducer, the best embedding position can be identified (Xiong and Wang, 2016). When the buried depth was 4–6 cm, the transducer could obtain a larger output and has less impact on the integrity of the pavement structure (Nyamayoka et al., 2018).

Table 29 – Piezoelectric energy harvesting system.

Reference	Structure design	Packaging material	Piezoelectric material	Test scenario	Electric output
Yang et al. (2021d)	The internal is a 3-layer stack array structure. External dimension is 30×30×6.8 cm.	Engineering plastic	PZT-5H	2.6 kN load at 4.5 km/h	280.000 V
Zhang et al. (2021d)	The piezoelectric embedded in the nylon bearing plate with 10×10×8 mm grooves, and the upper layer protected by rubber pads.	Nylon; fluororubber	PZT-554	5 kN load in 10 Hz	18.560 mW
Wang et al. (2020k)	Butterfly array structure composed of multilayer cantilever beams. External dimension is 16×16×7 cm.	Aluminum alloy	PZT-5H	Light traffic conventional speed of 50–90 km/h	22.090 mW
Cao et al. (2020b)	Φ 6×10 mm piezoelectric sheet. External dimension is Φ 56 mm×26 cm.	Engineering plastic	PZT-5H	0.7 MPa load in 20 Hz	0.231 mW
Khalili et al. (2019)	6 piezoelectric plates form a stacked structure. Fixed between two steel plates with the size of 127×27.5 cm.	Steel plate	PZT	11 kN load in 62 Hz	1400.000 mW
Yesner et al. (2019)	5×32 mm bridge transducer, 16 in each layer, 4 in total. External dimension is 17.8×17.8×7.6 cm.	Aluminum; nylon	PZT-5X	500 lb. load in 20 Hz	2.400 mW
Roshani et al. (2018)	11 piezoelectric sheets of Φ 50×3 mm form a stacked structure. External dimension is 152×152×47 mm.	Stainless steel	PZT-4	720 N load at 21.6 cm/s	0.078 mW
Jung et al. (2017)	10 PVDF films are paralleled into one group, 6 groups in total. External dimension is 15×15×9 cm.	Aluminum plate	PVDF	250 kgf load at 8 km/h	200.000 mW
Guo and Lu (2017)	The top and bottom are conductive asphalt layers, and the middle is the piezoelectric layer, forming a whole with the pavement structure.	–	PZT	200 N load in 30 Hz	300.000 mW
Song et al. (2019)	3-layer cantilever structure, 4 in each layer. External dimension is 15×15×10 cm.	Stainless steel	PZT	1 mm displacement in 10 Hz	0.184 mW
Roshani et al. (2016)	A cylindrical structure of Φ 152×20.7 mm, copper plate at the top and bottom, polystyrene plate with limit holes in the middle to fix the position of piezoelectric sheet.	Copper plate	PZT	3 kN load in 20 Hz	15.000 mW

5.1.1.2. *Thermoelectric pavement*. Thermoelectric asphalt pavement is a new multifunctional asphalt pavement structure that uses thermoelectric technology to collect pavement heat energy and realize green transformation. At the same time, thermoelectric asphalt pavement can reduce pavement temperature and increase pavement service life. It consists of the traditional asphalt pavement structure, the thermoelectric device, the hot side module, and the cold side module. Thermoelectric conversion device is based on the seebeck effect. One side is connected to the P-type and N-type (P-type is hole-rich material, N-type is electron-rich material) to form a PN junction, and it is placed in a high-temperature state. The other side starts at a low temperature. The concentration of P-type (hole) material and N-type (electron) material at the high-temperature side of PN material is higher than that at the low-temperature side. Driven by this concentration gradient, the hole and electron diffuse to the low-temperature end, thus forming the electromotive force, as shown in Fig. 60 (Sha et al., 2020). According to the above principle, several pairs of semiconductor elements are connected in series on the ceramic substrate. In contrast, they are connected in parallel in heat transfer, which constitutes a general thermoelectric converter. As shown in Fig. 61, it is a kind of structure of thermoelectric converter.

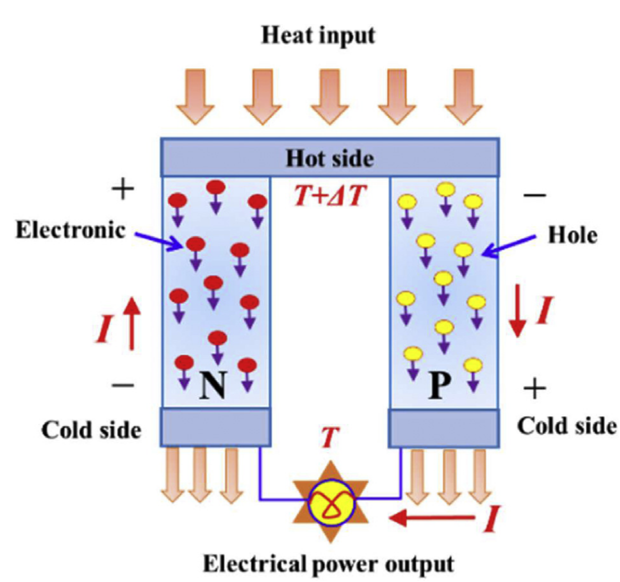


Fig. 60 – Principle of thermoelectric converter (Jiang et al., 2017).

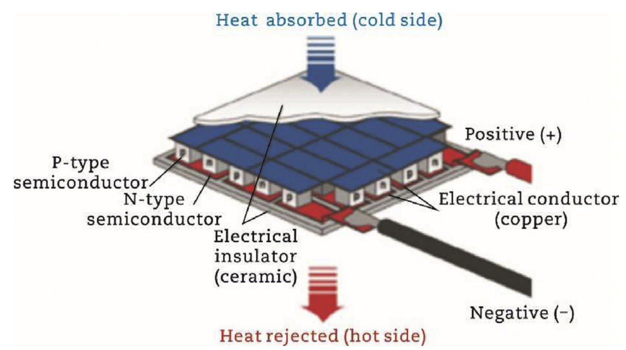


Fig. 61 – Structure of thermoelectric converter (Chen et al., 2016a).

Meiarashi and Toshimasa (1997) first put forward the concept of thermoelectric asphalt pavement. After more than 20 years of development, thermoelectric asphalt pavement can be divided into two types according to pavement heat energy utilization which are the derived-type and the embedded-type. The derived-type thermoelectric asphalt pavement is exported as the hot side module through the heat conduction device. The external environment medium is used as the cold side module, and the thermoelectric converter is set on the roadside. The embedded-type thermoelectric asphalt pavement directly embeds the thermoelectric converter into the asphalt pavement through specific protective measures. The thermal energy inside the pavement is directly used as the hot side module. The lower longitudinal temperature part of the pavement structure is used as the cold side module.

Table 30 lists the types of two kinds of thermoelectric asphalt pavement structures in recent years. It can be seen that the derived-type thermoelectric asphalt pavement was proposed (Hasebe et al., 2006). The system used the water pipe embedded in the asphalt pavement to export the heat energy of the pavement and takes the river as the cold end in the roadside. The maximum power generation of the structure is 0.3 W. The maximum temperature of the thermoelectric asphalt pavement surface and traditional asphalt pavement surface is 30 °C and 60 °C, respectively. Then the research on this kind of thermoelectric asphalt pavement structure is blank in nearly eight years. Until 2014, Hu et al. (2014) used the aluminum piece as the cold side module and used the aluminum piece to export the heat energy of asphalt pavement. The results show that the maximum power generation is 1.1 V. After that, this kind of thermoelectric asphalt pavement structure is mainly carried out by Professor Wei Jiang of Chang'an University and Professor Samer Dessouky of the University of Texas at San Antonio. Professor Wei Jiang used an aluminum vapor chamber as the pavement heat conduction device, the ambient temperature, and the subgrade temperature as the cold side module. He developed two thermoelectric asphalt pavement structures based on the temperature difference between pavement and environment and the temperature between pavement and subgrade. Professor Samer Dessouky set two kinds of thermoelectric asphalt pavement structures with the copper plate as thermal conduction device and heat sink with water and phase change material as cold side module.

For the embedded thermoelectric asphalt pavement structure, it was first proposed by Wu and Yu (2012). The system uses an aluminum rod as a heat conduction device to transmit the temperature at a depth of subgrade to the cold end of the thermoelectric conversion device. The results show that the structure can generate 0.05 mW. In 2014, the structure was improved based on the research of Wu and Yu (2012) and increased the power generation efficiency to 40 mW (Park et al., 2014). After that, because the thermoelectric converter was mainly made of ceramic matrix, which could not meet the requirements of pavement structural strength, Li et al. (2014), Liang and Li (2015), Xiao et al. (2019), and Khamil et al. (2021) set up hollow protection devices, which were embedded in asphalt pavement together with thermoelectric converter and achieved good results. To sum up, the hot end modules of thermoelectric asphalt pavement structure mainly include aluminum plate, aluminum soaking plate, copper plate, steel plate, etc., while the cold end modules mainly include environmental temperature, water, phase change material, subgrade temperature, etc.

In conclusion, the overall power generation efficiency of the thermoelectric asphalt pavement structure is low, which is far from meeting the power demand of the expressway. It is of great significance to improve the power generation efficiency of thermoelectric pavement.

5.1.1.3. *Solar pavement*. Solar energy is one of the most common and clean energy sources in nature. Solar pavement obtains solar energy within the pavement area through the solar energy capture module (Dezfooli et al., 2017; Zhou et al., 2021a). The collection and utilization of solar energy mainly include heat collection, thermoelectricity, and photovoltaic power generation. Research shows that the energy conversion efficiency of photovoltaic power generation technology is higher than the formers, and the technology is relatively mature. In addition, the nearby energy generation and utilization of energy in pavement avoid the loss of transportation. It also reduces the demands for thermal power and fuel as well as the pollution of air and water resources, bringing some economic, social and environmental benefits (Qin, 2016; Wu et al., 2010; Yang et al., 2021e).

Solar pavement is an innovative product of the integration of the photovoltaic industry and highway infrastructure. Solar pavement usually refers to the use of solar power modules to partially or entirely replace the existing asphalt or cement concrete surface to have the functions of solar power generation, energy storage and utilization. At the same time, the pavement will be used as a comprehensive energy supply platform to provide the basis for intelligent road functions such as mobile wireless charging, heating and melting ice or snow (Xu et al., 2021d). The commonly used structural forms from top to bottom are surface transparent layer, middle solar power generation layer and bottom waterproof adhesive layer (Choi et al., 2019).

Table 30 – Structure types of thermoelectric asphalt pavement.

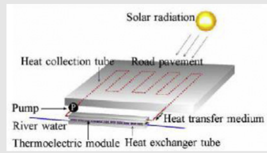
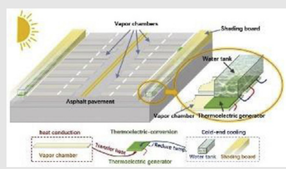
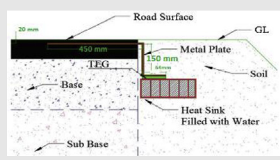
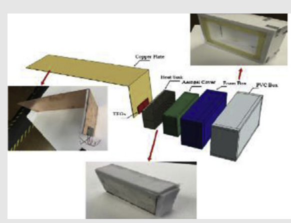
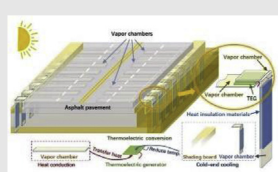
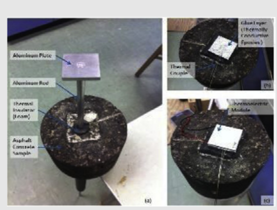
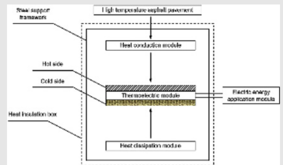
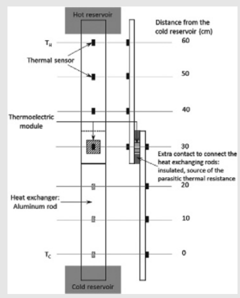
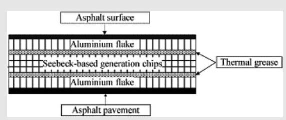
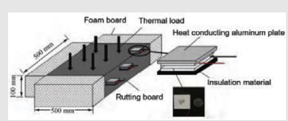
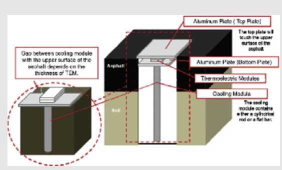
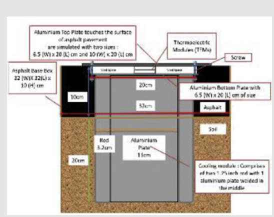
Type	Reference	Pavement structure	Hot side	Cold side	Functional feature
The derived-type	Hasebel et al. (2006)		Water pipe	Water pipe	Maximum power generation 0.3 W
	Hu et al. (2014b)		Aluminum piece	Heat sink	Maximum power generation 1.1 V
	Jiang et al. (2017)		Aluminum vapor chamber	Water tank	Maximum power generation 0.6–0.7 V, temperature-reduction 8 °C–9 °C
	Datta et al. (2017)		Copper plate	Heat sink (water)	Maximum power generation 4–6.5 mW
	Tahami et al. (2019a, 2019b, 2020)		Copper plate	Heat sink (phase change materials)	Daily power generation 29 mW
	Jiang and Huang (2020)		Aluminum vapor chamber	Subgrade	N/A
The embedded-type	Wu and Yu (2012)		Aluminum plate	Aluminum rod	Maximum power generation 0.05 mW

Table 30 – (*continued*)

Type	Reference	Pavement structure	Hot side	Cold side	Functional feature
	Li et al. (2014)		Steel plate	Air cooling system	Maximum power generation 1.4 V
	Park et al. (2014)		Aluminum plate	Aluminum plate	Maximum power generation 40 mW
	Liang and Li (2015)		Aluminum piece	Aluminum piece	Daily power generation 0.00072 kW·h
	Xiao et al. (2019)		Aluminum plate	Insulation material	Maximum energy conversion 66.23 J
	Khamil et al. (2020)		Aluminum plate	Aluminum plate	Maximum power generation 0.35 V
	Khamil et al. (2021)		Aluminum plate	Aluminum plate	Maximum power generation 1.02 V

The solar pavement needs to make full use of the vast pavement area and collects clean light energy. At the same time, it also needs to meet the basic performance requirements of the pavement (Hu et al., 2020c). To ensure the efficient collection of light energy, the surface transparent layer needs to have good transparency with the basic properties for the pavement surface layer, such as flatness, anti-sliding, wear resistance and so on. At present, the primary materials used for the surface transparent layer are inorganic tempered glass, high molecular polymer transparent materials. On the premise of ensuring sufficient strength, rigidity and stability, the intermediate photovoltaic layer needs to convert solar energy into electrical energy effectively. The bottom waterproof adhesive layer mainly protects the power generation layer, transferring load, isolating moisture and bonding. The primary materials used include tempered glass, concrete slab, polymer slab, etc. (Zhou et al., 2019a). When sunlight passes through the transparent layer, the photovoltaic effect of the power generation layer first converts the solar energy into direct current and then into alternating current through the inverter, finally uses and stores the electric energy (Zha et al., 2016).

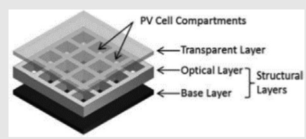
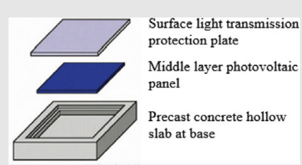
Many factors affect the efficiency of photovoltaic road power generation, including the structure of the road, the energy conversion efficiency of photovoltaic unit modules, the pavement laying method, the natural traffic environment, etc. Scholars from many countries have done some researches on it. The structure types of solar pavement and the conversion efficiency of solar panels are listed in Table 31. American engineers first proposed the concept of the solar road in 2006. The first solar parking lot was built in 2014, and a 13.9 m^2 square pilot project was built in 2016 (Hu et al., 2020c). Each solar panel can bear 1134 kN. When the road is wet, it can also ensure safe parking when the speed is about 120 km/h. Researchers from the University of Waterloo in Canada designed a three-layer solar road panel in 2012. The results show that the panel can bear traffic load and even improve the mechanical properties and service life of pavement structure (Northmore and Tighe, 2016). In 2014, the Netherlands Institute of Applied Sciences, in cooperation with Imtech and other companies, laid a 70 m long solar bicycle lane in Krommenie. The predicted annual maximum power generation of the bicycle lane is 93 $kW\cdot h/m^2$, and the measured value is 78 $kW\cdot h/m^2$. The analysis shows that these errors are related to bicycle shadow occlusion and operation loss (Shekhar et al. 2015). In 2016, 20 m was added to the 70 m length, and solar thin-film cells were embedded. The surface layer of toughened glass is replaced by the mixed coating of resin and glass particles, increasing the skid resistance and noise reduction performance. France has also studied solar pavement. In 2016, a 2800 m^2 solar road was built in Tourouvre, Normandy. The surface of the road is coated with transparent silicone resin and small glass particles, which have good performance of light transmission and skid resistance (Colagrande and D'Ovidio, 2020). The central solar cell is wrapped in a composite material composed of resin and polymer, which can pass through the wheel 1 million times without damage (Zhou et al., 2021a). Zha et al. (2016) started the research on the solar pavement in 2010, put forward the solar pavement model based on the hollow plate, and optimized the structure in 2017, which proved that it has good performance. In 2018, the first solar road in China was built in Jinan, Shandong Province. The length of the solar road is 1080 m, and the total area of the road is about 5875 m^2. The annual power generation is predicted to be 10^6 $kW\cdot h$ (Jiang et al., 2018). However, half a year after opening to traffic, part of the road was damaged.

5.1.2. *Pavement sensing function*

5.1.2.1. *Contact sensing device*. The contact sensing device must be embedded or inserted in the road, and come into direct contact with the physical quantity to be detected, so as to obtain the signal source. The main road contact sensing devices include temperature sensor, humidity sensing, stress sensing, strain sensing, salt sensing, etc. Tan et al. (2013) investigated the calibration technique and output characteristics of fiber Bragg grating (FBG) temperature sensor applied to asphalt pavement, and analyzed the influence of asphalt pavement rolling process on the calibration results of the embedded FBG temperature sensor. Abdel-Mooty et al. (1996) monitored the anti-reflective crack performance of pavement materials with FBG sensor. Feng et al. (2017) embedded stress, strain, temperature and humidity sensors on the asphalt pavement of Heda Expressway according to the experience of full-scale pavement burial in the United States, so as to obtain various dynamic mechanical responses and temperature and humidity data of the asphalt pavement and systematically evaluate the performance of the asphalt pavement. Zhang (2017) aimed at the problem of maximum principal stress and interlayer displacement which are difficult to monitor in the field of road engineering. He used 3D printing technology to design a sensor for maximum principal stress and interlayer displacement for roads, and then tested the sensor's stability and effectiveness in the lab. Zhou (2015) optimized and improved the circuit and system of the measuring module of the pavement salinity sensor to solve the existing problems. By establishing the temperature model of the salinity measurement module, the performance of the pavement salinity sensor was enhanced and accurate and effective data for real-time road monitoring of the pavement salinity were improved. Chen et al. (2007c) demonstrated a novel fiber optic sensor for simultaneous measurement of temperature and salinity with multiplexed polymer-coated fiber Bragg gratings. It has been found that the polyimide-coated fiber Bragg grating responds to temperature and salinity fluctuations, whereas the acrylate-coated fiber Bragg grating is just sensitive to the environmental temperature. The experimental results showed that the temperature and salinity sensitivities of the multiplexed fiber Bragg grating sensor are 0.0102 nm/°C and 0.0038 nm/%S, respectively.

In addition, common road contact sensing devices also include smart aggregate (SA) sensing, which is a piezoelectric sensor with a piezoelectric ceramic sensing element. Zhang et al. (2016a) studied the redistribution law of the internal strain and compressive stress of concrete embedded with smart aggregates under horizontal dynamic reciprocating

Table 31 – Different structure models of solar pavement.

Reference	Project	Picture	Pavement structure	Battery efficiency (%)
Hu et al. (2020c)	Solar roadways		Tempered glass + solar cell + tempered glass or fiberglass board	17.6
Northmore and Tighe (2016)	Solar pavement panel in Canada		Resin and glass particle coating + solar cell + resin and polymer substrate	17.6
Shekhar et al. (2015)	SolaRoad		Toughened glass or resin and glass particle coating + solar cell + concrete floor	12.1
Colagrande and D'Ovidio (2020)	Wattway		Resin and glass particle coating + solar cell + resin and polymer substrate	15.0
Zha et al. (2016)	Hollow slab of solar pavement		Organic glass panel + solar cell + precast concrete hollow panel	13.0
Jiang et al. (2018)	Jinan solar pavement		Resin and glass particle coating + solar cell + resin and polymer substrate	15.0

load. The tensile strength of concrete measured by experiment is consistent with that in theory. It is proposed that piezoelectric intelligent aggregate can monitor the process of concrete cracking, and the real-time monitoring of internal damage of concrete under dynamic load (Fig. 62) is important. Hou et al. (2014b) proposed to bury piezoelectric intelligent aggregate in asphalt concrete pavement to complete dynamic vehicle load monitoring. Through dynamic loading test study, it was found that the sensitivity of smart aggregate embedded in asphalt pavement was linear under dynamic vehicle load, which could be used to monitor dynamic vehicle load on pavement.

5.1.2.2. *Lidar based sensing technology*. As shown in Fig. 63, vehicle-borne multi-line lidar is generally utilized to collect road data, which is subsequently analyzed using a specialized algorithm to perform tasks such as road area division (Cremean and Murray, 2006; Zhang et al., 2018e), obstacle shape judgment (Huang et al., 2009), road boundary distinction (Cremean and Murray, 2006; Kammel and Benjamin, 2008) and road slope detection. Commonly used lidar is typically used to measures three-dimensional data, but one-dimensional lidar can also be used to sense the road cross-section length (Cremean and Murray, 2006; Kammel and Benjamin, 2008) and identify the lateral boundary of the road and some obstacles. Compared with three-dimensional radar, this kind of one-dimensional radar has a certain lag in recognizing obstacles (Hillel et al., 2014). Lidar algorithms are mainly divided into two categories: algorithms based on geometric features of laser point cloud and algorithms based on classification (Asvadi et al., 2016; Yan, 2017). Asvadi et al. (2016) used RANSAC algorithm to fit the road plane and extract the current driving road area based on the plane features of point cloud. Moosmann et al. (2009) and others realized point cloud plane segmentation in different regions based on local point cloud feature differences. Point cloud raster map was established, and Markov random field (MRF) was applied to the raster map for classification perception, taking full advantage of the relationship between adjacent point clouds (Byun et al., 2015; Guo et al., 2011). Compared with the detection method based on geometric features, the detection method based on classification has higher robustness and can adapt to a variety of complex terrain, but it has a large amount of calculation and poor real-time performance.

Fig. 62 – Intelligent sense aggregate (Jiang, 2013).

5.1.2.3. *Perception technology based on image/video stream*. In recent years, with the rapid development of image processing, computer vision and deep learning technology, and compared with other sensors such as lidar, vision sensor has the characteristics of low cost and rich image information, so the perception technology based on image/video stream has made great progress. Image/video stream sources mainly include industrial cameras, infrared cameras, global positioning system (GPS) satellite images and unmanned aerial vehicle (UAV) aerial images. Multiple cameras shoot the road from various angles, allowing for the acquisition of three-dimensional information of the road, realize stereo imaging, and perceptual effects comparable to lidar, such as obstacle recognition (Danescu and Nedevschi, 2009), edge detection (Chen et al., 2020a; Danescu and Nedevschi, 2009; Pradeep et al., 2012), and three-dimensional road geometry and slope estimation (Pradeep et al., 2012; Sach et al., 2009). Using a GPS can also obtain high-resolution image (Urmson et al., 2008), and can be converted into digital map and digital elevation model (DEM) for further analysis. Its accuracy

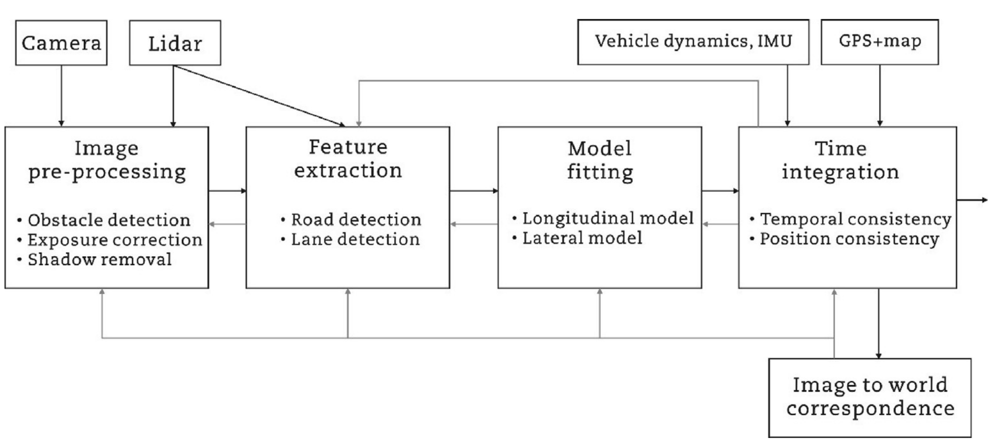


Fig. 63 – A generic system: functional decomposition (Hillel et al., 2014).

mainly depends on the link with the satellite (Caron et al., 2006; Yi, 2007). Using inertial measurement unit (IMU) can improve its accuracy (Pradeep et al., 2012; Urmson et al., 2008). Vision based road detection algorithms are mainly divided into two types, which are based on image features (He et al., 2004; Tan et al., 2006; Wang et al., 2014; Zhang et al., 2018e) and classifier (Chacra and Zelek, 2016; Zhou et al., 2010). The former is simple and easy to implement, but it is easily affected by illumination, occlusion and other factors. The latter relies on deep learning and has high accuracy, but needs a lot of parameter training and optimization.

5.1.2.4. *Temperature sensing*. The pavement materials with temperature sensing function mainly include phase change materials, thermochromic materials and thermoelectric materials. Temperature is one of the most critical elements affecting the performance of asphalt pavement (Agyenim et al., 2010; Huang, 2004). In recent years, some domestic scholars on the basis of heat energy storage technology, refer to the temperature-regulating mechanism of phase change material, mix asphalt mixture and use its latent heat of phase change to actively regulate the temperature of asphalt pavement, so as to prevent the asphalt pavement from heating up too fast due to too much heat absorption. The temperature-regulating mechanism of phase change material (PCM) is that it can absorb heat when it is radiated by high temperature, reducing the temperature of asphalt mixture. When the temperature of mixture is lowered to the crystallization temperature of PCM, the heat will be released (Lin et al., 2017c). Such multiple cycles will decrease the temperature of asphalt mixture and improve the high temperature stability of asphalt mixture. Tan (2021) prepared polyethylene glycol (PEG) 2000/silica sol phase change material and studied the influence of its ratio and dosage on the temperature-regulating effect of asphalt mixture. The results show that when the ratio of PEG 2000 to silica sol is 5:10 and the content is 3%, the phase change asphalt mixture prepared has good temperature regulating effect, and the road performance meets the requirements of the specification. Zhang et al. (2012d) tested and analyzed the heat storage capacity of a variety of phase change materials and the influence of the properties of phase change materials on the practical application of asphalt pavement according to the actual situation of asphalt pavement construction, and the results showed that PEG 4000 could be used as phase change heat storage material to be mixed into asphalt mixture. Ma et al. (2011) carried out a study on the application of organic phase change material in asphalt mixture. The results showed that the mixed organic phase change material has a certain temperature-regulating effect on the asphalt mixture, but it also has a certain influence on its pavement performance. As shown in Fig. 64, thermochromic material is the one whose color changes as the temperature rises (Li et al., 2018f, g). Each thermochromic material has a fixed transition temperature. Below this temperature, thermochromic materials are nonferrous materials with low solar radiation reflectivity. Above this temperature, they become colorless and show a strong solar reflection. This absorbing property helps keep the road temperature in a range that is beneficial to its performance (Li et al., 2018f; Zhang, 2017). In order to verify the temperature control effect of thermochromic materials, Yan et al. (2021) conducted indoor simulated illumination test of thermochromic modified asphalt pavement structure. The results show that the pavement structure with 5% thermochromic material has better performance in cooling in summer and heat preservation in winter than that of SBS modified asphalt pavement. After two rounds of thermal aging and ultraviolet aging, the temperature control effect of thermochromic pavement structure is still better than that of SBS modified asphalt mixture.

Thermoelectric material is a new type of material that converts heat into electricity by thermoelectric effect, which

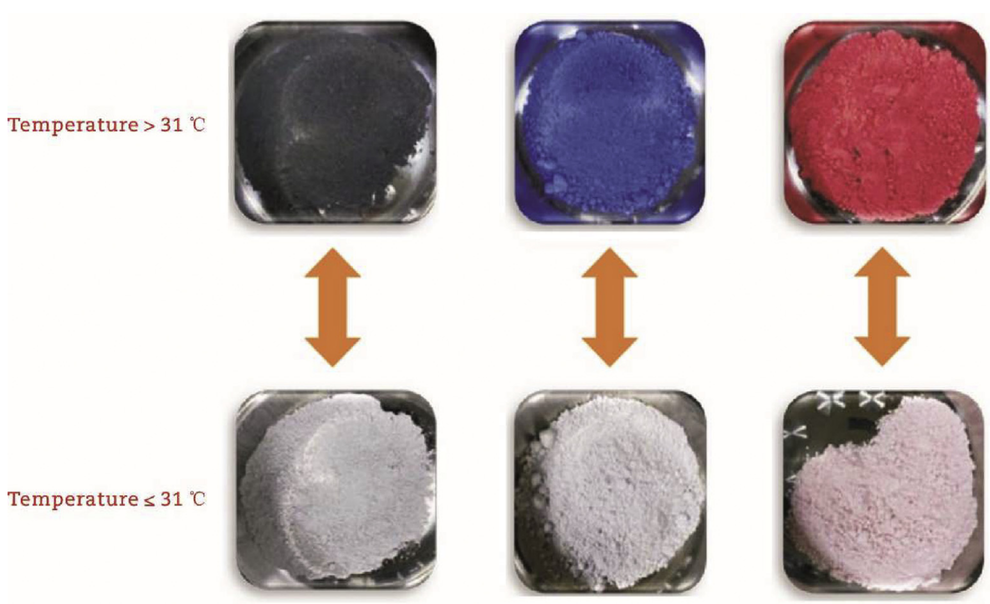


Fig. 64 – Thermochromic materials (Gao, 2020a).

has the effect of environmental protection and low carbon (Sha et al., 2020). Under the radiation of hot summer solar energy, the temperature of asphalt concrete pavement is up to 20 °C higher than the ambient temperature, and the asphalt pavement surface temperature is continuously up to 30 °C higher than the bottom of the pavement or even more. Thermoelectric materials are applied to asphalt pavement to convert thermal energy into electrical energy with the help of the thermoelectric materials inside the pavement based on the continuous temperature difference between above and below the pavement and between the road and the surrounding environment, which can not only reduce the energy consumption, but also alleviate the urban heat island effect (Loomans et al., 2003; Mallick et al., 2008a). Hu et al. (2014b) designed a thermoelectric power generation system for asphalt pavement using heat-conducting aluminum sheet instead of water flow pipe network as heat transfer body. The generation voltage of thermoelectric elements is shown in Fig. 65 (Li et al., 2015a). By constructing dynamic simulation models such as heat collecting mathematical model for asphalt pavement, heat transfer mathematical model for heat-conducting aluminum sheet and semiconductor thermoelectric power generation mathematical model, theoretical analysis and experimental study were carried out on the system. The results show that the heat transfer in asphalt concrete can be enhanced by using heat-conducting aluminum sheet as heat carrier, thus reducing the temperature gradient and thermal stress of pavement.

5.1.2.5. *Traffic detection based on ontology perception.* In the early 1990s, it was observed for the first time that adding short carbon fiber can improve the perceptual performance of ordinary concrete. By adding conductive phase materials to the matrix of road materials, the conductive phase materials are evenly dispersed in the matrix through effective dispersion and mixing technology to form a wide range of conductive network. The current can form percolation like current conduction through conductive network (direct contact of conductive phase materials) and quantum electron tunneling effect (spacing of conductive phase materials is less than 10 nm), so as to improve the electrical, magnetic, thermal and mechanical coupling characteristics of concrete (Han et al., 2015). When the concrete material is deformed or stressed, the conductive network inside the material will change, and the electrical properties of the material will also change. By monitoring these electrical and magnetic signal changes, people can play the role of real-time monitoring of road traffic conditions (Liu et al., 2021a). The collection of electrical signals usually involves the behavior of materials in various electric fields (direct current (DC) electric field and alternating current (AC) electric field with different frequencies). Under DC electric field, cement-based composites will produce obvious polarization phenomenon, which will affect the collection of electrical signals. It needs to be polarized for a period of time, and the influence of polarization under AC electric field is very small (Han et al., 2014; Öztürk et al., 2020). By adding different carbon based materials to concrete materials, including carbon nanotubes (CNTs), graphene nanosheets (GNP), carbon black (CB) and carbon fiber (CF), all cyclic loading and unloading processes can be successfully perceived (Al-Dahawi et al., 2017). The sensing signal collection system is shown in Fig. 66. On the road research facility of Minnesota (MnROAD), the prefabricated and cast-in-place self-sensing CNT concrete sensors are integrated into the pavement test part at the same time which can realize real-time vehicle flow detection with high detection rate and low false alarm rate (Han et al., 2013). Compared with device sensing, ontology sensing has the advantages of long-term durability and good compatibility with concrete structure. However, there are still many deficiencies in structural design, evaluation

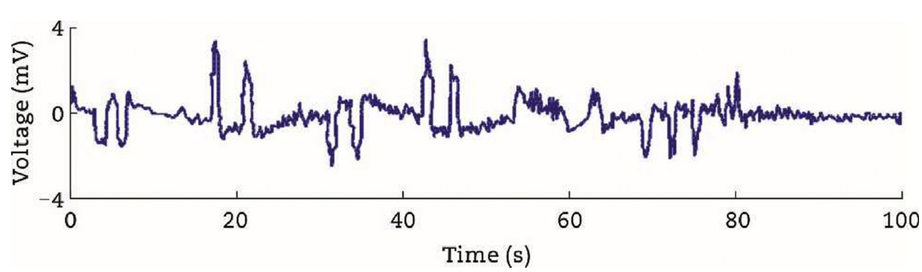


Fig. 65 – Voltage diagrams generated by testing thermoelectric components (Li et al., 2015a).

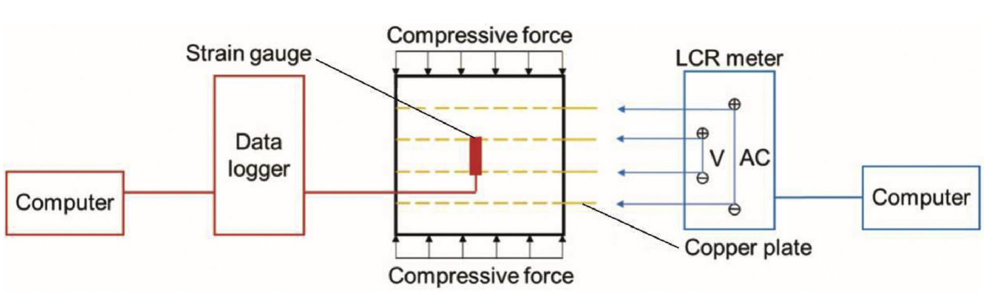


Fig. 66 – Working principle diagram of ontology sensing concrete (Al-Dahawi et al., 2017).

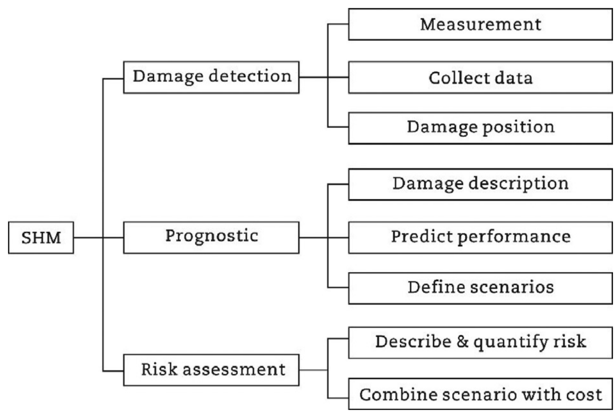


Fig. 67 – SHM functionalities (Doghri et al., 2021).

criteria and model construction, which need further research.

5.1.2.6. *Structural health monitoring based on ontology perception*. With the continuous growth of road structure, under the comprehensive influence of vehicle load and external environment, the integrity of the structure continues to decline, resulting in pavement diseases will have an impact on road safety. Therefore, it is very important to monitor the integrity of road structure based on structural health monitoring (SHM). SHM system usually includes three functions: damage detection, prognostic, and risk assessment (Fig. 67). The common SHM technology is to obtain the real-time data of the structure by installing sensors such as optical fiber, strain gauge and piezoelectric strain sensor into the structure (Li and Ou, 2009). Optical fiber sensor is an ideal choice for SHM at present, because it has the characteristics of wide measurement range, high sensitivity, good durability, good stability, small volume, and is less affected by the external environment (López-Higuera et al., 2011). Although the sensor components such as strain gauge and piezoelectric strain sensor have appropriate structural health monitoring accuracy, the installation quantity of these sensors is limited, and the monitoring accuracy is easily affected by the environment, so there are great limitations in use (Glisic and Inaudi, 2012). The ideal solution is to transform the whole road structure into a self-sensing system similar to the biological nervous system. Conductive concrete materials with self-sensing function are made possible by adding conductive phase materials such as carbon fiber (CF), carbon nanotube (CNT) or graphene nanoflake (GNP) to the pavement materials. For example, it is found that the conductive concrete with CNT has higher detection accuracy, wider detection range and excellent robustness than the strain gauge, which can resist the polarization inside the concrete and the change of external environment (Han et al., 2013). It is considered that adding CNT and CF to concrete properly can make up for the high cost of CNT and the inability of CF to measure high strain (Yildirim et al., 2018). It is found that conductive concrete with high mechanical properties, high microstructure properties and high durability can be prepared by using CNT and GNP (Abedi et al., 2020). The electrical properties of road materials can not only realize the self-monitoring of road structure, but also sense the road traffic conditions. Therefore, building SHM system based on ontology perception is one of the main research contents of SHM technology. However, it is still in the preliminary experimental stage, and further research on conductive concrete materials, evaluation standards and design theory is needed.

5.1.3. *Road adaptation and adjustment function*

5.1.3.1. *Radiation reflective pavement*. Urban heat island effect refers to an increased temperature in urban areas compared

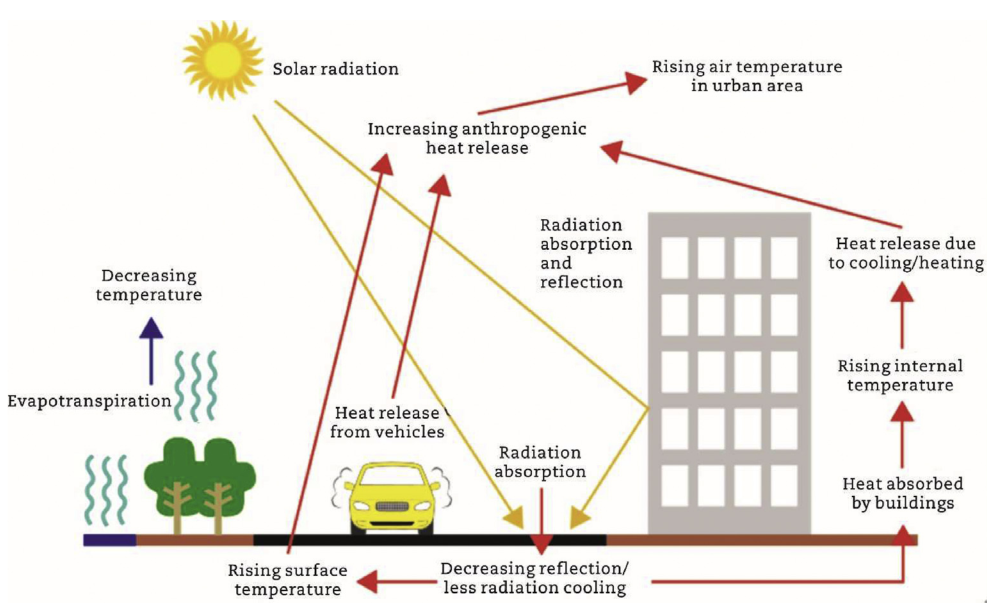


Fig. 68 – Mechanism of the rising air temperatures in urban areas due to an increasing anthropogenic heat release, especially the increased absorption of solar energy (Mohajerani et al., 2017).

to its surrounding rural areas (Fig. 68). The increased temperature is mainly caused by the transformation of natural ground into artificial surfaces and the resulting increase of solar radiation absorption (Mohajerani et al., 2017; Rizwan et al., 2008; Santamouris, 2007). Especially asphalt pavements have a high solar absorption and thermal mass for energy storage (Aletba et al., 2021), increasing the surface temperature of the pavement and in turn increasing the surrounding air temperature. Different strategies have been developed and researched to mitigate the urban heat island effect. The strategy of cool pavements can significantly reduce the surface temperature and hence, reduce the air temperature in urban areas. A reduced surface temperature can be achieved through heat storage modified pavements, evaporative pavements and reflective pavements (Anupam et al., 2021).

Reflective pavement has higher solar reflectance characteristic (albedo). A higher reflectance entrails a lower absorption of radiation energy, which is converted into thermal energy. Hence, the pavement structure remains cooler. As Fig. 69 shows, since the asphalt mixture design has no significant influence on the surface temperature due to radiation in dry conditions (Aletba et al., 2021), various strategies have been developed to increase the reflectance of asphalt road surfaces.

A promising strategy is the application of the reflective coating on the pavement surface. Light colored surfaces reflects mainly visible light. Brighter colors exhibit a higher reflectance than darker colors. A temperature reduction of 10 °C was achieved through pink colored coating (pink pigments embedded in an epoxy resin) (Zheng et al., 2015). Red colored coating showed the least significance in temperature reduction (Carnielo and Zinzi, 2013). In addition of reducing the surface temperature, the energy consumption of street lighting can be reduced and driving safety is increased due to an increased visibility at night (Hussain et al., 2021; Li et al., 2016d; Wang et al., 2021f). The driving safety advantage is limited to the occurrence of driving glare for bright color, requiring a balance between surface temperature reduction and driving safety (Wang et al., 2021f). Increasing the reflectance in the near infrared region through TiO_2 particles in the coating is potential mitigation of the driving glare issue (Xie et al., 2019). Another option is to utilize retro-reflective pavements, which reflects light back in the same incidence angle (Rossi et al., 2016). Additionally, retro-reflective pavements prevent the surface temperature of surrounding objects to increase, which occurs for reflective pavements due to multi-directional radiation reflection. The environmental impact of reflective coatings is similar to other surface treatment methods like slurry seal and overlays (Li et al., 2016d). However, an increase in durability is necessary to further advance reflective coated pavements. The lack in durability is mainly attributed to the different mechanical response of asphalt binder and resin used in the reflective pavement coating (Li et al., 2016d; Sha et al., 2017; Xie et al., 2020b).

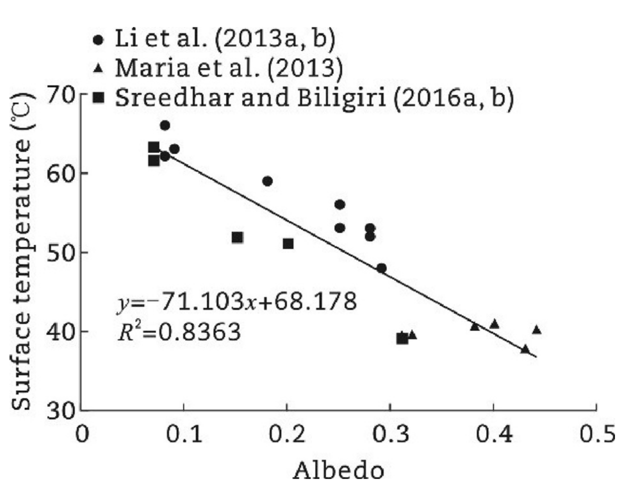


Fig. 69 – Relationship between albedo and pavement surface temperature (Aletba et al., 2021).

Adding pigments or translucent aggregates to the binder or asphalt mixture can increase the albedo of the paved surface (Balan et al., 2021; Xie et al., 2019). Thermochromic materials are able to change colors due to a change in temperature. The addition of thermochromic materials to binder revealed a temperature reduction proportional to the dosage of thermochromic material. The highest temperature reduction occurred at the bottom of the top bituminous layer (Hu et al., 2015; Li et al., 2020b).

A concern regarding the durability of reflective pavements is the change in the solar reflectance characteristics due to natural weathering and tyre interactions. The albedo of an asphalt surface increases by about 0.1 due to a weathering induced color change. Whereas concrete surfaces show the opposite effect and become darker (0.25) with time (Aletba et al., 2021; Hu et al., 2015). Colored and white surfaces lose about 5% and 10%, respectively, due to the weathering process (Xie et al., 2020b). Long-term effects of reflective pavements on the urban heat island effect are still missing to determine the effect of weathering and traffic on its performance.

5.1.3.2. *Catalytical degradation of vehicle exhaust gases on pavement surface*. The increasing number of vehicles on roads causes an increased emission of exhaust gases. The combustion process mainly emits carbon dioxide (CO_2). However, due to incomplete combustion and the high heat, carbon monoxide (CO), volatile organic compounds (VOCs) and nitrogen oxides (NO_x) are emitted, which are major pollutions of cities (Jia et al., 2021; Kovács et al., 2021). These emissions are directly related to health issues like respiratory and cardiovascular diseases and environmental damage like acid rain (Kotowski et al., 2020; Pang et al., 2021). Air pollution reduction measurements commonly addresses traffic, aiming to reduce pollutant concentrations below a limit values. Since in urban environments the air quality is largely influenced by local traffic conditions, traffic restrictions are an effective measurement (Jia et al., 2021; Santos et al., 2020). However, increasing traffic and public pressure on political legislation can moderate the effectiveness. Additional measures to traffic reduction and catalysts at the source of pollutant emission are photocatalytic surfaces in urban environments. As a relative near structure to the emission source, pavements can be functionalized to degrade vehicular exhaust gases to reduce environmental pollution.

Different photocatalysts like titanium dioxide (TiO_2, mainly anatase structure), zinc oxide (ZnO), iron oxide (Fe_2O_3), copper oxide (Cu_2O), and cadmium sulphide (CdS) are efficient in degrading air pollutants emitted by vehicles (Chen and Liu, 2010; Hu et al., 2021). Among them, titanium dioxide is widely used as photocatalysts due to mild reaction conditions, low energy consumption, low costs, easy access, environmental friendliness and minor generation of secondary pollutions (Chen and Liu, 2010; Guo et al., 2019c).

The titanium dioxide has a bandgap of 3.2 eV and an electron-hole pair is induced though radiation in the ultraviolet (UV) region ($\lambda < 387$ nm). The transfer of charges at the surface of the catalysts accelerates natural chemical reaction (Guo et al., 2019c). Hence, due to the presence of water, the molecules on the catalyst surface produce hydroxyl radicals, which have a high oxidation potential (Ren et al., 2021a). This radical oxidise carbon monoxide and volatile organic compounds to carbon dioxide and water, removes nitrogen oxides by the formation of nitrous and nitric acid and is part of the tropospheric ozone generation.

Different procedures have been developed to incorporate the catalyst in pavements (Fig. 70). The application as coating is independent from the underlying road material, requires less catalytic material, can be integrated in surface maintenance methods, and has a potential higher photocatalytic efficiency (Osborn et al., 2014; Zhang et al., 2021h). The incorporation in maintenance methods, such as fog seal, slurry seal and sprays, is a cost efficient way as lower quantity of catalyst are required compared to incorporation in surface wearing course. However, due to the abrasion of the pavement surface and deposition of dust, the efficiency declines with time. A reduction to 50% efficiency was observed after about 2.5 months of service for spray applications with a service life of 10 to 16 months for asphalt pavements (Osborn et al., 2014; Wang et al., 2017b). In contrast, the modification of asphalt binder with catalysts ensures a constant degradation of pollutants, as the material is distributed throughout the surface layer, giving a longer duration to the functionalised pavement (Fan et al., 2018).

The degradation efficiency of photocatalytic surfaces depends on the weather conditions, radiation and catalyst content. High degradation efficiencies for all air pollutant are found in laboratory studies. The efficiency increased with increasing catalyst content until about 5% to 7% was reached, afterwards no significant improvement was detected (Carneiro et al., 2013; Hu et al., 2021; Zhang et al., 2019, 2021h). The efficiency can be improved by doping titanium dioxide to modify the bandgap. These modifications allow to utilise different radiation wave lengths, with the aim to shift the bandgap into the visible light region. The doping with transition metals, especially iron as non-toxic element, or nitrogen, enhanced the sensitivity to visible light, and allow the application of the photocatalytic pavement surface in tunnels, as the artificial spectrum of the illumination is different compared to the solar spectrum (Hu et al., 2021; Zhang et al., 2021d).

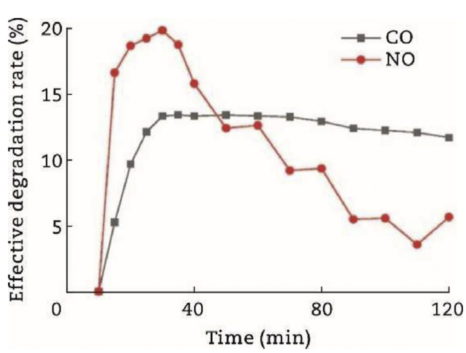


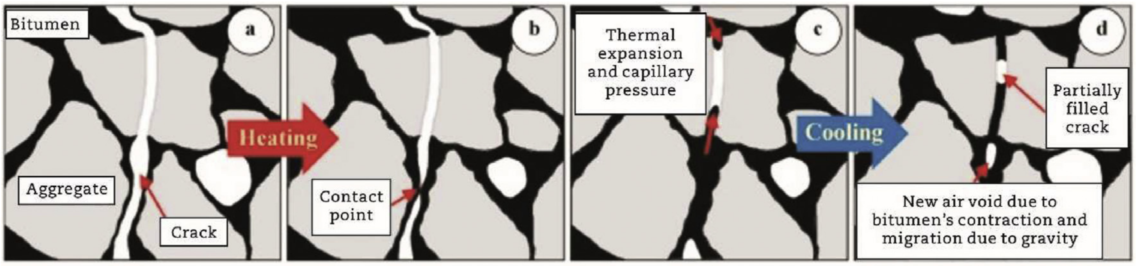
Fig. 70 – Effective degradation rate of asphalt containing 5.7 wt.% nitrogen doped titanium dioxide (N-TiO_2) in the removal of CO and NO exhaust gases (Zhang et al., 2021h).

Adding titanium dioxide to the asphalt binder positively affects the binder's ageing process. The ageing process is slowed down through high reflectivity and absorption of UV radiation and interaction with atmospheric radicals. Furthermore, titanium dioxide is used for the production of self-cleaning materials, due to the degradation of organic matter, similar to the degradation of volatile organic matter. Water rinsing removes contaminations on the catalyst's surface and restores initial degradation efficiency (Carneiro et al., 2013; Cheraghian and Wistuba, 2020; Qian et al., 2019b). To ensure that the inorganic catalyst adheres better to asphalt surfaces, silane coupling agents are used to improve the bonding (Hassan et al., 2013; Liu et al., 2015c).

Field measurements of the photocatalytic efficiency shows a high variability ranging from 0 to 56%. The reason for the discrepancies within field studies and to laboratory studies is that field studies are performed under different conditions and sampling. A mean effectiveness of 2% to 4% was estimated, attributed to the low proportion of pollutant air in direct contact with the pavement surface (Cordero et al., 2021; Fernández-Pampillón et al., 2021; Toro et al., 2016).

5.1.3.3. *Self-healing pavement*. Asphalt pavements are deteriorating faster due to the accumulation of damage caused by the increasing traffic volume. In addition, an ageing road network requires increased maintenance for its functional operation. Approximately half of the produced asphalt is consumed in maintenance, contributing to the depletion of primary materials. An environmental and economic beneficial solution to prolong the service life of asphalt roads is the utilisation of asphalt's self-healing ability. Self-healing is the ability to repair damaged areas and/or recover lost or diminished functionalities through using inherent resources. The origin of self-healing in asphalt is due to its binder, which is responsible for the viscoelastic behaviour and has fluid characteristics at higher temperatures. Self-healing is the direct response to damage and is influenced by asphalt mixture composition (filler and fine aggregates, binder type and content), traffic (damage degree and rest period), pavement condition (ageing degree) and environmental conditions (temperature and moisture).

The main investigated distress type in regards to self-healing is the cracks. As shown in Fig. 71, the closure of cracks is mainly governed by the viscosity of the binder and partly by pressure, either internal due to thermal expansion or external



Assembling of the beam halves. Initial adhesion is caused by initial contact points.	During heating, contact points are created as bitumen and to a minor degree aggregates expand. The start of bitumen flow, draining into the crack.	Further heating increases the pressure due to thermal expansion and enhances the flow of bitumen into the crack.	During cooling, bitumen contracts. Thus, new air voids can be created.

Fig. 71 – Illustration of the self-healing process induced through heat to decrease binder viscosity and utilise thermal expansion (Grossegger and Garcia, 2019a).

due to a compressive force (Grossegger and Garcia, 2019a). The closure of cracks was observed on different scale levels, ranging form nano to macro scale. At the bitumen scale, the binder's viscosity and the gap width affected the closure speed (Shen et al., 2016). Similar results of crack closing were observed at the meso scale in asphalt mastic (Lyu et al., 2017). Recently, it was theorised that the increasing crack volume due to fatigue damage and the crack volume closed due to healing induce an optimum moment to achieve a maximum self-healing efficiency. The optimum moment would occur in a range for an asphalt mixture, due to the variability in damage and healing for individual samples (Grossegger, 2021).

The loss of stones from the asphalt surface, known as ravelling, is initiated by micro cracks occurring in the mastic surrounding the stone. It shows that self-healing could reduce the ravelling of porous asphalt pavements. As shown in Fig. 72, the amount of material lost during Cantabro loss tests was reduced for interruptive healing events compared to standard testing (Liu et al., 2014). However, the already lost material could not be restored, leading only to a deferral of the ravelling process. This delay was observed for inductive heating test sections as well (Lizasoain-Arteaga et al., 2019).

Moisture accelerates the degradation of the asphalt pavement and has an ambiguous influence on self-healing. Since water and bitumen have similar densities, water filled cracks prevents the surrounding binder to drain into the crack to close it, thus inhibiting the self-healing of asphalt. The prevention of self-healing was observed in asphalt mastic and on bitumen layers between solid surfaces for instantaneous and long-term healing. Self-healing, measured through binder bond strength test, was enhanced for short-term healing of 4 to 94 h for bitumen layers (Lyu et al., 2017). In asphalt mortar, a slight enhanced healing was observed during water evaporation, due to a faster evaporation in the crack area and the resulting increased hydrostatic pressure of water filled pores. Moreover, stripping of binder due to moisture is partly reversible during water evaporation (Grossegger and Garcia, 2019b).

Permanent deformation are mainly due to volume change and to a minor degree due to shear related deformation. Since permanent deformation are considered irreversible, self-healing is assumed to not be able to reverse the process. However, due to intermediate resting, residual strain is reduced by up to 30% (Sarsam and Husain, 2018). This reduction mitigates further deformation and reduces the occurrence of rutting, which prolongs the service life of the asphalt pavement. A reversing effect to volume reduction occurred during induction heating (Garcia et al., 2020). Induction heating induced self-healing increases the temperature locally with the main purpose to specifically decrease the viscosity of the binder. The increase in temperature causes thermal expansion and degradation of the binder. These two mechanisms cause a reduction of the grain to grain contact area and an increase of void volume and smaller air voids. It is still unknown if the increase in void content is reversing the deformation and how it effects the service life.

Since natural self-healing is a slow process and requires temperature above a threshold to occur. Different self-healing methods are developed to enhance the self-healing of asphalt. The enhancement is based on the binder's viscosity reduction to increase the self-healing rate and self-healing efficiency. Reducing the viscosity is achieved through either increasing the temperature or adding viscous oleaginous liquids to blend with the binder by diffusion. Two promising and common researcher methods to increase the asphalt temperature are induction and microwave heating (Norambuena-Contreras and Garcia, 2016). Both methods require conductive material, distributed throughout the mixture, to convert transmitted energy to heat. Common used materials are steel fibres, metal girt or recycled materials such as blast sand from steel cleaning or steel slag with a sufficient amount of metal remaining. These conductive materials often increase the price of the mixture. Reducing the binder's viscosity by diffusion of low molecular oil requires a suitable storage system (Li et al., 2021d). Capsule or vascular

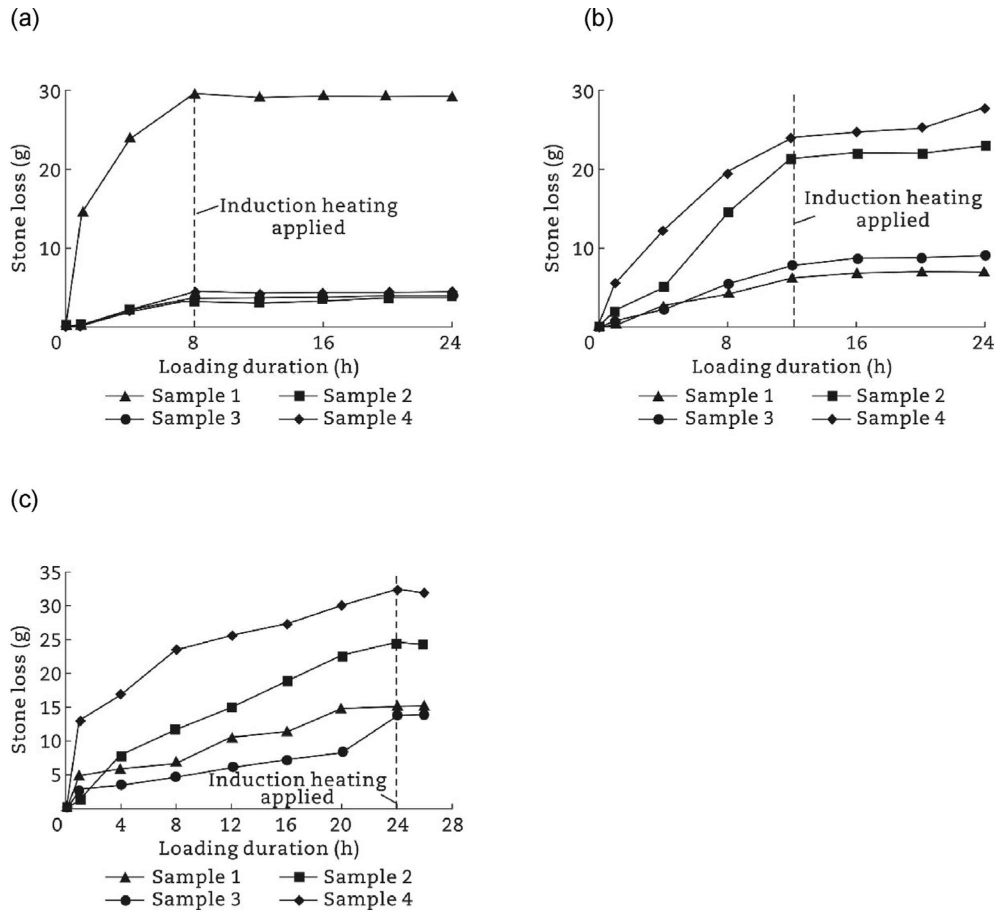


Fig. 72 – Stone loss of four samples with induction heating applied after different duration of loading (Liu et al., 2014). (a) 8 h. (b) 12 h. (c) 24 h.

network based approaches are used to distribute oil storing reservoirs. Different capsule production methods, shell materials and liquids are used in the production of the self-healing enhancing system (Li et al., 2021d). The diversity allows to create a system that response to a specific damage form or releases the oil at a specific damage stage. Multi-layer or multi-cavity capsules can be used in several healing events. The usage of low-molecular oil also has the function of a rejuvenator, compensating the fractional changes during ageing (increased molecular weight and polarity) (Xu et al., 2021b). However, production price, storage stability and passive trigger of capsule based self-healing are a disadvantage of this self-healing enhancement. To actively trigger the release of oil, compaction methods can be used. The combination of induction heating and capsules has the advantage that the increased heat increases the diffusion of the oil to reduce the binder's viscosity, which continuous healing after the temperature reverts to ambient conditions. In addition, the rejuvenating properties of the oil mitigates any enhanced ageing processes caused by the locally generated high temperature (Xu et al., 2020a). Other combination to enhance the self-healing and mitigate negative effects are researched like heating and re-compaction to further advance this technology (Gallego et al., 2021).

5.1.4. *Summary and outlook*

Energy harvesting pavement is a technological innovation for the development of the transportation infrastructure industry towards smart green roads, which will have great potential in the future. At the same time, the technology still needs further development. It is necessary to improve the harvesting efficiency of the pavement. For example, traditional piezoelectric materials are harmful to the environment, accelerating the development and application of lead-free piezoelectric materials. Thermoelectric materials with high thermoelectric properties should be developed. On the premise of ensuring the anti-skid texture of the surface, the transmittance of the solar road should be improved. The corresponding energy harvesting circuit should be improved, according to the energy harvesting characteristics of different roads, such as the characteristics of high voltage and low current of piezoelectric pavement, the low energy density of thermoelectric pavement, and random variation of power generation capacity of solar road. It is necessary to form a complete construction process of energy harvesting pavement, forming the integrated design method of material and structure of piezoelectric pavement, looking for high thermal conductivity device suitable for pavement structure, as well as improving the on-site construction, operation, and maintenance methods to reduce the failure rate and maintenance loss of solar pavement components.

At present, it is a common way to improve the road sensing ability to embed the contact sensor device into the road surface, which is mainly used to measure the road temperature, humidity, stress strain, salt and other indicators. Non-contact sensing devices are mainly used to sense the alignment, obstacles and surface defects of the road, and cannot sense the internal stress and temperature of the road structure, etc. For non-contact sensing, various non-contact sensors should be applied according to the actual road conditions to enhance the sensing accuracy. Materials with temperature sensing function, such as phase change materials, color-changing materials and thermoelectric materials, all have problems affecting the mechanical properties of asphalt mixture and cement concrete. The next step is to explore the layout form and structure combination of asphalt pavement structure, and gradually reduce its influence. The ontology-sensed concrete is still in the preliminary test stage, and further research on the material, evaluation criteria and design theory of ontology-sensed concrete is needed. In the future, nanotechnology, microelectronics, artificial intelligence, 3D printing and concrete digital manufacturing will be associated with ontology-sensed concrete, which will help improve the overall performance of ontology-sensed concrete and transform the entire road structure into a self-sensing system similar to the biological nervous system.

5.2. *Renewable and sustainable pavement materials*

This section introduces the latest achievements of solid waste recycling, including reclaimed asphalt pavement materials, construction and demolition waste, solid industry waste and waste tire rubber in asphalt pavement construction. The greenhouse gas (GHG) emission, energy consumption and VOC emission will also be discussed in this section.

5.2.1. *Reclaimed asphalt pavement*

Asphalt pavement represents an important asset for prosperity and daily life in both developed and developing countries (Cheraghian et al., 2020). However, asphalt pavement tends to be gradually deteriorated during its service life due to the effect of traffic load and environment (Mehranfar and Modarres, 2018; Wei et al., 2017). As a result, a large number of asphalt pavements requires preservation, maintenance even rehabilitation to ensure their good service index. Asphalt pavement rehabilitation contributes a considerable amount of waste produced each year. It is estimated that approximately 790 million tons of reclaimed asphalt pavement (RAP) were produced per year in China. In this context, there is an urgent demand to efficiently dispose RAP to minimize its adverse effect on the environment. Nowadays, recycling of RAP is the most efficient and economical disposal technology of RAP in the asphalt pavement industry because it can greatly reduce virgin pavement materials and costs in pavement construction and rehabilitation (Hajj et al., 2008; Shrestha, 2009; Zheng et al., 2021; Zhu et al., 2020b). Generally, RAP recycling technologies can be divided into hot recycled mixture (HRM) technology, warm recycled mixture (WRM) technology and cold recycled mixture (CRM) technology according to their different construction temperatures (Sukhija and Saboo, 2021).

5.2.1.1. *Hot recycled mixture technology*. The HRM technology include hot in-plant recycled mixture technology and hot in-place recycled mixture technology (Du et al., 2019). HRM is composed of RAP, virgin aggregates, rejuvenating agent and new asphalt. Its production process is similar to that of new hot mix asphalt. Accordingly, its performance can be almost equal to that of new hot mix asphalt, especially for hot in-plant recycled mixture. As a result, HRM can be suitable for the treatment of most of pavement diseases and also all layers in pavement structure.

Although the performance of HRM is satisfactory to reach the requirement of all layers in pavement structure, there are still many challenges in the application. The first challenge is how to control the quality of RAP. RAP shows variability in composition, such as gradation, binder ratio, etc. (Gao et al., 2021; Li et al., 2019b; Shirodkar et al., 2011; Sreeram and Leng, 2019; Zaumanis et al., 2018). Therefore, the properties of RAP should be well characterized to minimize the variability of HRM. It is recommended that five to ten samples be collected and tested from each RAP stockpile to characterize the RAP. Besides, the asphalt content and gradation of each sample should be checked (Newcomb et al., 2007). The second challenge is the RAP utilization rate. Due to the milling and crushing operations of RAP, excessive fines can be generated so that the RAP gradation may be significantly different from its original gradation (Zaumanis et al., 2018). This may increase the risk of the variability of HRM, thus potentially limiting the amount of RAP. Besides, the HRM with high amounts of RAP can be excessively stiff, brittle, and prone to cracking (Shirodkar et al., 2011; Sreeram and Leng, 2019). To improve these performances, more rejuvenating agents are needed to activate the aged asphalt. However, the high rejuvenating agent content may reduce the road performance, especially high temperature stability (Ahmed et al., 2021; Devulapalli et al., 2020; Dony et al., 2013; Song et al., 2018). The final problem about HRM is high emission. The production temperature of HRM is normally 5 °C–15 °C higher than that of traditional hot mix asphalt (Li et al., 2021e; Ma et al., 2020b), thus more harmful gases can be produced during construction (Mazumder et al., 2016; Stimilli et al., 2017). Besides, the high production temperature may make the RAP secondary aging, which may be harmful to the performance of HRM.

5.2.1.2. *Warm recycled mix asphalt technology*. To reduce the carbon emission and energy consumption of HRM, WRM technology, which combines the regenerative asphalt technology and warm mix asphalt technology, is proposed in pavement engineering. Essentially, the difference between WRM and HRM is that the production temperature of WRM can be reduced by approximately 20 °C–60 °C due to the effect of warm mix additive. Because of the relatively lower production temperature, WRM technology can save energy from 18% to 30% compared to HRM technology (Almeida-Costa and Benta, 2016). In addition, lifecycle cost assessment studies show that WRM technology can reduce costs by 10%–30%

according to different technologies (Saboundjian et al., 2011). At present, various technologies have been developed to produce the warm mix asphalt (Goh and You, 2009; Oliveira et al., 2013; Xiao et al., 2012c), including organic additives, chemical additives and foaming (Alimohammadi et al., 2021; Cheraghian et al., 2020). The warm mix additives can reduce the viscosity of asphalt binder at the production temperature range, thus the compatibility and workability of WRM are greater than HRM. This characteristic is very helpful to the paving and compaction of WRM (Hettiarachchi et al., 2019; You et al., 2011b). Because of this characteristic, the RAP content of WRM can be higher than that of HRM.

Although the WRM technology has been widely used in pavement rehabilitation and construction, there are still some issues to be solved in the application. Because of the low production temperature, the RAP and virgin aggregates may retain some water so that the water stability of WRM should be carefully concerned (Guo et al., 2014). Besides, many scholars believed that more RAP can be utilized in WRM compared to HRM due to its lower production temperature (Frigio and Canestrari, 2016; Stimilli et al., 2017), however, its low-temperature performance and fatigue life can be degraded if more RAP is added (Ameli et al., 2016; Babagoli et al., 2021; Huang et al., 2013).

5.2.1.3. *Cold recycled mixture technology*. As mentioned above, HRM and WRM technologies have been widely used in pavement engineering. Their overall performances can be nearly equal to those of traditional asphalt mixture. However, the amount of RAP should be limited in these two technologies to obtain the desirable performances. In this context, CRM technology is proposed to maximize the amount of RAP. Compared with HRM and WRM, CRM is an more environment-friendly and economic recycling technology. It can maximize the amount of RAP to be recycled and minimize carbon emissions and energy consumption due to its low construction temperature (Day et al., 2019; Meocci et al., 2016). The utilization rate of RAP in CRM is normally between 70% and 100% (Flores et al., 2020; Lin et al., 2017a; Rodríguez-Fernández et al., 2019; Wang et al., 2021g). According to the different binder types, CRM technologies can be divided into CRM with foamed asphalt and CRM with asphalt emulsion. Some investigations indicated that the overall performances of CRM with asphalt emulsion are superior to those of CRM with foamed asphalt (Dash, 2013; Ren and Zhu, 2015). Therefore, only CRM with asphalt emulsion is reviewed in the following part.

(1) Strength and performance of cold recycled mixture with asphalt emulsion

The strength and performance of cold recycled mixture with asphalt emulsion (CRME) can greatly dominate its application scope and service life in the application, thus it has been extensively studied after this material was reported. Cement is normally added into CRME to improve its performances, such as early strength, permanent deformation resistance, water stability, etc. (Grilli et al., 2012; Lin et al., 2018; Niazi and Jalili, 2009). Due to the reinforcement effect of cement hydrates on asphalt binder (Wang and Sha, 2009), CRME can have higher residual modulus and dynamic stability (Al-Hdabi et al., 2013; Baghini et al., 2015; Oruc et al., 2007), thus CRME has a satisfactory rutting resistance. However, cracking issue is easily occurred in the application of CRME due to its low tensile strength and low ductility. The indirect tensile strength of CRME is much lower than that of hot mix asphalt in most studies (Bocci et al., 2011; Graziani et al., 2016; Grilli et al., 2016; Kavussi and Modarres, 2010; Meocci et al., 2016; Niazi and Jalili, 2009). Besides, the indirect tensile strength (ITS) of CRME also shows high moisture susceptibility. The conditioned to unconditioned ITS ratio is normally lower than 0.7 (Du, 2018; Ouyang et al., 2020). Overall, CRME has lower performance compared to HRM and WRM, especially in cracking resistance.

Due to the low tensile strength, CRME has a relative low cracking resistance. To improve the cracking resistance of CRME, factors influencing the mechanical and pavement properties of CRME were intensively investigated in the past, such as the gradation type, asphalt emulsion content, the additional water content, the cement content and cement types, filler types, curing condition, and compaction method (Al-Hdabi et al., 2013; Bocci et al., 2011; Du, 2018; Fang et al., 2015; García et al., 2012; Graziani et al., 2016; Grilli et al.,

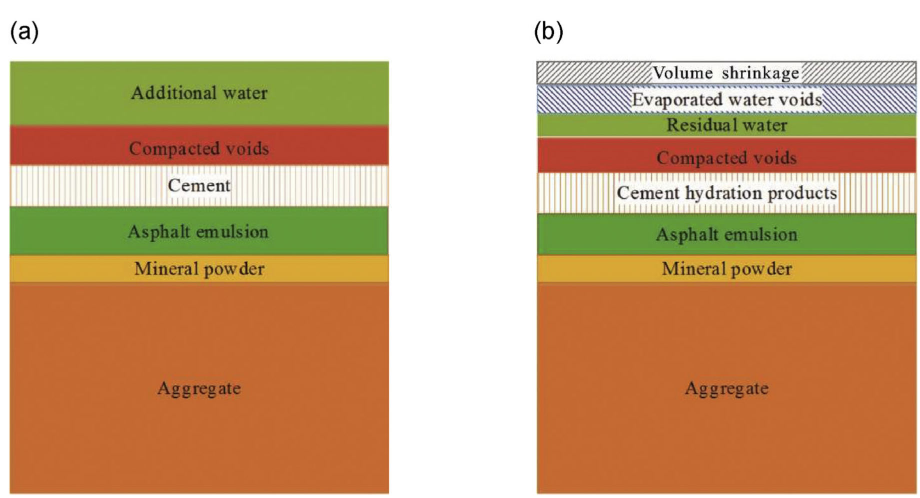


Fig. 73 — Volumetric composition of CRME. (a) After compaction. (b) After curing.

2016; Kavussi and Modarres, 2010; Lin et al., 2015; Miljković and Radenberg, 2014; Ouyang et al., 2014a; Wang et al., 2018c; Zhu et al., 2019a). Comparing the results, it can be found that increasing cement content is the most efficient method for increasing the tensile strength of CRME. However, the ductility of CRME can be greatly degraded (Ouyang et al., 2014a), which can be greatly harmful to the cracking resistance of CRME. Therefore, the upper cement content in CRME is usually no more than 2%. In short, there is still a growing need to improve the mechanical properties of CRME to promote the use of RAP.

Because of the relative low pavement performance, CRME is normally used in the base and sub-base layers in motorway. The low performance of CRME is attributed to two reasons. Firstly, the void content of CRME is very high (>8%) (Ouyang et al., 2014a). As shown in Fig. 73, water is acted as lubricant in CRME during compaction (Yang et al., 2021b). However, water can be evaporated during curing to leave voids in hardened CRME. As a result, the high void content is a feature of CRME compared to HRM and WRM. Secondly, the adhesive ability of asphalt emulsion residue can be lower than that of traditional hot mix asphalt. Hot asphalt is a low-viscosity fluid. It can easily penetrate to the surface texture of aggregate and coat aggregate well. However, asphalt droplets are difficult to penetrate to the surface texture of aggregate. As a result, asphalt emulsion mastic may have a poor bonding interface with aggregate (Ouyang et al., 2019).

(2) Variability analysis of asphalt emulsion

Compared to HRM and WRM, except for the relative low performances, CRME also shows larger variability in performances. The performance variability of CRME can be due to the variability in RAP and asphalt emulsion. In the aspect of RAP properties, because the RAP content of CRME is higher than that of HRM and WRM, the aggregate gradation of CRME is more difficultly controlled than that of HRM and WRM. In the aspect of asphalt emulsion, the properties of asphalt emulsion, such as demulsifying behavior, drying behavior, properties of residue and film formation structure, can greatly affect the workability, hardening rate and mechanical properties of CRME. Compared to the issue of the variability of RAP, the properties of asphalt emulsion is more difficult to be understood by pavement scholars and engineers, thus they are reviewed in this paper.

The demulsifying behavior of asphalt emulsion can greatly affect the workability and mechanical properties of CRME. To better utilize asphalt emulsion in CRME, the demulsifying behavior of asphalt emulsion was extensively studied. Generally, the demulsifying behavior of asphalt emulsion is both the reactivity of filler and the chemical stability of asphalt emulsion (Acevedo et al., 2001; Fang et al., 2016b; Ouyang et al., 2018; Wang et al., 2009, 2013a; Ziyani et al., 2013). As shown in Fig. 74, it was proved that there are two demulsifying behaviors when asphalt emulsion is mixed with fine solid (Ouyang et al., 2018). One is asphalt droplet coalescence. The other is the direct droplet adhesion on solid surface. Which demulsifying behavior is dominated depends on the reactivity of mineral filler with emulsifier and asphalt droplets. High reactive fillers like cement can have a strong adsorption ability with emulsifier and asphalt droplets (Ouyang et al., 2018; Wang et al., 2009). Direct droplet adhesion on solid surface can be dominated. To ensure the good workability of CRME, two common alternative ways are to reduce the reactivity of mineral filler, i.e., changing mixing sequence (Ouyang et al., 2016) and adding surfactant (Ouyang et al., 2014b, 2016) and improving the chemical stability of emulsifier by employing nonionic emulsifier as co-emulsifier in emulsion production. Besides, scholars recently realized that the demulsifying behavior of asphalt emulsion could affect its coating ability on aggregate and asphalt membrane structure (Ouyang et al., 2019, 2020), further affecting the mechanical properties of bitumen emulsion materials. The first demulsifying behavior (i.e., droplets coalescence and further adsorption on solid surface), which is more beneficial to the asphalt membrane structure, can obtain better mechanical properties of CRME (Ouyang et al., 2020).

Except for the demulsifying behavior of asphalt emulsion, the drying behavior, properties of residue and film formation structure of asphalt emulsion can also greatly affect the hardening rate and mechanical properties of CRME. However, these properties are seldom investigated in previous studies. Most of the previous studies on CRME are based on only an asphalt emulsion. Besides, no index is proposed to evaluate the drying behavior, properties of residue and film formation structure of asphalt emulsion. Fortunately, the

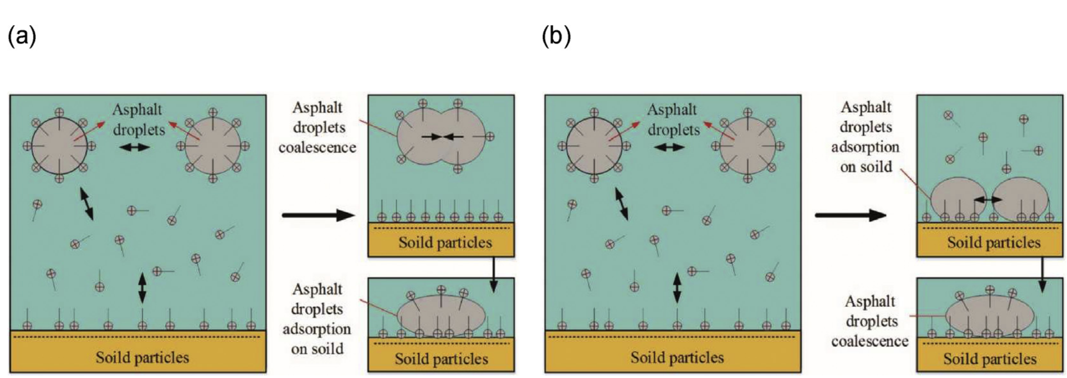


Fig. 74 – Demulsifying behavior of asphalt emulsion. (a) Droplets coalescence and further adsorption on solid surface. (b) Direct droplets adsorption on solid surface and further coalescence.

maximum packing fraction of asphalt droplets, which is formed during drying, is proposed in the year of 2021. The maximum packing fraction of asphalt droplets can be determined from the drying curve of asphalt emulsion (Ouyang et al., 2021b). A higher value of the maximum packing fraction of asphalt droplets indicates that asphalt emulsion can be dried more quickly (Ouyang et al., 2021b). Meanwhile, this index can be also a quantitative index to evaluate the demulsification process of asphalt emulsion (Ouyang et al., 2021a). Moreover, it is a general consensus in the latex field that maximum particles packing fraction can greatly affect the film structure and properties of latex film (Chevalier et al., 1992; Keddie and Routh, 2010). Therefore, the maximum packing fraction of asphalt droplets can be a reasonable index to judge the quality of bitumen emulsion from the aspects of drying, demulsifying, properties of residue and film structure.

(3) Future prospect of cold recycled mixture with asphalt emulsion

Since CRME has relatively weaker mechanical properties and pavement performance than hot mix asphalt, it is normally limited to base and sub-base layers when it is applied in motorway in most countries. As a result, most of RAP from the surface layer is actually downcycled in pavement engineering by this technology. In recent years, pavement engineers and scholars have been trying to use CRME as surface layer material. To achieve this ambitious objective, the following principal issues should be solved.

- The relatively weaker performances of CRME are due to its high voids content. Therefore, how to reduce the voids content of CRME is a vital technical issue.
- The properties of asphalt emulsion can greatly affect the performance of CRME. However, current evaluation methods of asphalt emulsion in the specification do not consider the important technical properties of asphalt emulsion, such as the drying behavior of asphalt emulsion, the cohesive and adhesive properties of emulsion residue cured under the ambient temperature. Therefore, the quality of bitumen emulsions cannot be reasonably distinguished by current evaluation methods. Thus, a better method index for evaluating the quality of asphalt emulsion is urgently required. In this aspect, the maximum packing fraction of asphalt droplets formed during drying may be a good choice to evaluate the quality of asphalt emulsion.

5.2.2. *Solid waste recycling in pavement*

Asphalt pavement construction requires huge amount of natural materials due to its enormous mileage which is keeping growing world widely. Such highly material dependent makes it as an ideal application area for the recycling of industry solid wastes. In China, the dramatic increasing of pavement construction is nowadays facing the shortage of natural aggregates, and environmental issues as well. Many types of solid waste were therefore recycled in pavement engineering, while construction and demolition waste, steel slag and waste tire rubber were considered as the major reused solid waste.

5.2.2.1. *Construction and demolition waste*. Construction and demolition (C&D) waste, which contains concrete, brick, glass, metal, wood and many other things, is a giant of solid waste due to the continuous booming construction of infrastructures (Zhao et al., 2020a). More than 480 million tons of C&D waste is annually generated in the United States, while the amount in China is about 3500 million tons. Such massive landfilling of C&D waste leads to serious environment problems. It is therefore an urgent concern to efficiently reuse C&D waste in the most affordable way. The wide-ranging material characteristics of C&D waste, depending on the original used materials in local demolished projects, makes it more complex to achieve efficient reuse. In road engineering, C&D waste can be reused in the form of recycled concrete aggregates (RCA) and mineral fillers, after proper mechanic treatments like crushing, separation and grinding.

(1) Recycled concrete aggregate

RCA can be reused as base materials for highways with the stabilization with cement and fly ash, as coarse aggregate in asphalt mixture layer. A carbon uptake estimation analysis by AzariJafari et al. (2021) stated that reuse C&D waste as RCA in pavement engineering can result in a maximum of 52% carbon uptake within the pavement life cycle. But the mechanic properties of RCA are always not comparable to natural aggregates, due to the highly porous cement paste attached to the original aggregates. This cement paste is the major reason that contributes to the higher porosity, higher water adsorption and quality validation of RCA (Paranavithana and Mohajerani, 2006). So, there are many opposite research findings when RCA was reused in asphalt mixture. Aggregate treatment and mixture enhancement are therefore widely studied to improve the performance of asphalt mixtures that contain RCA, by improving the mechanic behavior of the attached porous cement paste layer. Fig. 75 concludes the pre-treatments on RCA to improve the physical characteristics of recycled aggregates and their resulted asphalt mixtures, according to the literatures' publication time. Table 32 concludes the reported pre-treatments of RCA and their advantages.

The aggregate treatments include chemical treatment, heat treatment and carbonization. In the category of chemical treatment, silicon resin was used to improve the surface morphology (Zhu et al., 2012), water stability (Hou et al., 2014a; Lei et al., 2020), calcium hydroxide solution, methanesiliconic acid sodium salt solution (You et al., 2020d), acetic acid (Kazmi et al., 2019), sulphuric acid (Jindal et al., 2017), and cement slag paste (Lee et al., 2012) and cement slurry was used to increase the mechanical strength (Hou et al., 2014a; You et al., 2020d). As early as the 1990s, Lee et al. (1990) concluded that coating and sealants can minimize the binder absorption by porous RCA. Kazmi et al. (2019) carried on a comparative study on the resulted mechanical behavior of RCA with different treatments, including acid immersion, mechanical rubbing, carbonation and combination treatments. They found that the stress-strain behavior, like split tensile strength and flexural strength, can be significantly improved. Presoaking

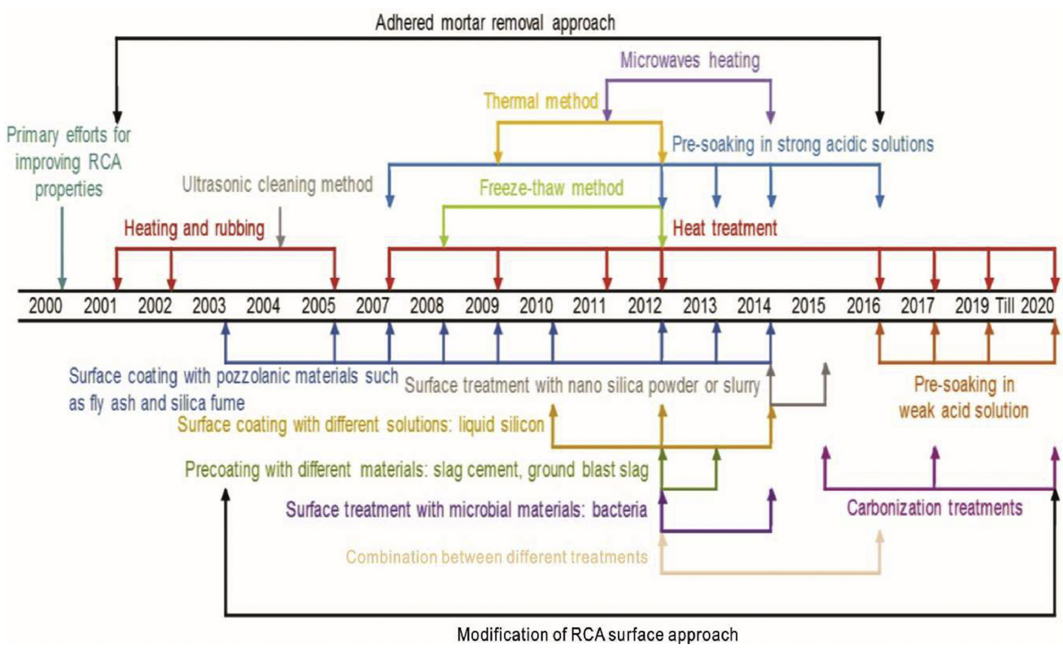


Fig. 75 – Pre-treatments for enhancing physical characteristics of RCA in the literatures.

in acidic solution, heat treatment followed by a short mechanical treatment was carried on with RCA based asphalt mixture in the research from Al-Bayati et al. (2018), to improve the volumetric properties.

Heating techniques were also applied on RCA to enhance the aggregate properties. Wong et al. (2007) reported that heating from 27 °C to 950 °C can convert the constituent calcium carbonate component into free lime (calcium oxide), hence improve the rutting resistance of asphalt mixtures (Al-Bayati and Tighe, 2019). Bitumen emulsion was used to pre-treat RCA for asphalt mixture by Kareem et al. (2020), and heating condition of 155 °C was applied at the same time to minimize the uncoated area (Kareem et al., 2020) and improve their stripping resistance (Pasandín and Pérez, 2014). Carbonization treatment by Zhang et al. (2015b) indicated that the carbonation increased the density and

Table 32 – The reported pre-treatments of RCA and their advantages.

Pre-treatment		Achievement	Reference
Chemical treatment	Silicone resin	Improve the strength, absorption, adhesion with asphalt and surface morphology of RCA	Zhu et al. (2012) Lei et al. (2020) Hou et al. (2014a)
	Calcium hydroxide solution	Satisfy the Marshall criteria with increased resilient modulus	Wong et al. (2007)
	Sodium salt solution	Improve the high- and low-temperature performances of RAP mix	You et al. (2020d)
	Acetic acid	Improve the tensile strength and flexural strengths	Kazmi et al. (2019)
	Sulphuric acid	Improve the split tensile strength and water absorption	Jindal et al. (2017)
	Cement slag paste or cement slurry	Improve the moisture resistance of mix	Lee et al. (2012) Lei et al. (2020) You et al. (2020d)
Heating treatment	Heating energy will promote the convert of constituent calcium carbonate component into free lime.		Wong et al. (2007) Al-Bayati and Tighe (2019) Kareem et al. (2020)
Carbonization treatment	Carbon dioxide react with calcium hydroxide and C-S-H to form calcium carbonate and silica gel.		Zhang et al. (2015b) Kazmi et al. (2019)

decreased the water absorption and crushing value of RCA. Both $CaCO_3$ and silica gel formed during carbonation can be found on the RCA surface, which positively contribute to the decreased absorption and increased hardness of RCA.

Thanks to the high-value added research, the physical properties of RCA can be ensured to meet the specification requirements for asphalt mixtures. Although Mills-Beale and You (2010) approved that the mixtures with 75% of RCA can be used in low-traffic condition, and there is no doubt that increase the adding ratio of RCA in mixture will decrease the pavement performance. Secondly, the life cycle environmental analysis is needed during RCA based asphalt pavement applications. A construction energy index was proposed to determine the relative amounts of energy saved by recycling RCA in asphalt mixture (Mills-Beale and You, 2010). Construction energy index analysis indicates that more compaction energy is needed before opened to traffic when RCA adding ratio decreases.

(2) Recycled mineral filler

Mineral filler from C&D waste, with the nominal maximum size not less than 0.16 mm, can be reused in asphalt mixture design as mineral filler. For instance, recycled concrete powder (Chen et al., 2011c), cement kiln dust (Ekblad et al., 2015), waste glass (Androjić and Dimter, 2016), and brick powder (Chen et al., 2011d) were found from the literatures on replacing of traditional mineral filler for asphalt pavement design. But the performance of resulted mixture with C&D waste as filler shows a wide range of variations due to the morphologies of the reused mineral filler, including specific shape and surface texture.

Most of these studies compared the performance of asphalt mixture made with the alternative fillers and that made with traditional limestone filler. The results revealed higher stiffness, longer fatigue life and better rutting performance using brick powder (Chen et al., 2011d) and recycled concrete powder (Chen et al., 2011c), although low-temperature properties decreased with the latter filler. The hydrated lime from C&D waste would give a positive contribution to the moisture resistance of asphalt mixture, which acts as anti-stripping agent (Ekblad et al., 2015).

5.2.2.2. *Steel slag*. In pavement engineering, another common practice of environmentally sustainable pavement materials is reusing industry solid wastes in the pavement construction, which include blast-furnace slag, fly ash, packaging waste, ceramic waste, etc. Steel slag, a by-product during the steel-making industry in an electric arc furnace, has been reused in pavement engineering as aggregate since the 1970s based on its high friction and abrasion resistance. It can be used not only in surface layers, but also in unbound bases and sub-bases, after successfully pre-treated to minimize its volumetric expansion (Shen et al., 2020).

Khan and Wahhab (1998) and Bagampadde et al. (1999) approved that the mixture resistance to moisture and fatigue can be improved when coarse slag aggregates were supplemented with Portland cement, lime, polymer, and amine additives. Replacement analysis by Asi et al. (2007) indicated that up to 75% of limestone aggregate replacement with steel slag aggregates would not weak the mechanical properties of asphalt mixtures. Cui et al. (2020d) and Wang et al. (2020c) reused steel slag in micro-surfacing and found that the skid resistance can be enhanced due to the outstanding morphologies and hardness. Wu et al. (2007) reused steel slag as aggregate in stone mastic asphalt mixtures, with the result indicating that the replacement of basalt with steel slag increased the low-temperature cracking resistance. Ahmedzade and Sengoz (2009) studied the mechanical properties of asphalt mixtures containing steel slag and found that the use of steel slag as coarse aggregate could improve the mechanical properties and conductivity of asphalt mixtures.

The major concerns that limit the recycling percentage in asphalt pavement are the volume expansion of steel slag and its high construction cost that resulted from higher optimal binder content. Steel slags contain certain proportion of free calcium oxide (f-CaO) and magnesium oxide (MgO), which can get hydrated $Ca(OH)_2$ and cause large volume expansion. The porosity of steel slags also leads to higher optimal binder content and poor thermal efficiency. Therefore, pre-treatments are studied to ensure the stabilized steel slag aggregate. Chen et al. (2016b) conducted hydration process by keeping slags wet but not immersed in water, followed by silicone resin treatment. They found that the combination treatment with hydration and resin can obtain both lower porosity and coarse surface texture.

The environmental impacts of reusing steel slag in road engineering is important as well. Behnood et al. (2015) used toxicity characteristic leaching procedure (TCLP) test to assess the environmental impacts of reusing steel slag, and claimed that the concentration of all heavy metals and PAHs were below the regulatory levels, according to the drinking water standard from World Health Organization and Environmental Protection Agency.

5.2.2.3. *Waste tire rubber*. It has been a long time on recycling waste tire rubber in asphalt paving applications, as it is nowadays being identified as a polymer modifier for providing well-accepted property enhancement in the asphalt mixtures. The raw materials of waste tire rubber are natural rubber, synthetic rubber and carbon black. Literatures show that natural rubber provides the elastic properties, while the synthetic rubber improves the thermal stability and carbon black improves the durability of asphalt mixtures (Akisetty et al., 2009; Liu et al., 2019b). Two methods can be found to recycle rubber waste in asphalt mixture, which are wet process and dry process. The wet process blends crumb rubber with asphalt binder before mixing the binder with aggregates, while the dry process blends the crumb rubber with aggregates before the mixing. The wet process is used more often, because it can ensure homogenous crumb rubber modified mixture (Liu et al., 2019b).

The drawbacks of crumb rubber modified asphalt binder are high viscosity, low storage stability and released harmful components during its heating process. Amirkhanian et al. (2015) and Xiao et al. (2020) developed a unique pelletized asphalt rubber by blending of premium quality asphalt cement, crumb rubber made from recycled waste tires, hydrated lime and other preparatory additives. It created a pre-manufactured matrix of asphalt and modifiers in a free-flowing form that was transported and stored at ambient temperature. Environmental concerns exist in recycling rubber tires in asphalt. Further researches and experimental applications need to be best utilized by focusing on crumb rubber modified binders in hot mix asphalt.

5.2.3. *Environment impact of pavement material*

5.2.3.1. GHG emission and energy consumption of pavement material. Due to the emission intensive and energy-driven nature of pavement construction and maintenance, a large amount of GHGs and energy are produced and consumed in the paving materials production, which includes the production of asphalt binders, cement, aggregates, mineral, powder, etc., as well as the mixing of cement concrete and asphalt mixtures. To what extent the materials production would impact the environment and how they can be improved are critical questions to be answered in order to develop environment-friendly pavement.

(1) Estimation of GHG emission and energy consumption

The GHG emission and energy consumption of pavement materials production account for an overwhelming proportion in the life cycle (Yu and Lu, 2012). It is necessary to calculate the environmental burdens of producing materials that are needed in constructing and maintaining pavements. The regular pavement materials include asphalt, cement, aggregate, steel, water, etc. The energy inputs and pollutant emissions to manufacture raw materials depend on many factors, e.g., source, transportation mode and distance, production technology. For instance, Butt et al. (2014) developed a method to calculate the feedstock energy of asphalt and quantify the mass and energy flows of the additives, such as wax and polymer. For mixtures, the blending process (especially for hot mix asphalt) and recipe account for a large portion of the energy consumption and vary significantly by cases. Chong et al. (2016) developed thermodynamic models for energy consumption prediction of asphalt mixture production.

It is reported that the use of warm mixing technology can notably reduce the GHGs and energy consumption generated by heating raw materials. Compared with HMA, energy consumption and GHG emission are reduced by 25% and 30% using WMA (Dinis-Almeida and Afonso, 2015). Despite WMA has significant advantages in energy saving and emission reduction, due to different types, sources, and regions of road construction materials, the specific cooling effects that WMA can achieve are significantly different. A unified quantitative evaluation method shall be further refined. Moreover, a routine assumption of WMA application is its competent performance as to HMA, but whether this assumption is tenable remains to be verified.

(2) Challenge and prospect of environment burden estimation

For the estimation of carbon footprint of pavement, the data acquisition has always been plaguing the estimation of GHG emissions and energy consumption. Santero et al. (2011) reported energy intensity ranges for the two main paving materials, being 4.6–7.3 MJ/kg for cement and 0.7–6.0 MJ/kg for asphalt. Such a wide range is not surprising due to the differences of system boundary selection, technology assumptions and production processes selections. Unfortunately, many available studies employed a certain value without justifying the reliability, which may alter the results significantly when facing wide variations in the published emission factors. It is therefore prudent to adopt sensitivity analysis or uncertainty analysis to verify the robustness of the results (Yu et al., 2018b). A transition from deterministic results (based on single best value) to probabilistic results (based on statistical analysis) is emerging to improve the reliability of results (Noshadravan et al., 2013; Yu et al., 2018a; Zheng et al., 2020). However, there is not yet a systematic methodology to quantify the uncertainties associated with the calculations of GHGs emission and energy consumption in the life cycle.

An important aspect in environmental analysis is the applicability of data in a specific location. Ducreux et al. (2020) released the latest version of life cycle inventory (LCI) of asphalt while LCI for cement concrete is rather outdated (Marceau et al., 2006). The GHG emission factors for asphalt, aggregate and mineral powder were also reported respectively in accordance with China's specific emission factors. Most of the existing researches on pavement GHGs emission and energy consumption use national databases or commercial software, e.g., Gabi, SimaPro. Regional disparities are difficult to be captured under the existing framework. There is a need to establish a method to investigate the GHG emissions and energy consumptions from paving material production and construction at both the national and provincial levels.

5.2.3.2. VOC emission of pavement material. Asphalt binder is extensively utilized in highway and urban road due to its favorable adhesive properties, while the release of volatile organic compounds (VOCs) during its production and construction has posed unprecedented challenges to the environment and stirred up considerable concerns.

(1) Characterization and sources of VOC emission

VOCs, commonly released in the production and construction of asphalt, are complex organic compounds with low concentration, strong activity and great endangerment, which have adverse impact on both human health and environmental safety. The composition and content of VOC largely depend on the composition of crude oil and asphalt as well as the oxidation level of asphalt (Boczkaj et al., 2014). The VOC components of nearly 80 asphalt materials were quantitatively analyzed by defining the fingerprint components of VOCs (Xue et al., 2020). In other studies, the composition of VOC was analyzed by simulating the production of asphalt fumes in laboratory. However, its chemical composition in lab may be distinct from that in the field. To compare such differences, binder storage tanks, outlets of mixture plant emission and biography sites were selected and VOCs from field and lab were analyzed (Li et al., 2021c). Aliphatic hydrocarbons are primary constituents of asphalt VOCs, with more than 74% of which collected under laboratory test consistent with field samples.

(2) Health injury of VOC emission

The potential hazard to workers' health was examined by assessing the VOCs generated by the construction of HMA mixture on-site (Chong et al., 2014). The authors believe that the most common VOC is toluene, followed by 4-ethyltoluene, p-xylene, 1, 3, 5-trimethylbenzene, and ethylbenzene. The VOCs concentrations during filling paver hopper are generally higher than those during paving, while the corresponding concentrations during compaction are the lowest (Chong et al., 2014). Consistent scenarios have been reported (Li et al., 2021c) that the VOC emissions of pavement paving > compaction > cooling > service at normal temperature. The concentration of VOC in paving is remarkably dependent on the extent of air flow, which denotes that asphalt fumes can be more toxic when there is insufficient wind. To determine the health injury of VOC concentrations and pathways on construction workers, the researchers also developed a probabilistic model based on Monte Carlo simulations and workers' construction behavior to better protect workers on site (Cui et al., 2020e). During construction, the VOC emission from paving is the most harmful to workers, with its concentration varies from 0 to 137.97 mg/m^3. Studies have shown that the carcinogenic risk index of VOCs in asphalt paving ranges from 1.89×10^{-6} to 5.35×10^{-5}, and the main contributions are benzene and ethylbenzene, which have a large potential carcinogenic risk (Li et al., 2021c).

VOC emissions during road construction are temporary as the construction operation will not last more than a few hours. On the contrary, in the processing and mixing plant of asphalt binder and asphalt mixture, the main sources of VOC emissions are the refining process and the heating device used in heat storage tank, where VOC pollutions are prone to be an issue for months during road construction (Boczkaj et al., 2014). Similar conclusions were found in another study that asphalt storage tanks were the largest VOCs emission, which is approximately 3 times and 27 times of the relevant concentrations in asphalt plants, respectively (Wang et al., 2020e).

(3) Inhibition of VOC emission

Reducing asphalt VOC emissions during production, mixing, transportation and paving is an ongoing issue and challenge for transportation institution. Various approaches and chemical processes have been developed to reduce VOCs. Among them, activated carbon is considered to possess favorable adsorption and is widely used. When the mass ratio of activated carbon changes from 3%, 4% to 5%, VOCs volatilization decreased by 26.9%, 30.7% and 32.6%, respectively (Xiao et al., 2017a,b). The same is true from layered dihydroxides (LDHs). The multi-nested layered structure of LDHs is able to shield and adsorb ultraviolet light, prevent the release of small VOC molecules, and reduce volatile rate (Cui et al., 2014). Despite a reduction in VOC observed from the two additives, activated carbon and LDHs were reported to reduce the crack resistance of asphalt mixtures (Cui et al., 2015, 2016). Furthermore, biochar (Zhou et al., 2020b, c), tourmaline anionic powder (Zhang et al., 2021l), geopolymer additives (Tang et al., 2020), fluid catalytic cracking catalyst (Xue et al., 2020), mesoporous hollow silica particles (Wu et al., 2020c), association of alumina trihydrate and organic montmorillonite (Yang et al., 2020a) have been found to inhibit the release of VOC and can be regarded as promising VOC inhibitors. Unfortunately, the deterministic inhibitory mechanism of these inhibitors remains to be further illustrated.

Another effective method to reduce VOC is to lower the production temperature of asphalt materials by using WMA mixture (Espinoza et al., 2020; Rubio et al., 2013; Xiu et al., 2020). The option of WMA is receiving increasing attention due to the extended pressure of limiting asphalt fumes on site construction. Organic waxes have been demonstrated during the production of WMA due to their viscosity-reducing potential. In addition to reducing VOC emissions from construction temperatures, wax crystals tend to interact with asphalt components to form a crosslinking structure, thereby inhibiting the release of lighter compounds (Autelitano et al., 2017). Previous studies have also found that zeolite incorporated with $Ca(OH)_2$ can effectively reduce the overall VOCs emissions and toxicity by more than 37% (Sharma and Lee, 2017; Zhang et al., 2021k). The incorporation of RAP also led to a positive conclusion (Wei et al., 2021). RAP mainly affects the release of aliphatic hydrocarbons (ALH) and oxygen-containing hydrocarbon derivatives in VOCs. When RAP aggregate content reached 70%, VOCs emission was dramatically reduced by 94.82%.

(4) Prospect of VOC emission study

In general, the composition characterization of asphalt VOCs remains further explorations. VOC is closely related to the production conditions and types of asphalt, which determines the complexity of its analysis. How to better establish the correlation between laboratory simulation and field VOC emissions remains the direction that should be paid attention to in future researches. Furthermore, it is of necessity to reveal the internal mechanism of inhibitors to mitigate VOC emissions to better serve the development of renewable and sustainable pavement materials.

5.2.4. *Summary and outlook*

This section firstly discussed the latest research findings on hot recycled, warm recycled and cold recycled mixture technologies. Newly designed materials, such as rejuvenators, self-healing agents and asphalt emulsion, have contributed a lot to the enhancement of recycled mixtures, making it satisfactory for the requirements of all layers in pavement application. However, there are still many challenges in the RAP recycling, including the variability control of RAP, ultrahigh RAP adding ratio, lower environmental impact during the asphalt pavement recycling, as well as water stability of warm and cold recycled mixture. Newly qualified additives, better characterization methods and updated mixture design criteria are urgently required to enhance the service performance of recycled asphalt mixtures, by improving the interfacial mechanical properties between RAP aggregates and fresh aggregates.

Recycling of solid waste, including C&D waste, steel slag and waste tire rubber, in asphalt pavement construction was then reviewed. Chemical surface treatment, heating treatment and carbonization treatment were developed to rearrange the surface characteristics, decrease the porosity and increase the hardness of recycled solid wastes that expected to be used as aggregates in asphalt mixture. The ultra-high adding ratio in asphalt mixture is part of the most concerned issues during the solid waste recycling in asphalt pavement. Life cycle environmental impact is another key research direction for the reusing steel slag and waste tire rubber in asphalt mixture. The recycling of solid wastes as mineral filler or modifier needs further study on their micro-morphologies and chemical behavior.

Carbon neutral is nowadays becoming a global strategy, while China has promised to become carbon neutral before 2060 and begin cutting carbon emissions within the following ten years. Environmental issues, including GHG emission, energy consumption and VOC emission, related to the solid waste recycling in asphalt pavement full life cycle were therefore discussed at the end of this section. Although many literatures reported successful GHG emissions and energy consumption of asphalt pavement in its life cycle, further estimation at both national and provincial levels are expected. VOC emission is another serious environmental concern during the application of asphalt pavement. Its emission mechanism, reduction methodologies and corresponding additives are the key focusing for green asphalt materials.

6. Intelligent pavement

6.1. *Automated pavement defect detection using deep learning*

As the major highway network in China has been basically completed, monitoring the health of the current in-service road and then conducting necessary maintenance are of great importance to ensure the public transport safety.

Real-time and accurate monitoring of the conditions (stress, strain, deformation, etc.) of the road, including structure and materials, are quite important for construction quality control, maintenance scheme, and early damage detection and prevention. Through the monitoring of dynamic response of road structure and evaluation of road conditions, many of the existing pavement distresses can be detected, analyzed and repaired as early as possible. In the past, it is widely seen that road engineers carry out monitoring services based on the manual field detection. With the development of advanced technologies such as wireless communication and internet of things (IoT), more wireless sensor networks have been used to monitor the road conditions. The automated monitoring can not only significantly save time and human resources, but also can obtain massive road structure monitoring data in a long, continuous and real-time manner. Thus, how to analyze the obtained monitoring data has become crucial for road engineers.

Recently, deep learning and other artificial intelligence (AI)-based technologies have been gradually applied for the analysis of road monitoring data (Shtayat et al., 2020; Wang et al., 2019i). Meanwhile, due to the large sample sizes and complex features of long-term monitoring dataset, the traditional statistic method may not be as powerful as machine learning methods and deep learning method. Milad et al. (2021) established four prediction models of pavement temperature, based on deep learning methods including convolutional neural network (CNN), long-term short-term memory (LSTM), Bi-directional long short-term memory (Bi-LSTM) and gate recurrent unit (GRU). The air temperature, depth from asphalt surface and time from March 2012 to February 2013 were all used as datasets to predict the asphalt pavement temperature. Choi and Do (2020) used the road condition monitoring data, obtained by Korea national highway pavement management system, to predict the road condition index in the next year based on LSTM network. Pu et al. (2020) developed a data-driven prediction model of road surface friction using LSTM neural network. According to the experimental results, the proposed deep learning model is better compared with other methods.

Deep learning is usually involved with image processing to achieve object detection and subsequent analysis (Hou et al. 2020; Yang et al. 2021a). It has been widely applied in the defect detection of various civil engineering structures, such as bridges, roads, buildings, tunnels, etc. Generally, the application of deep learning involves defect classification, localization and segmentation. Classification is enough if

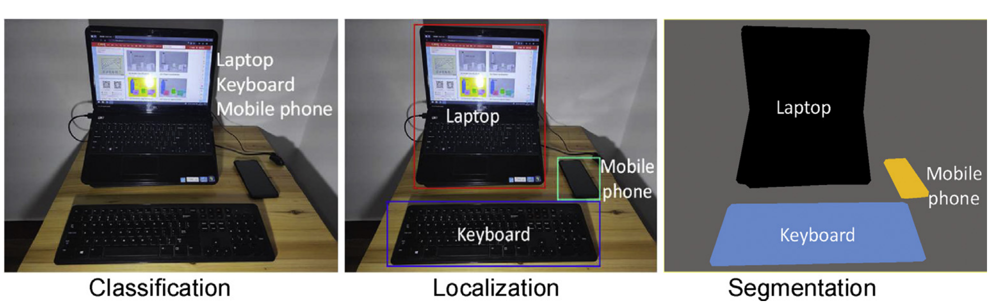


Fig. 76 – The illustration of classification, localization and segmentation (Pu et al., 2020).

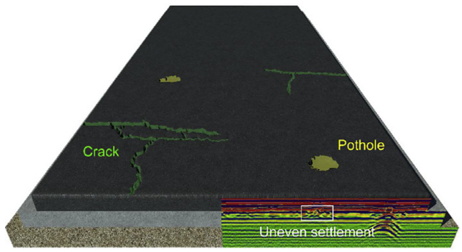


Fig. 77 – The illustration of pavement distresses.

only the existence of a certain type of defect is needed. Localization needs to be conducted if the defect needs to be found out. If the detailed information (i.e., pixel level information), segmentation is needed. The illustration of the three types of defect identification can be seen in Fig. 76, taking laptop, keyboard and mobile phone as an example. Regards of defect detection in pavement engineering, it mainly involves with the surface defect and internal defects. Surface defects include cracks, potholes, rutting, raveling, etc., while internal defects include crack, hole, uneven deformation, interface failure, etc., as seen in Fig. 77.

On the other hand, for non-traditional monitoring methods, like monitoring using mobile devices such as smart phones, can also be used for road condition analysis by deep learning method. Basavaraju et al. (2020) proposed to analyze the road surface conditions based on data collected by accelerometer, gyroscope and GPS data in smartphones. Jeong et al. (2020) presented a prediction method of international roughness index (IRI) based on CNN using the multimetric vehicle dynamic data obtained by smart phones and real IRI data.

To sum up, with the continuous improvement of the road monitoring system and the continuous collection of road monitoring data in the future, combined with the advanced machine learning method, it will provide a more accurate and reliable analysis on road conditions, helping the road engineers conduct better maintenance work (Fig. 77).

6.1.1. *Automated data collection method*

With the development of image processing technology, the pavement images can be collected by vehicle-mounted digital cameras with driving speed, smartphones, action cameras and UAVs. The inspection vehicle with well-configured cameras can obtain the whole pavement lane videos while driving, which usually collects pavement distress images from a top-down view. For example, digital highway data vehicle (DHDV) is applied in pavement distress images acquisition and detection with a fast speed on the road (Wang and Gong, 2005). On another thought, high-resolution mobile smartphones with proper configurations on the driving vehicles can collect distress images at a constant speed, which is cost-effective and convenient (Maeda et al., 2018). At the same time, some cars equipped with action cameras like Gopros, which is an economic substitute for industrial cameras (Mei and Gül, 2020).

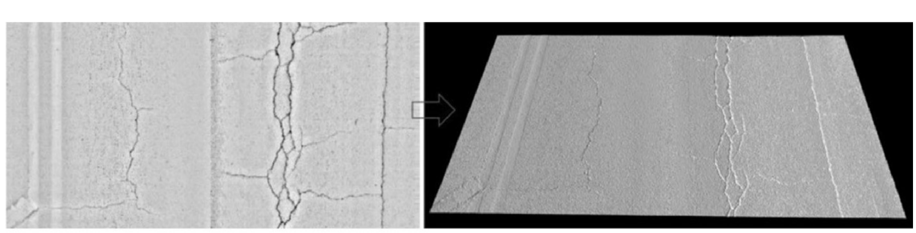
6.1.1.1. *Digital camera*. In recent year, digital cameras are widely used into automated pavement surface distress detection areas for image data collection. The collected pavement surface images are then used for surface distress detection and pavement performance assessment using advanced digital image processing technologies. For this purpose, two types of sensors are widely used in digital cameras for image capturing, which are charge-coupled device (CCD) camera and complementary metal oxide semiconductor (CMOS) camera.

CCD is a semiconductor device that can convert optical images into digital signals. The CCD image sensor has the following characteristics. (1) Small size and weight light. (2) Low power consumption, low working voltage, anti-shock and vibration, stable performance, and long life. (3) High sensitivity, low noise, large dynamic range. (4) Fast response speed, self-scanning function, and image. The distortion is small and there is no afterimage. (5) It is produced by very large scale integration (VLSI) process technology, with high pixel integration and precise size.

CMOS is a low-cost photosensitive element technology developed. Its photosensitive elements are mainly CCD or CMOS, especially low-end camera products, while high-end cameras are usually CCD photosensitive elements. Compared to CCD, CMOS has the following characteristics. (1) Higher noise generated during imaging. (2) High integration. (3) Fast readout speed, address strobe switch can be randomly sampled to obtain higher speed.

Taking into consideration of all the advantages and disadvantages of CCD and CMOS cameras, CCDs are most widely used in automatic pavement data collection.

6.1.1.2. *3D laser camera*. A 3D camera is also called a depth camera. As the name implies, the camera can detect the depth of field distance in the shooting space. This is also the biggest difference from an ordinary camera. For road detection, it can rapidly obtain 3D road information, automatically identify all types of pavement defection and greatly reduce the man-



3D pavement image   3D virtual pavement surface

Fig. 78 – 3D pavement distress image (Hsieh and Tsai, 2020).

machine interaction workload and the influence of human factors. This technology has been highly recognized by industry experts and attained the international advanced level. It is at the leading level of international similar research in data intelligent processing and automatic calibration technology. Two 3D line laser sensors were mounted at the rear of the inspection vehicles to collect 4 m full-lane-width 3D pavement images (Hsieh and Tsai, 2020). Raw point clouds are transformed into 3D pavement images, or range images, through compression and rectification by the software. Compression rescales the height value of the point cloud to between 0 and 255 to generate a grayscale image, which is shown in Fig. 78. In recent years, high-performance digital line-scan cameras are used for this type of surface inspection. Several main problems associated with analog area-scan cameras do not exist with digital line-scan cameras, such as relatively low resolution and the necessary digitizing process of analog area-scan cameras (Wang and Smadi, 2011).

6.1.1.3. *Structure from motion*. Structure from motion (SfM) is a 3D reconstruction technology which can build 3D models from multi-perspective 2D images (Schonberger and Frahm, 2016). Feature mapping of those pixels from different pictures are essential for SfM. Different from 3D cameras, SfM does not need the exact position of cameras that take the pictures of the object, which makes SfM a more promising approach to obtain the 3D information. On the other hand, SfM requires the surface texture of the object to find out those matching points for the 3D reconstruction. While SfM was initially used to reconstruct 3D models for body objects, pavement surface can also be reconstructed so that the surface defect information can be displayed in the model (Guan et al., 2021). Fig. 79 displays an example of pavement surface 3D image generated from SfM. It can be seen that the depth image is similar to that generated from 3D image from laser scanning.

6.1.2. *Automated road surface distress detection*

6.1.2.1. *Image processing-based method*. Pavement distress can be identified from their intensity differences in a distress image. For example, the crack is darker than the surrounding environment, the intensity value of crack is smaller than background. So the crack can be inspected by threshold segmentation and edge detectors. A proper threshold can segment cracks from background in an image, extracting the cracks geometry shown in images (Chambon and Moliard, 2011; Oliveira and Correia, 2009; Tsai et al., 2010; Zhang et al., 2017b). But a proper threshold is difficult to be chosen to segment the whole crack geometry from the background. Therefore, an adaptive threshold method is used to extract cracks in different regions in an image (Fan et al., 2019). At the same time, the intensity value changes called gradient can be detected by edge detectors to distinguish cracks from background, such as canny and sobel edge detectors (Ayenu-Prah and Attoh-Okine, 2008). But all these methods based on image processing is vulnerable to pavement conditions and illuminations from the environment, which is not generalized to be applied into different datasets.

6.1.2.2. *Machine learning and deep learning-based methods*. The computer vision pavement distress detection is composed of machine learning methods and deep learning methods. Some popular detection algorithms based on machine learning is support vector machine (SVM) (Chen et al., 2017c; Fujita et al., 2017; Wang et al., 2017e), artificial neural network (ANN) (Hoang, 2018; Wang et al., 2019k, l) and random forest algorithms. The main problem with traditional machine learning (ML) methods is that they contain only shallow learning techniques. Without learning higher level features, those techniques are not able to deal with the complex information contained in the images. For example, the background of pavement images is largely affected by illumination and the environment (Hsieh and Tsai, 2020).

Deep learning pavement distress detection is benefit from convolutional neural network (CNN). Deep learning algorithms with convolutional layers can learn image features better and give reliable results based on deep features. Deep learning algorithms are used widely in pavement distress classification, distress object detection and distress semantic segmentation, which change from image level, block level to pixel level shown in Fig. 80.

The pavement distress classification is based on image-level, in which the whole image from the data set is classified (Gopalakrishnan et al., 2017; Xu et al., 2019a). By using the sliding windows to give classification to each kind of

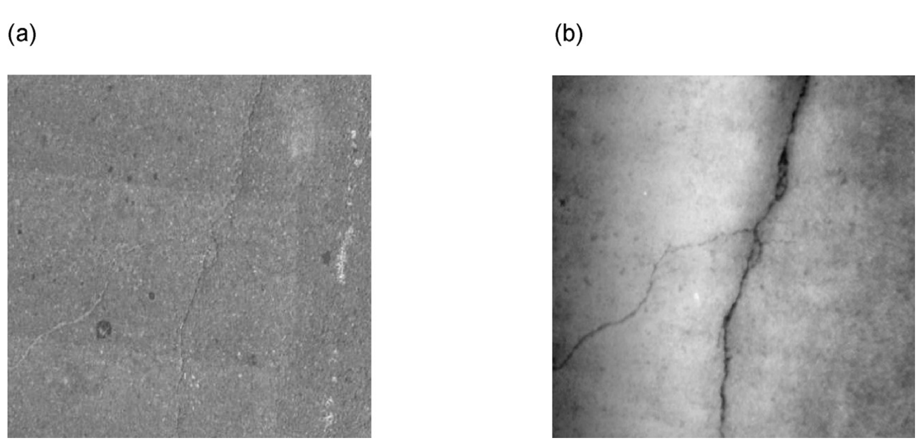


Fig. 79 – 3D model of pavement surface. (a) 2D image. (b) Depth image from SfM (Guan et al., 2021).

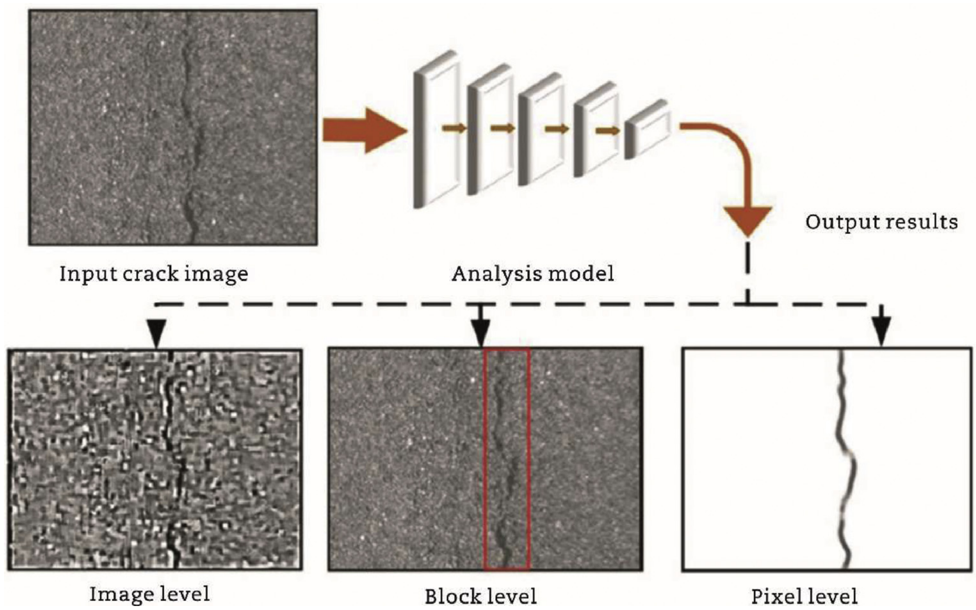


Fig. 80 – Crack detection trend with different analysis levels (Huyan et al., 2020).

distresses. But the distress classification can not predict the exact location of distress in images, therefore, the objection detection algorithms are applied into the pavement distress detection, which can not only classify the distresses, but can output localization of distress with a bounding box (Cha et al., 2018a; Chen et al., 2017c; Cheng and Wang, 2018). Popular state-of-the-art (SOTA) algorithms like faster region convolutional neutral network (R-CNN) (Ren et al., 2017) and YOLOV3 (Redmon and Farhadi, 2018) can predict distress successfully with high accuracy and fast speed. However, in order to get the exact geometry of distress, semantic segmentation is introduced into distress detection. The final extracted images only contain distress information, eliminating the background. Segmentation generates a pixel-wise prediction of distress in the images, each pixel is classified as distress or non-destress. The precise distress location and structure generated by crack segmentation can be used both to classify crack type and to obtain important crack features. Unet and segnet with encoder-decoder structure can concatenate the shallow location feature with deep semantic information can better segment distress from the background (Badrinarayanan et al., 2017; Bang et al., 2019; Tabernik et al., 2020; Zou et al., 2019b).

6.1.3. *Pavement internal defect detection*

Subbase and subgrade provide support function for the overall road structure, and thus they also require timely monitoring and maintenance to ensure the public transportation safety. As subbase/subgrade layer generally stays below the surface layer, the distresses in subbase/subgrade layer are hard to seen manually. The widely used core-extraction sampling method may easily cause irreversible damage to the road structures (Zhang, 2010). Normally, such methods may also need a lot of manual labor work and time, where the low efficiency may not be suitable for subbase disease detection with very long mileage.

As an advanced nondestructive testing technology, the ground penetrating radar (GPR) has advantages in high resolution, easy operation and intuitive results presentation, which can effectively detect the conditions in the subbase/subgrade layer (Luo, 2007; Yang et al., 2015). The identification of information is from the difference of dielectric constant for different materials. The information obtained from GPR can include layer thickness, interface debonding, cracks, uneven settlements, water-damage pits, etc. Manual identification has been widely used based on the GPR images. Generally, GPR data analysis and detection is more challenging compared with pavement surface defects due to the complexity of the images, since the defects from GPR images are not as obvious as that from visual images. Nevertheless, deep learning has been applied in the automated identification and detection of distresses from GPR images in recent years. Shao et al. (2011) analyzed the features of GPR images, and used support vector machine (SVM) method to complete the automatic classification and detection of railway subgrade ballast diseases. Du et al. (2017b) realized an intelligent recognition for railway subgrade diseases and structures by extracting the 2D characteristic values from detected images based on SVM method. Zhou et al. (2013) combined digital processing and pattern recognition technology, and proposed an automatic detection algorithm for highway subgrade diseases based on SVM. However, all the above studies require manual extraction of features and the identification accuracy is related to data processing, sample diversity, kernel function and parameter selection. The thickness of pavement layers can be automatically obtained based on the analysis of GPR data using artificial neural networks and support vector regressions (Le Bastard et al., 2012; Sukhobok et al., 2019). Li et al. (2021b) applied YOLO version 3, 4 and 5 to detect the concealed cracks from GPR images. The results of using the three different YOLO versions were also compared and it was found that the

YOLO version 4 has the highest robustness. Fast CNN and region-based CNN have also been used to identify pavement distresses in an autonomous way, including cracks, water-damage pits and uneven settlements (Gao et al., 2020; Tong et al., 2020b). Todkar et al. (2017, 2018, 2019) proposed a supervised machine learning method called support vector machine (SVM) for detecting the debondings within the pavement. The results based on asphalt pavement validated the efficiency of this method. Similarly, the debonding can also be detected using step-frequency GPR with a linear prediction and support vector regression (Le Bastard et al., 2019). To summarize, multiple internal defects of pavement layers can be effectively obtained from GPR data with machine learning.

The deep learning-based methods can partially solve these problems. Tong et al. (2017) realized the automatic identification, location, measurement and 3D reconstruction of concealed cracks under asphalt pavement in GPR images by using convolutional neural network. Liu et al. (2021d) used You Only Look Once Version 5 (YOLOV5) model to identify internal defects of asphalt pavement, and verified the effectiveness of GPR in pavement detection and maintenance. Du et al. (2010) extracted eigenvalues of various diseases from radar images and realized intelligent recognition of subgrade diseases by using learning vector quantization neural network.

Another trend to use the deep learning methods for subbase/subgrade conditions analysis is to conduct distress detection based on the object detection methods. Object detection is an important research direction of computer vision (Sharma and Mir, 2020), and its purpose is to accurately identify the category and location of a specific target object in a given image. The current widely used object detection algorithms are mainly divided into two categories: classification-based detection algorithm and regression-based detection algorithm. Among them, the major algorithm based on classification is R-CNN (Girshick et al., 2014), which has relatively high accuracy. The main algorithm based on regression is You Only Look Once (YOLO) (Redmon and Farhadi, 2017), which is relatively fast. Road engineers can use the two algorithms based on the specific research target.

Du et al. (2010) extracted the characteristic values of subgrade distress such as sectional energy, variance and plane position from radar images, trained these characteristic values with neural network, and obtained the classification decision rules for classifying various distresses. Besaw and Stimac (2015) adopted deep convolutional neutral network (DCNN) to classify B-scan profiles into threat and non-threat classes, and the results showed that DCNN could extract meaningful features. Lin et al. (2017d) used the deep learning methods to realize the automatic extraction of structural subgrade distress features, and the results show that the automatic extraction of structural distress features by deep learning methods is not disturbed by background noise, and the positioning results can meet the requirements of engineering purposes. Pham and Lefèvre (2018) adopted the faster R-CNN framework to detect underground buried objects in B-scan ground penetrating radar images, and the proposed technique can provide significant improvements compared to classical computer vision methods. Sha et al. (2019) proposed cascade convolution neural network to overcome the traditional convolution neural network in the recognition of low-resolution ground penetrating radar images of low accuracy.

As can be seen, the use of GPR for subbase/subgrade conditions monitoring and the corresponding machine learning methods for data analysis are still under development. There are still lots of work to do for road engineers for future engineering-level monitoring, detection and analysis.

6.1.4. *Summary and outlook*

More than 700 literatures related to the application of AI in pavement engineering have been summarized recently, as seen in Figs. 81 and 82 (Yang et al., 2021). It can be seen that the number of literatures has been increasing significantly in recently years. AI can be used in multiple areas in pavement engineering such as design, construction, monitoring and

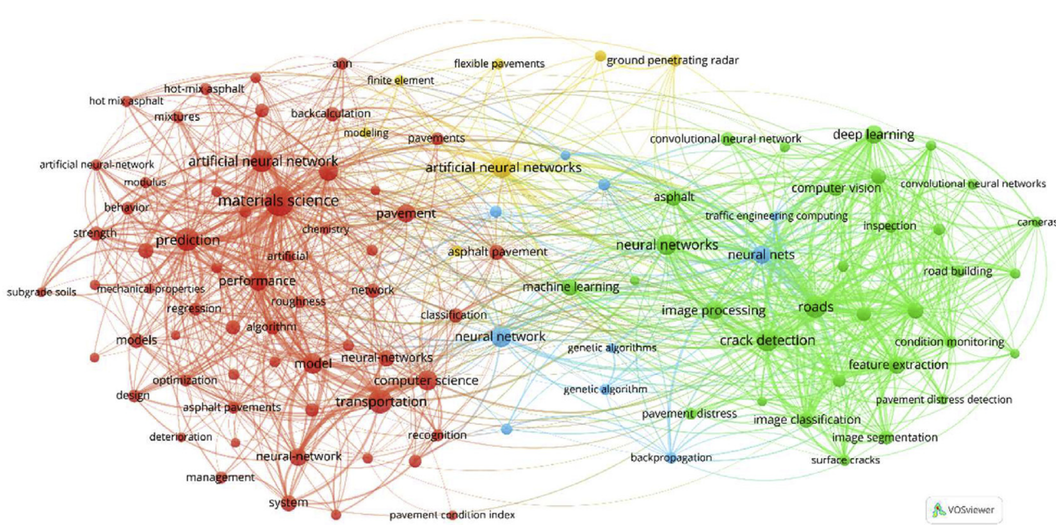


Fig. 81 – Literature review topics of AI in pavement engineering (Yang et al., 2021).

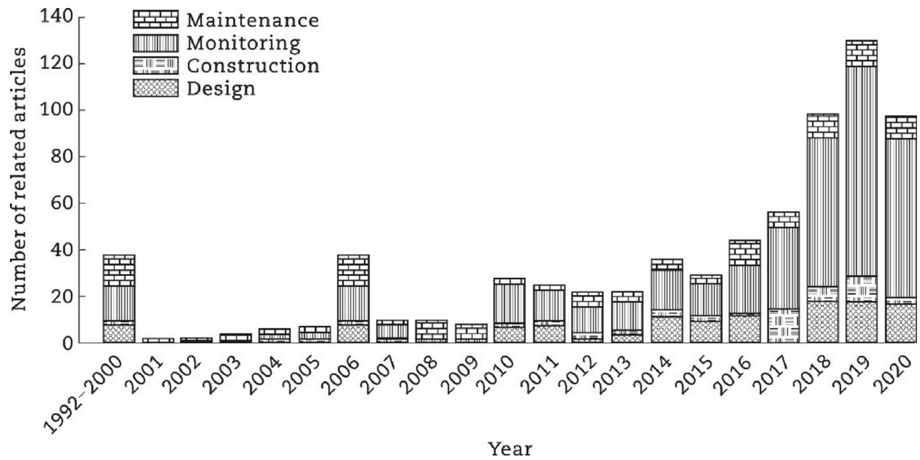


Fig. 82 – Literature review results of AI in pavement engineering (Yang et al., 2021).

maintenance. Out of the four categories, pavement monitoring, which is usually related to defect detection, occupies the majority, indicating that pavement defect detection is the major area for the application AI in pavement engineering.

In this section, we conducted research in analyzing the research trend on pavement surface distress detection in terms of top affiliations, territories, citations and authors in recent years. These results are shown in Fig. 83.

It can be seen that the top 10 affiliations are Georgia Institute of Technology, University of Toledo, University of Texas at Austin, Chang'an University, Southeast University, University of California, etc. Obviously, the most research conducted by United States and China, followed by Italy, Germany, UK, Canada, etc. This is the reason why this review focused summary on these two territories. Meanwhile, it also indicates that more research on pavement surface distress detections are required in China, because the total miles of highways in China is far higher than that of US. However, the amount of research conducted in US are much more than China, which also explains why the service life of pavements of US is generally longer than that in China.

The proceedings of SPIE seem continuously have the highest total citations than the other publications in the past 15 years. However, this difference has a significant drop from 2018, especially in 2021, at least till this review. This phenomenon indicates that other popular journals are catching up this conference proceeding, which shows that more high-quality research papers in pavement surface distress detection are published in recent years. The following four ranked publications are Transportation Research Record (ranked the 2nd), IEEE Transactions on Intelligent Transportation Systems (ranked the 3rd), Journal of Computing in Civil Engineering (ranked the 4th), and International Journal of Pavement Research and Technology (ranked the 5th).

When it comes to the top contributed researchers in this field, the first one is Salari, E (Sun et al., 2009; Ying and Salari, 2010; Yu and Salari, 2011) from the University of Toledo, whose research covers the topics of target detection, CT image, image fusion, super resolution, sparse representation, etc. With broad background and research interests, he has made significant contributions to automatic pavement crack detections using intelligent technologies. Correia, P.L., Oliveira, H., and Xu, B., also have broad research interests covering computer science, image processing, pattern recognition, machine learning and deep learning, data analysis, etc, also made significant contribution to automated pavement distress detection and performance assessment (Huang and Xu, 2005, 2006, 2007; Li et al., 2009, 2010; Oliveira and Correia 2008, 2009, 2013, 2014; Ouyang and Xu, 2013; Xu and Huang, 2005; Yao et al., 2015).

In view of this results, the following findings can be concluded as following.

(1) Utilizing the state-of-the-art machine learning and deep learning technologies for automatic pavement distress detection and performance assessment is the future trend in this area without any doubt.
(2) More researches in using advanced computer vision and machine learning technologies for pavement distress detection should be conducted to prolong the service life of pavements.
(3) Even though a significant number of researches have been conducted in using the state-of-the-art technologies for road distress analysis, most of the proposed solutions are still tested on laboratory level. Therefore, the overall performance of those method should be optimized to meet the requirement of practical application.

6.2. *Intelligent pavement construction and maintenance*

Pavement construction and maintenance inside the scope of transportation infrastructure industry is now facing their own problems, which covers pavement construction management, compaction technology and pavement maintenance decision-making along with human experience and interactions. In the context of "industry 4.0", pavement engineers have paid more attention to the digitalization and intelligence for their construction-related activities. By incorporating the artificial intelligence-based technologies, the traditional pavement construction and maintenance works have been reshaped and

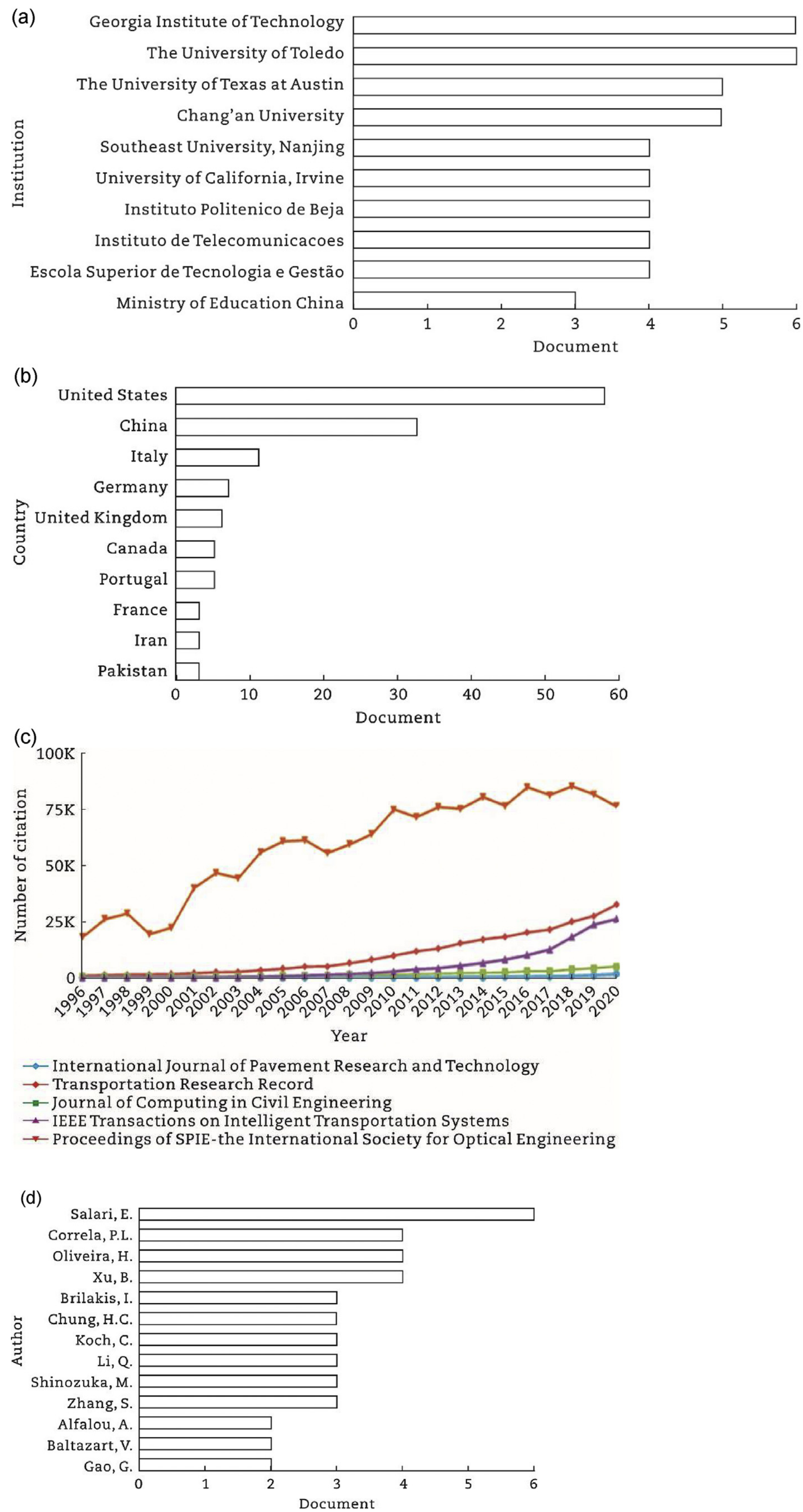


Fig. 83 – Pavement distress research trend analysis. (a) Top affiliations. (b) Territories. (c) Citations. (d) Authors in recent years.

the automation, efficiency, reliability and productivity can be significantly improved. At present, most of the relevant studies are still conceptually proposed and limited to theoretical hypotheses (Pan and Zhang, 2021). To accelerate extensive applications of these intelligent technologies toward a growth phase, it is believed that the interest in these topics will keep on the rise and become more acknowledged. The overall objective of all related studies in the near future is to pursuit the long-term sustainability of pavement networks (Dabous et al, 2020).

6.2.1. *Intelligent pavement construction management*

Building Information Modeling (BIM) is proposed as a digital information database that can collect, manage, analyze, and process construction-related information throughout the whole construction duration (Alizadehsalehi et al., 2019). Comparing with the traditional construction management system, the BIM is capable to generate multi-dimensional (*n*-D) and data-rich models and is generally accepted as the most promising technology to optimize the construction quality, cost-effectiveness, efficiency, and sustainability (Alizadehsalehi et al., 2020b). Specifically, BIM can be utilized as an effective and efficient management tool in different phases of a new or existing infrastructure with varying purposes, such as position determination, energy simulation, construction schedule fabrication, cost evaluation, visualization, equipment management, and design drawings revision (Alizadehsalehi et al., 2020a). In addition, with the increasing pursue of safety in architecture, engineering, and construction (AEC) industry, BIM was utilized by many scholars to conduct safety inspections (Ibrahim and Golparvard-Fard, 2019).

6.2.1.1. Standardized integration of BIM information resources. Data is the basis of digitization and information construction. With the progress of project construction, the existing data and information resources will be gradually increased, continuous updating of multi-source data is the foundation of information resource management. Large scale and complex structure of transportation infrastructure lead to heterogeneity, diversity and scattered storage of information resources. Nowadays, BIM just involves a certain stage of the whole life cycle of the project or a professional field of application, at the same time, due to differences in application system or software, the software information sharing is difficult, and a wide range of information resources integration lead to data redundancy and waste of resources. For example, the BIM modeling software in the design stage mainly provides the geometric information of engineering components, and the budgeting software in the construction management stage provides the cost information of BIM components. Project information integrated management is beneficial to provide the integrity, timeliness and interactivity of information, and realize the dynamic optimization or active control in the whole process of the project, it reduces the cost of information asymmetry and improve the benefits of the project (Le et al., 2019; Marinho et al., 2021). Therefore, effective integrated management of information resources is the basis of efficient engineering construction management.

By identifying, screening and classifying information resources and integrating them with BIM model, a multi-dimensional BIM model is formed, which is an effective way to integrate information resources. BIM and information can be integrated in the whole life cycle, conceptual framework for the integrated implementation of BIM is established to present building information, such as BIM information flow, BIM model chain and BIM workflow (Ma et al., 2018b). Based on spatial decomposition structure and information decomposition structure, realizing the connection between construction site drawing file and 3D design components (Cha et al., 2018b). Considering the construction project duration, task priority relationship, resources, cost, application mode and other information, the corresponding relationship between BIM model components and work package template is built (Wang et al., 2020f), furthermore, identified progress, safety report and other document information are generated in the construction process as structured information according to the degree of information overlap (Lee et al., 2018). Besides, risk breakdown structure (RBS), work breakdown structure (WBS) and BIM are adopted to construct a triangular conceptual framework (Zou et al., 2019a), so as to build a 4D BIM model that can be used to identify the duration of risk impact and support risk management analysis, equipment inspection and maintenance data are integrated to improve the efficiency of BIM visualization (Motamedi et al., 2014).

BIM technology mainly employs industry foundation class (IFC) as a common standard for information integration and exchange. Due to the limitation of the number of entities described by the IFC standard, the IFC standard is expanded and applied according to construction needs. The IFC standard is used to propose the structure analysis model to realize the meshless stress analysis of the model, the IFC building structure model and integrated legal data establish the IFC database for land management to meet the needs of spatial analysis of engineering management (Park et al., 2020). During the process of traffic infrastructure construction, information integration based on BIM model aim at the specific object of construction stage. To improve information extraction, database building, BIM data access method and computer visualization of three-dimensional model, BIM information integration method for traffic infrastructure in the whole life cycle is still a problem. In addition, a large amount of information is recorded in external databases (spreadsheets, electronic documents, scanned copies of paper documents, video files, etc.), but the extraction and integration methods of information resources in the existing electronic documents remain to be studied (Maryam et al., 2021; Wu et al., 2021).

6.2.1.2. Construction field capturing technologies. BIM is defined as the integration of structural characteristics, information and functional requirements of the whole life cycle phase of a project into a high-precision model, while covering the time dimension related to the schedule. The establishment of the operation and maintenance management platform provided a new idea for the application of BIM technology in the whole life cycle stage. To sum up, the application of BIM has developed rapidly from the 3D visualization stage to the 5D stage where time and cost are taken into consideration, and construction schedule can be simulated and controlled. At the same time, a cost management system based on BIM platform has been formed. However, these cost benefits have not been quantified and the whole life cycle cost calculation has not been carried out, so it is impossible to quantify the benefits brought by BIM in the project, which has certain limitations. Nowadays, to capture and monitor the changes in the construction site, many sensors are used, such as the global positioning system (GPS) (Wu et al., 2017b), radio frequency identification (RFID) (Zheng et al., 2013), and ultra-wide band (UWB) (Hwang, 2012). However, those sensors can only obtain the rough shape of obstacles but are difficult to acquire high-resolution 3D information of the environment. And, those onboard sensors can only observe some nearest dynamic change or obstacles, thus, the re-planned path which is adjusted based on such local information may keep close to obstacles, this increases the collision possibility during the crane operation (Chen et al., 2018d). To fully identify the shape of obstacles and changes of environmental information in the construction site, many 3D measurement technologies are developed to build a comprehensive 3D model of the as-is construction site, such as the GIS and the laser-based sensors (Cheng and Teizer, 2012) and the camera-based sensors (Chen et al., 2017d; Yang et al., 2014b). However, both the LiDAR and camera systems are required to be fixed on the construction site. As a result, when in the congested construction site, it is difficult for the two technologies to always maintain a clear line-of-sight under the influence of moving objects, which limits their information gathering effectiveness (Fang et al., 2016a). To address this challenge, mobile information capturing system is considered, such as the camera system on mobile unmanned aerial vehicles (UAV) (Nakano et al., 2016). Based on the onboard cameras on the UAV, a series of hybrid images can be continuously collected during low-altitude flights, meantime, the GPS and camera pose information will be captured and stored for each image. Thus, the image position can be determined, based on which, contextual UAV images can be matched. Then, a 3D surface model can be modeled by photogrammetry methods quickly (Fig. 84).

6.2.1.3. Multi-source spatial data fusion. In the context of the establishment of digital twins, the integration of the data model of traffic infrastructure such as roads, railways and sidewalks (Beil and Kolbe, 2020) and geographic information system (GIS) is proposed, and the establishment of BIM model of traffic infrastructure provides a solution for it. The complementary relationship between BIM and GIS is reflected in that BIM and GIS adopt different geometric expression and semantic information description methods in the data model: BIM focuses on 3D visual intelligent construction design and geometric semantic expression; GIS focuses on hierarchical organization and management for multi-source data. 3D GIS system should not only pay attention to 3D visualization rendering ability, but also need to improve the depth of 3D GIS application. The research on the integration of the two systems is mainly focused on the data format conversion, the conversion of IFC to CityGML and the coursing processing of high-precision BIM model data into GIS data. The conversion of the two mainly includes two aspects, geometry and semantics. The conversion methods include BIM and GIS basic model data conversion or integration with the help of intermediate format. Based on IFC and CITYGML, a lot of research work has been done on the geometric and semantic information conversion (Biljecki et al., 2021; Chen et al., 2018e; Deng et al., 2016; Donkers, 2013; El-mekawy et al., 2012; Mignard and Nicolle, 2014; Skandhakumar et al., 2018; Tolmer et al., 2017). Based on the analysis of the accuracy of IFC model and the multi-level details of CityGML, IFC geometric model is extracted and reconstructed to provide information into GIS surface model with correct semantic information, so as to realize the conversion of IFC model to CityGML LOD3 model. Besides, the research on the integration of the two is also focused on the practical thematic application (Alsaggaf

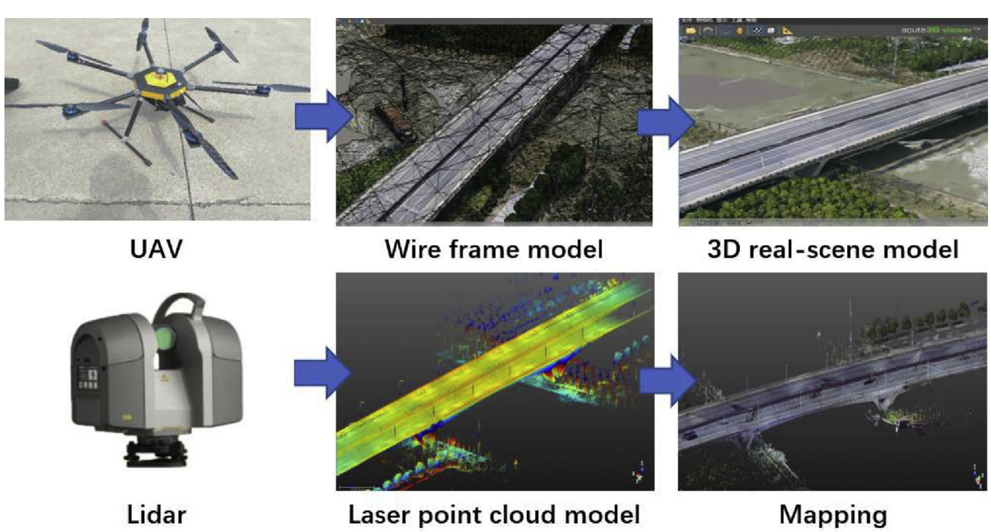


Fig. 84 – Difference between UAV and Lidar modeling.

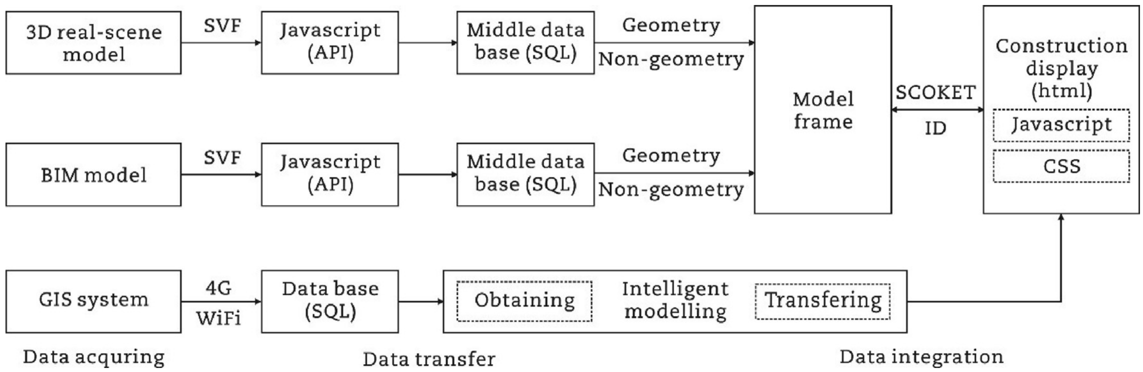


Fig. 85 — A typical multi-source spatial data fusion.

and Jrade, 2015; D'Amico et al., 2020; Karan and Irizarry, 2015; Zhao et al., 2019). From the perspective of application, there are few effective conversion tools for format conversion between BIM and GIS, and their integration still faces various challenges. Research on multi-source data fusion is mostly based on specific cases, so it is difficult to guarantee its universality and scalability. Therefore, integration means applicable to the whole industry in the field of transportation infrastructure still need to be studied. In addition, the semantic mismatch between BIM and GIS due to the differences in detail levels, data types and coordinates still needs to be reasonably solved, and the advantages of BIM integration GIS technology in the analysis and utilization of information resources are not fully reflected (Fig. 85).

6.2.1.4. *Research on schedule management based on BIM*. A 4D model can be obtained by linking the construction period information of BIM model components. Therefore, the progress model based on BIM is also called 4D model. 4D model first appeared in the construction industry, such as 4D CAD technology, and later became a professional term, and gradually developed into 4D theory. In 1998, the Center for Integrated Facilities Engineering (CIFE) of Stanford University in the United States proposed to combine graphic information with progress information and to simulate the construction process with the help of computers. The main method adopted was to insert time progress into the 3D model, which formed the early 4D theory (Hu and Zhang, 2011). On the basis of their research, many scholars tried to associate 3D graphics with progress information through computers, and found that the construction process could be expressed visually (Collier and Fischer, 1996; Norberg, 2008; Vaugn, 1996). Later, due to the development of BIM technology, foreign scholars conducted further studies on 4D technology based on BIM model, and achieved more results in 4D model creation and 4D construction progress software development (Chau et al., 2005; Chen et al., 2013; Kataoka, 2008). In terms of 4D construction schedule software development, the CIFE of Stanford University in the United States has also developed a 4D product model system that can optimize construction collisions. The system consists of three modules: collision detector, progress simulator and result analyzer. Three-dimensional collision identification, construction schedule simulation, schedule modification and actual construction time formulation are completed respectively (Mckinney and Fischer, 1998). The center later developed a new 4-dimensional product model system that can efficiently generate production schedule and cost analysis reports while performing 4D construction simulations. Bechtel has done a lot of research on 4D simulation and developed a graphic simulation tool, 4D-Planner software, which supports direct import of 3D models and plane plans, and the correlation between BIM models and plans, so as to automatically generate 4D simulation animations, which is convenient for managers to conduct comprehensive 3D construction schedule management (Fig. 86).

6.2.1.5. *Application of BIM information management system*. Nowadays, the transportation infrastructure information resource management system is not only limited to the application of two-dimensional business management system, but also integrates the transportation infrastructure information management system with BIM technology, GIS technology, artificial intelligence technology and virtual reality technology to realize the immersive, omnidirectional and three-dimensional visualization information management

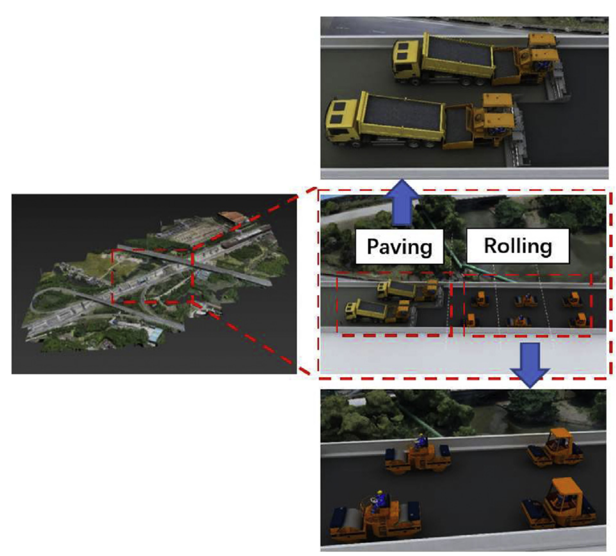


Fig. 86 — 4D simulation of pavement construction.

and utilization. The BIM information resource management platform takes the BIM model as the core, comprehensively integrates and innovatively applies modern information technologies such as cloud computing and big data, and realizes the digitization of information resource elements such as three-dimensional model data, management resources and fixed assets of the whole life cycle of transportation infrastructure construction.

Information resources are continuously integrated, classified and integrated through scene carriers such as BIM and GIS 3D models. Focusing on collaborative design, fine construction, intelligent operation and maintenance, the framework of core business system integration and application management system is constructed. Web-oriented model and information interaction framework based on cloud computing improve the model analysis ability, and the improved BIM model could adapt to a variety of analysis requirements. This conceptual framework can provide automatic and intelligent decision support for design and construction, and can be popularized in construction projects in many fields (Chen et al., 2016c; Juan, 2013; Sanguinetti et al., 2012; Singh et al., 2011). The WebGL 3D BIM service based on this framework can realize the distributed storage of big data of massive building models and the dynamic expansion of BIM model based on concurrent access of multiple users (Getuli et al., 2016; Zou et al., 2017), In order to meet the requirements of updating heterogeneous data from multiple sources, concepts and technologies such as cloud computing, service-oriented architecture, distributed storage and WebGL rendering have been widely applied in the establishment of system architecture (Jardim-goncalves and Grilo, 2010; Polter and Scherer, 2017).

To meet the needs of multi-party coordination and fine construction, large-scale construction projects focusing on transportation infrastructure have developed a new professional information management mode in the construction field (Alreshidi et al., 2016; Beach et al., 2017; Zhang et al., 2017c). Considering security issues such as data privacy and unified authorization from the perspective of the platform, the logic between multi-data and proposed simulations are analyzed to present deduction system based on micro-service and mixed display. In the process of transportation infrastructure construction, improving the utilization rate of information resources is beneficial to the application value of information resources. At the same time, by strengthening the construction of information management platform, the identification and processing efficiency of information resources should be improved to lay a more solid foundation for the full utilization of information resources and information (Chen and Nguyen, 2017; Grilo and Jardim-Goncalves, 2013; Ivson et al., 2018; Jiao et al., 2013a, b; Li et al., 2018e; Su et al., 2021).

6.2.2. *Intelligent compaction technology for asphalt pavement*

As we all know, the compaction is a key procedure in construction process of asphalt pavement. Lack of compaction and undemanding quality control of compaction will directly affect the strength, stability and durability of asphalt pavement (Alireza et al, 2014; Dan et al., 2020b; Jia et al., 2020; Mohiuddin and Rafiqul, 2017). At present, asphalt pavement compaction detection equipment and methods (core sampling, nuclear densitometer, non-core densitometer, etc.) are all point instead of surface, which cannot meet the requirements of representing the compaction quality of a large area of asphalt pavement. Meanwhile, it cannot meet the needs of the rapid development of domestic highway construction in China. Therefore, the development of nondestructive, continuous and quantitative technology and its application to detect the compaction degree in road construction projects has been the general trend under the background of "new infrastructure" and "intelligent construction".

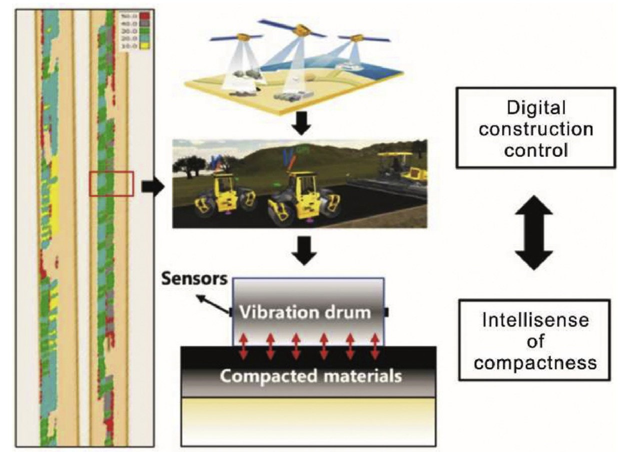


Fig. 87 – Schematic diagram of intelligent compaction system.

The "intelligent compaction technology (ICT) of asphalt pavement" is based on the vibratory roller as the carrier. By installing GPS positioning system and embedded vibration characteristic testing equipment in the vibratory roller, the vibration characteristics of the vibratory roller and the feedback parameters of the road surface to the vibration characteristics can be collected in real-time during the vibratory compaction (Fig. 87). Through a series of data analysis, the parameter characteristics of the pavement materials in the construction process are obtained, so as to achieve the purpose of analyzing and monitoring the quality of the pavement compaction (Hu et al., 2017; Xu, 2016). However, the current intelligent compaction technology of asphalt pavement is far from reaching such a standard. Although many scholars have also conducted a series of exploratory studies in this field (Antonio et al., 2013; Beainy et al., 2012; Chang et al., 2014; Hu et al., 2018; Kassem et al., 2015; Oloufa, 2002; Prakash et al., 2013; Singh et al., 2015; Wang et al., 2017a, 2019b; Xu et al., 2012, 2015a; Xu and Chang, 2014; Zhu et al., 2018a), due to the nonlinear change of material properties during the compaction process of asphalt pavement materials, the multiple influences of pavement structure, and the complexity of vibration compaction system, the current empirical and experimental methods are faced with new challenges which is mainly reflected in the following three aspects.

6.2.2.1. *Weakened IntelliSense of ICT*. As the ICT mentioned above, its essence is to continuously identify the physical parameters of the compacted material according to the vibration response of the roller, and then automatically adjust the compaction process parameters of vibratory roller according to the value and distribution of the parameters to optimize the compaction operation, so as to obtain better compaction degree (Xu, 2016). Nevertheless, it is a pity that most of current methods are not real intelligent technology, but the digital construction recording device for the rolling construction of filling materials (asphalt mixture, soil and soil-stone, etc.). Generally speaking, such devices are basically equipped with satellite positioning system (GPS, BD or GNSS), and some of them also integrate compaction meter, whose main function is to collect and record parameters such as rolling times, rolling speed and vibration frequency, etc., and the temperature also needs to be collected in asphalt pavement compaction (Chang et al., 2014; Oloufa, 2002; Prakash et al., 2013; Singh et al., 2015; Wang et al., 2017a, 2019b, i). Due to the large limitation of compaction meter value (CMV), this kind of device seldom mentions the problem of identifying the compaction quality itself, and too much emphasis on the role of high-precision satellite positioning system in intelligent compaction technology, which does not reflect the real meaning of intelligent technology.

In fact, the digital construction method is mainly the compaction process control method, which monitors and controls the rolling times in the compaction. Digital construction method pays more attention to quantification, and its construction of rolling section must be exactly the same as test section, otherwise the control parameters (rolling times, rolling speed, etc.) will be insignificance and meaningless (Wu et al., 2017a). In essence, this kind of device or method mainly lacks the key technology to identify the parameters of filling materials and control the compaction process with real-time feedback, which is the "technical bottleneck" of intelligent compaction.

6.2.2.2. *Poor adaptability of asphalt pavement compaction index*. In the intelligent compaction technology, whether the compaction quality control index can truly reflect the compaction degree of the filling materials is the critical problem to be solved (Fig. 88). At present, it is generally divided into empirical indicators (such as the harmonic ratio index of the compaction meter CMV, CCV, RMV, THD, etc.) (Huang et al., 2020b; Wu et al., 2017a) and mechanical indicators (such as dynamic modulus E_{vib}, resistance coefficient K_s) (Anderegg, 1998; Krober et al., 2001).

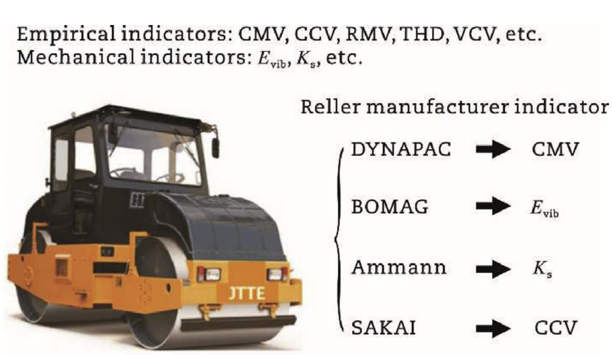


Fig. 88 – Types of compaction quality control index.

As the compaction process progresses, the dynamic characteristic parameters of the compacted material and the vibrating drum also change regularly, which must be related to the compaction degree of the material. As long as this law can be grasped and utilized, it can be used to characterize the compaction degree of the filling material (Qiu, 2015). Based on this concept, many scholars have proposed the intelligent compaction meter value (ICMV) (Hu et al., 2017) and a series of derived indexes (Anderegg, 1998; Hu et al., 2017; Huang et al., 2020b; Jia et al., 2019; Krober et al., 2001; Qiu, 2015; Wu et al., 2017a; Zhu et al., 2018a), which represent the pavement compaction degree by using the response law of vibrating drum of roller. However, its disadvantages of large dispersion and small correlation are gradually exposed with the change of working conditions.

Compared with the empirical method, the mechanical method can fully consider the influence of many factors and better reveal the changes of the compaction process. Therefore, this method is more suitable for the intelligent compaction control system. However, it also encounters technical bottlenecks in theory and engineering practicability, the reasons are mainly reflected in the following aspects.

(1) The construction process of asphalt pavement is affected by many complex factors

In terms of compaction machinery, the influencing factors mainly include the exciting force, compaction work, amplitude, vibration frequency and rolling speed of the roller, while in terms of compressed materials, subgrade and base, type of asphalt mixture, temperature of asphalt mixture and support conditions of the underlying layer are all major influencing factors (Fig. 89).

(2) Difficulty in model calculation caused by jumping vibration of vibrating drum

In the construction of asphalt pavement, the jumping vibration phenomenon is mainly caused by the excessive amplitude and frequency of vibratory roller, and also includes the excessive rebound caused by the uneven pavement materials. The basic precondition for the application of the existing model is that there is no jumping vibration between the vibrating drum and the compacted materials, and they need to be in close contact. In reality, the phenomenon of jumping vibration generally exists in the vibratory roller after the filling materials is fully compacted. In the case of jumping vibration, the vibration is nonlinear, and the frequency domain of vibration will become very complex rather than simply the occurrence of frequency doubling harmonics, so the reliability of the harmonic ratio model will be greatly reduced (Wu, 2020). Moreover, in the case of jumping vibration of various indicators based on vibration mechanics model, the vibration mechanics model cannot carry out accurate calculation, that is, the model is no longer applicable (Xu and Chang, 2018).

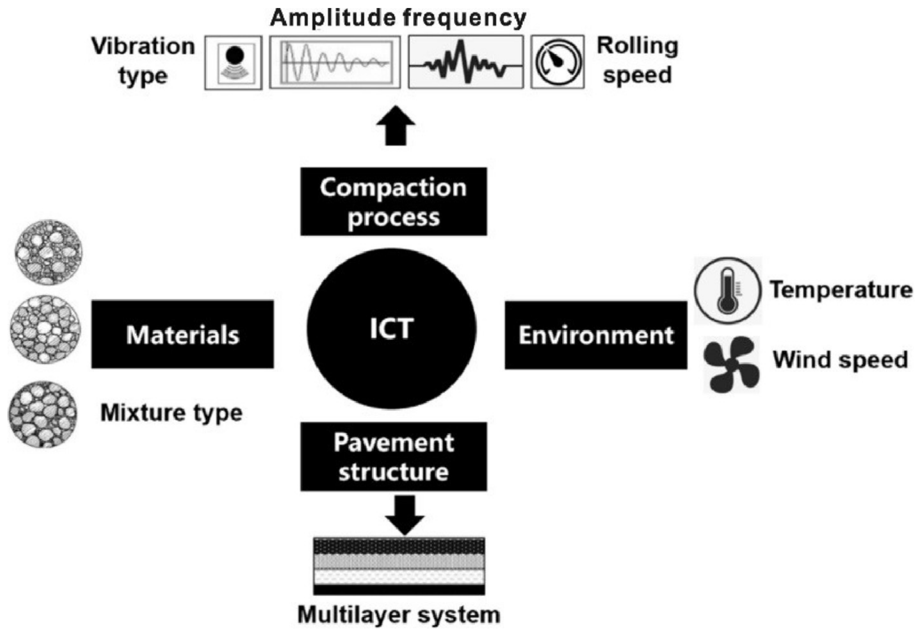


Fig. 89 – Influence factors for ICT in construction process of asphalt pavement.

(3) There are challenges to the numerical stability and computational efficiency of the theoretical model

The actual pavement structure is layered and it is usually simplified to a semi-infinite space under plane-strain condition in modeling and solving. In order to simplify the solution, some researchers assume that all the acceleration terms are zero (Dan et al., 2015), making it a statics problem. However, this simplification will deviate from the actual situation and requires a semi-empirical solution to correct it completely, and the correction is also highly variable. On the other hand, various mathematical methods, such as transfer matrix method (Lu et al., 2012), stiffness matrix method (Wang et al., 2021b), finite element method (Dong et al., 2013) and Galerkin method (Peng and Fu, 2020), are adopted to solve the problem. The above methods have some disadvantages, such as the singularity matrix is easy to be generated in the process of analytical method, which reduces the calculation accuracy, and the calculation efficiency of numerical method is low and time-consuming under the premise of ensuring the accuracy.

6.2.2.3. *Insufficient research on asphalt mixture in vibratory rolling*. In the process of pavement compaction, asphalt mixture is in a state of low compactness and high temperature, and the compaction process of asphalt mixture is a process of gradual transition from loose and plastic state to cohesive state with high tensile strength. In this process, the particles of asphalt mixture will be deformed and rearranged, thus forming a compact structure (Fang et al., 2019c). As for the compaction of loose hot asphalt mixture, many literatures are based on the relationship between compaction technology and pavement compaction degree (Masad et al., 2015; Liu et al., 2019a). However, there are few studies on the change law of mechanical properties of materials in the process of compaction. At present, the research on mechanical properties of materials focuses on visco-elasto-plastic constitutive model and dynamic modulus, and the characterization methods mainly include three categories. The first method generally adopts indoor test to simulate the stress conditions of asphalt mixture through the MTS test (Chen et al., 2007d), gyratory compaction molding test (Fattah et al., 2019) and viscous, elastic and plastic theory (Beainy et al., 2013; Zheng et al., 2010) to analyses the rheological properties of asphalt mixture compacting process, establish the constitutive relations of hot asphalt mixture, and use test data for fitting to obtain the material parameters of visco-elasto-plastic model. In the study of elastic modulus, SGC and UTM equipment are mainly used to test the dynamic modulus under a certain temperature (−10 °C–60 °C) and a certain loading frequency (<25 Hz). The time-temperature equivalence principle is adopted to obtain the master curve of dynamic modulus of asphalt mixture (Luo et al., 2020b; Witczak and Fonseca, 1996). The second type mainly adopts finite element and discrete element numerical simulation methods to simulate the compaction deformation process of asphalt mixture under vibration load (Masad et al., 2015). In the third category, sensor elements are used to test the material mechanical response of asphalt pavement in the process of vibration rolling, including acceleration, stress, particle deflection angle, etc. (Wang et al., 2019g, h). From the above three research methods, there are some qualitative and quantitative problems that cannot be avoided between the theoretical model and engineering application.

(1) During the service of asphalt pavement, the pavement temperature is generally no more than 60 °C, while the pavement temperature in the process of compaction can reach 150 °C, and the temperature after compaction is also about 90 °C (Wang et al., 2019a). The difference of temperature leads to a great variation of the stress

distribution in the pavement. The key is that the hot loose asphalt mixture is more prone to stress concentration, and Poisson is relatively large. The lateral constraint plays a more important role in the deformation of the compacted pavement. Therefore, in the actual pavement vibration rolling construction, the force of asphalt pavement material must be lateral confined, and the contact stress under the vibrating drum can reach more than 1.5 MPa. The loading frequency is generally 30–50 Hz, and the high-frequency roller can reach 67 Hz (Dan et al., 2020a). However, at present, there are few researches on the mechanical behavior of asphalt mixture under the condition of lateral confined.

(2) To ensure the pavement can be fully compacted, it is necessary to adjust the compaction work (energy) for different compacted materials, that is, to adjust the vibration rolling parameters (amplitude and frequency). However, how to adjust the compaction work and energy in intelligent compaction is mainly based on experience at present (Van and Moony, 2008). There is an inevitable relationship between the degree of compaction of compacted materials and the compaction energy. Some researchers have proposed to use energy-related indexes to represent the compaction degree of pavement (Mooney and Rinehart, 2007; Wu, 2020). However, the quantitative method of energy dissipation is greatly influenced by the compacted material and structure, especially the change rate of energy dissipation of the compacted material is the most important sensitive parameter.

6.2.3. *Intelligent pavement maintenance decision-making*

Transportation infrastructure acts as an essential component of civil infrastructure, providing vast mobility and economic benefits to the modern society. With the expanding pavement network and growing traffic, the pavement system has been deteriorating and the demand for maintenance, rehabilitation, and replacement (MR&R) activities has become ever greater and more complicated (Donev and Hoffmann, 2020). Thus, how to effectively maintain the large-scale pavement network with limited resources and increasing demands is one of the major challenges for decision makers from the department of transportation (Torres-Machi et al., 2017). In most cases, the decision makers need to figure out which pavement sections need to be treated, when to take the MR&R actions and which maintenance treatments are appropriate. Effective MR&R strategies can greatly improve the pavement performance after maintenance, extend the service life, and maximize the social and economic benefits of the roadway infrastructure. As Fig. 90 illustrates, Galehouse et al. (2003) found that if $ 1 is spent on "the right treatment on the right pavement at the right time," it can eliminate or delay spending $ 6 to $ 10 on rehabilitation or reconstruction later.

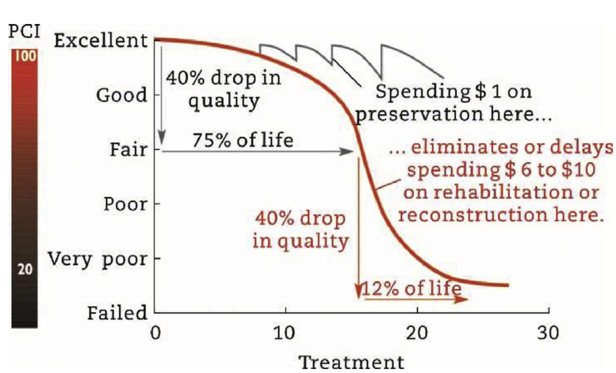


Fig. 90 – Relationship between pavement condition when treatments are applied and the treatment cost (Galehouse et al., 2003).

6.2.3.1. *Basic functional framework*. A thorough look at the pavement maintenance decision-making is a process to optimize the allocation or utilization of the resource including budget, labor, and facility to achieve a better overall pavement performance (Dos Santos et al, 2019). Many strategic decision-support tools (e.g., pavement management system (PMS)) have been developed by the transportation stakeholders to evaluate and predict the pavement performance over time, identify the maintenance demand for each pavement section, determine the most cost-effective MR&R activities and ultimately realize the efficient allocation of limited resources (Yao et al, 2019; Zhou et al, 2014).

The pavement maintenance optimization problems could be classified into different types according to various criteria. In terms of the level of decision-making, it can be divided into project-level and network-level. Project-level generates decisions for specific projects while network-level deals with the budgets and general resource allocations over an entire network.

According to the number of optimization objectives, the problem can also be divided into single-objective and multi-objective optimization. Single-objective optimization aims to find the best solution that satisfies all the constraints and produce the best value on the single objective, such as cost minimization, performance maximization, carbon emission minimization, etc. In contrast, multi-objective optimization needs to find a vector of decision variables that optimizes various objective functions at the same time. It considers the coordination and tradeoffs between multiple goals which are usually in conflict with one another. Various techniques have been used to formulate and solve the multi-objective optimization problems in pavement management, including weighting sum method, Pareto optimization and so on (Wu et al., 2012).

The modeling methods for resource allocation in pavement management can be categorized into top-down or bottom-up approaches (Yeo et al., 2010). Top-down approaches usually divide the whole pavement network into several groups and pavements in the same group have the same characteristics. The optimal strategy is represented by the probability distribution of various maintenance treatments under a given state. The computational cost of this approach is attractive and almost independent to the size of the pavement network. However, the top-down approach considers all pavement sections as a homogeneous whole but ignores the specific characteristics of each single pavement section. Bottom-up approaches first determines the optimal treatment for each pavement section and then evaluate the segment-specific decisions at the network level. It can accommodate heterogeneity across the network, and provide segment level recommendations. However, in most cases, the bottom-up approaches only consider the budget constraint for the current year while ignoring the budget constraints for the future year. As a result, the optimistic assumption of implementing the optimal policies in the future years cannot always be guaranteed (Medury and Madanat, 2014). The simultaneous optimization approach selects both the optimal segment-level treatment and the optimal budget allocation decision, but the computational complexity is considerably increased.

To obtain a cost-effective and even eco-friendly pavement maintenance and rehabilitation strategy, it is of great importance for highway agencies to incorporate the powerful analytical and mathematical tools into the PMS to realize the effective and informed decision-making. Meanwhile, the maintenance optimization methods were constantly changing with the changes in pavement management practices and the development of mathematical tools.

6.2.3.2. *Expert experience-based methods*. Expert knowledge and engineering experience play an important role in the pavement maintenance decision-making. At the very beginning, the determination of pavement maintenance treatment heavily relied on the expert's judgement on the current condition of the in-service asphalt pavement (Allez et al, 1988). Although this method is quite simple and easy to implement, it highly depends on the experience of the technical experts. With the development of autonomous pavement condition survey technologies, the quantitative evaluation of pavement performance using various indicators (e.g., pavement condition index (PCI)) become available, which makes the threshold-based decision-making methods widely used in practice (McQueen and Timm, 2005). In this method, pavement MR&R would be triggered once the pavement condition meets its prescribed threshold, which was determined through experts' experience (Chen et al, 2017e). Other expert experience-based methods such as decision tree are also widely utilized in PMS (Hicks et al., 1997; Dong et al, 2015). These methods are straightforward, flexible and easy to be implemented by practitioners. Decision tree usually establishes a set of rules for selecting a particular type of treatment through the use of branches that define various sets of decisions. Currently, the expert experience-based methods are still the most widely used decision-making methods in practice. However, these methods can hardly consider all the influencing factors and the complex combination of pavement conditions. They may not be able to give a decision considering the long-term effectiveness of the treatment and the future deterioration of the pavement either.

6.2.3.3. *Priority-based methods*. The priority-based methods evaluate the prioritization of the maintenance activities considering different criteria or objectives. A typical representation is the ranking method (Peraka and Biligiri, 2020). The ranking method could be used in both project-level and network-level decision-making. In network-level, a cumulative priority index is defined with a variety of factors such as traffic loading, distresses, and future condition. The segment with the high priorities would be maintained first. In project-level, economic indicators such as the cost-benefit ratio and life cycle cost of all alternatives for each segment would be calculated first. Ranking method would then be used to select the most cost-effective treatment. The limitation of priority-based methods is that only limited alternatives or scenarios are considered. When the problems are complicated, the priority of the alternatives or projects cannot be easily measured or enumerated.

6.2.3.4. *Mathematical programming-based methods*. Mathematical optimization methods are increasingly applied to assist in pavement management decision-making as it faces more and more challenges, such as the expanding pavement networks, limited resources and facilities, environmental pollution problems, conflicting optimization objectives, and uncertainties. To date, various mathematical programming-based methods have been used with different characteristics and application scope, including linear programming (Amin and Amador-Jiménez, 2016; Golabi et al., 1982; Mbwana and Turnquist, 1996), zero-one integer programming (Guo et al., 2020a; Li et al., 1998), mixed integer programming (Lee and Madanat, 2014; Medury and Madanat, 2014), dynamic programming(Yeo et al., 2010; Zhang et al., 2010a) and so on. If an optimization problem can be expressed in terms of linear relations and there is no discrete constraint, then the problem can be solved by using linear programming. Golabi et al. (1982) first developed a linear programming formulation for the Arizona pavement management system (PMS). Integer programming is a mathematical optimization problem in which some or all of the decision variables are restricted to integers. A large number of researchers simplify the pavement maintenance decision-making optimization as an integer programming issue and the solution could be divided into exact algorithms and heuristic methods (Ouyang and Madanat, 2004). The dynamic programming decomposes an optimization problem into simpler sub-problems and uses the optimal solution of the sub-problems to find an optimal solution of the up-scale problem. Dynamic programming is generally used to optimize multi-year pavement maintenance strategies because of the sequential nature of pavement maintenance and reconstruction strategies in the analysis period. Although these methods could produce the optimal MR&R strategy considering the long-term effectiveness and resource constraints, they would become computationally intensive in larger scale pavement optimization problems. This also motivated the application of various approximation approaches to solve such problems, including Lagrangian relaxation technique (Gao and Zhang, 2012), approximate dynamic programming (Kuhn, 2010), etc.

6.2.3.5. *New-gen machine learning-based methods*. Due to the recent advances in optimization theory and artificial intelligence, growing number of studies in pavement management have attempted to solve the pavement optimization problems using advanced ML methods. Neural networks (NN) has gained increasing attention in solving complex engineering

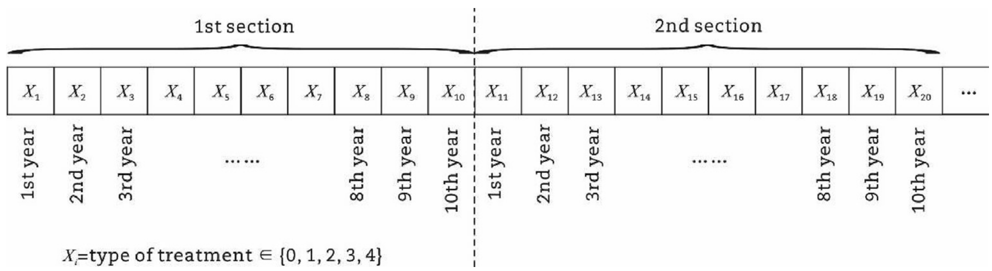


Fig. 91 – Representation of decision variables (Chootinan et al., 2006).

problems in different disciplines. Pavement maintenance optimization is also one of its important application areas. NN is a nonlinear dynamic system. It does not need to assume the relationship between input variables and output variables in advance, but establishes the nonlinear mapping relationship between input and output through sample learning. The common application of NN in pavement maintenance optimization is to model the expert experience system to simplify the decision-making process (Abdelrahim and George, 2000; Elbagalati et al., 2018). However, this method is essentially a structured representation of the expert experience, so it is still heavily influenced by subjective factors.

Genetic algorithm (GA) and its variations are the most popular methods for both single-objective and multi-objective optimization in pavement community due to its good problem-solving capability for complex optimization problems. Chan et al. (1994) applied GA in pavement management for the first time. Since then, a large number of studies started to use GA to deal with the maintenance optimization problems (Chootinan et al., 2006; Fwa et al., 1996; Santos et al., 2019). These studies usually defined the pavement MR&R strategies as genes and then simulates the crossover and mutation of genes to obtain the solutions. Fig. 91 shows an example of the decision variable in GA which is represented as a chromosome In Fig. 91 X_i is the type of treatment ∈ {0, 1, 2, 3, 4}. In this case, the chromosome is coded as a series of multi-year maintenance activities for all pavement segments. However, it was also reported that GA may suffer from long computing time and premature convergence problems.

Furthermore, recent studies also leveraged reinforcement learning to solve the pavement maintenance optimization problems (Renard et al., 2021; Shani et al., 2021). Fig. 92 illustrates the framework of the reinforcement learning (RL) model proposed by Yao et al. (2020). RL is one of the three major areas of machine learning, alongside supervised learning and unsupervised learning. It is a common ML technique used for sequential decision-making problems. RL-based maintenance optimization methods promote the managerial flexibility for pavement infrastructure and has the potential to solve the complicated real-world optimization problems.

6.2.4. *Summary and outlook*

In the future, it is evident that more advanced technologies will be implemented to the pavement constitution and maintenance, which will be a rapid digital and intelligent transformation. Based on the above issues, difficulties and technical bottlenecks, future research is proposed to address the challenges summarized above from three aspects of "pavement

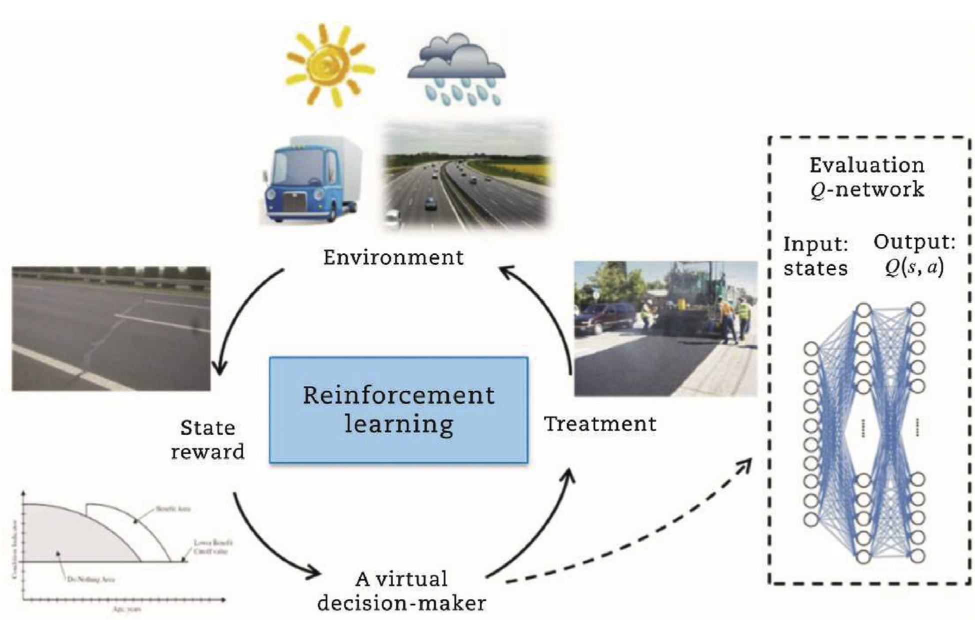


Fig. 92 – An example of the RL model in pavement management (Yao et al., 2020).

construction management", "pavement compaction technology" and "pavement maintenance decision-making".

(1) Pavement construction management

At present, the information management system based on BIM has been applied and verified in the project, but its main application stage is relatively single, mainly in the construction stage. At the same time, the research on BIM information resource management process oriented to the whole life cycle is mostly in the stage of theoretical or conceptual framework, and further research on the solution of information creation, integration and utilization oriented to the life cycle of transportation infrastructure is still needed. Furthermore, to enhance the resolution of BIM and monitor the construction schedule, more innovative technologies should be proposed to couple with the BIM, such as UAV, one of the innovative technologies used in industry construction safety monitoring and laser point cloud, an effective method to reconstruct spatial model. Innovative technologies should have the ability that capture the real-time images or videos of a construction site, realizing functions of site surveys, visual detection, construction monitoring, infrastructure measurement, and safety risk detection.

(2) Pavement compaction technology

On the basis of the existing mechanical test methods of asphalt mixture, it is necessary to expand the laboratory vibration compaction molding and unconfined material mechanical test combined with the characteristics of vibration compaction. It is necessary to focus on the main external factors of vibration compaction of asphalt pavement, such as pavement layer system structure, vibration compaction process parameters (compaction work, etc.), frequency, and rolling speed. Therefore, it can improve and perfect the existing mechanical and empirical models for vibration compaction system analysis, so as to illustrate the interaction mechanism of vibrating drum and compacted materials, and decoupling problem of compaction contact. The compaction process of asphalt mixture is inevitably accompanied by energy dissipation. Based on the test and analysis of mechanical dynamic response, and combined with the change law of material properties, it is possible to establish the energy dissipation model of vibratory compaction system, and the quantitative relationship between asphalt mixture compactness and asphalt mixture compactness. Therefore, it will help to break through the technical bottleneck of asphalt pavement compactness perception.

(3) Pavement maintenance decision-making

Given the importance of environment protection and energy saving, it is necessary to incorporate the environmental and social impact of the pavement maintenance treatments into the decision-making framework to enhance the sustainability of roadway infrastructure. Also, the expanding pavement network and frequent pavement maintenance demands necessitate the consideration of the interdependency between individual road segment in a network, such as benefits/costs associated with joint maintenance, the collective impact of segments on the road network connectivity or capacity, etc. At the same time, it is necessary to explore the effective method to solve the real-world large-scale pavement maintenance optimization problems. Most likely, RL-based maintenance optimization methods could be one potential most effective and efficient method for the complex pavement maintenance optimization problems.

7. Conclusions

The innovative pavement engineering theories and technologies are significant and the strong supports for the high-quality development of highway engineering. In this paper, the latest research efforts in pavement engineering were summarized and they were divided into the five categories: asphalt binder performance and modeling, mixture performance and modeling of pavement materials, multi-scale mechanics, green and sustainable pavement, intelligent pavement. The research advances, hot frontiers, challenges, and countermeasures for problems were analyzed and the future trends were prospected. In the future, JTTE will continue to pay attention to the latest research advances in order to provide reference for the majority of experts, scholars and engineers, and promote the intelligent, green and sustainable development of road materials and engineering.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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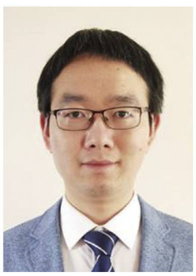

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Dr. Xin Qu is an assistant professor, master supervisor of roads and airport pavements at School of Highway, Chang'an University. His specialty areas include the technical properties, constitutive model, aging and modification mechanism of asphalt binder, separation of asphalt binder and exploration of the micro chemical structure of each fraction, and micro-scale modeling for asphalt binder; technical performance of emulsified asphalt binder and its mixture; as well as the recycling technology for SBS modified asphalt mixture.

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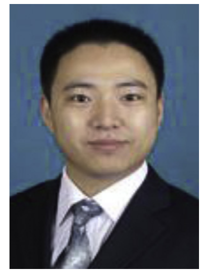
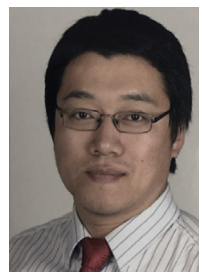
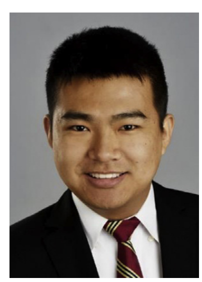


Chaohui Wang is a full professor and PhD supervisor of road engineering at the School of Highway, Chang'an University, China. His specialty areas include functional road materials, intelligent pavement technology, recycling of waste resources, and durability improvement technology of roads.



Prof. Dr.-Ing. habil. Dawei Wang is the professor in the School of Transportation Science and Engineering at Harbin Institute of Technology. His research interests and expertise focus primarily on asphalt pavement skid resistance, multi-scale characterization of the asphalt pavement mechanical behavior and functional pavement theory and technology. So far, he has directed or participated in more than 24 government-aided scientific research projects and published nearly 200 academic publications.



Dr. Di Wang is currently working in Department of Civil Engineering, Aalto University, Finland. He once worked as a post-doc researcher at the Technical University of Braunschweig, Germany. His research interests focused on the performance properties of asphalt pavement, especially in intermediate and low temperature characterization of bituminous materials, rheological properties of asphalt binder and mixtures, green and circular materials used in asphalt pavement, and sponge city, intelligent infrastructure.

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Changhong Zhou is a distinguished professor at Guilin University of Electronic Technology. His research interests mainly focus on the "road + x" multidisciplinary research field, including discontinuous numerical calculation theory, multi-physics coupling and multi-scale calculation method, intelligent simulation algorithm, GPU parallel acceleration technology, cold mix asphalt materials, natural disaster risk assessment, and development of road material experimental system.

Dr. Changjun Zhou serves as associate professor in School of Transportation & Logistics, Dalian University of Technology. He obtained his PhD degree in civil engineering from University of Tennessee, Knoxville. His research interests include long-life pavements, sustainable paving materials, paving material durability.

Xingyi Zhu is a professor of College of Transportation Engineering in Tongji University. She has been devoted to the research of multi-scale analysis and numerical simulation of asphalt concrete and functional/smart pavement.