Shanbara, HK, Dulaimi, AF, Al-Mansoori, T, Al-Busaltan, S, Herez, M, Sadique, M and Abdel-Wahed, T

The future of eco-friendly cold mix asphalt

Shanbara, HK, Dulaimi, AF, Al-Mansoori, T, Al-Busaltan, S, Herez, M, Sadique, M and Abdel-Wahed, T (2021) The future of eco-friendly cold mix asphalt. Renewable and Sustainable Energy Reviews, 149. ISSN 1364-0321

The Future of Eco-Friendly Cold Mix Asphalt

Hayder Kamil Shanbara [a], Anmar Dulaimi [b,*], Tariq Al-Mansoori [c], Shakir Al-Busaltan [d], Manar Herez [e], Monower Sadique [f], Talaat Abdel-Wahed [g]

[a] Department of Civil Engineering, College of Engineering, Al-Muthanna University, Al-Muthanna, Samawah, Iraq, hayder.shanbara@mu.edu.iq

[b] Department of Civil Engineering, College of Engineering, University of Warith Al-Anbiyaa, Karbala, Iraq; Ministry of Education, Karbala, Iraq; Department of Civil Engineering, Liverpool John Moores University, Liverpool, UK, a.f.dulaimi@uowa.edu.iq, A.F.Dulaimi@.ljmu.ac.UK

[c] Department of Civil Engineering, College of Engineering, Al-Muthanna University, Al-Muthanna, Samawah, Iraq, tariq.almansoori@mu.edu.iq

[d] Department of Civil Engineering, College of Engineering, University of Kerbala, Karbala, Iraq, s.f.al-busaltan@uokerbala.edu.iq

[e] Department of Civil Engineering, Faculty of Engineering, University of Kufa, Al Najaf, Iraq, manar.hirz@uokufa.edu.iq

[f] Department of Civil Engineering, Liverpool John Moores University, Peter Jost Enterprise Centre, Byrom Street, Liverpool L3 3AF, UK, M.M.Sadique@ljmu.ac.uk

[g] Civil Engineering Department, Faculty of Engineering, Sohag University, Egypt, dr.talaat_ali@eng.sohag.edu.eg

*Corresponding author.

E-mail addresses: a.f.dulaimi@uowa.edu.iq, A.F.Dulaimi@.ljmu.ac.uk (A.F. Dulaimi)

Abstract

Road pavements are pivotal to the infrastructure, transportation and ultimate efficiency of both the public and the economy. However, they are undeniably having detrimental effects on an already compromised environment. Consequently, a re-think about road pavement construction materials is of paramount importance. Cold mix asphalt (CMA) is a low carbon manufacturing approach to the production of flexible pavement material that has proved to be very promising, both economically and ecologically. This technology allows the manufacture of mixtures at ambient temperatures without heating huge amounts of aggregates and bitumen, this decreasing CO_2 emissions and saving energy. In spite of these positive impacts, CMA has a high sensitivity to traffic and environmental stresses due to the existence of water within the mixture, this of major concern to the industry. This study aims to review types of CMA and the main developments involved in cold bitumen emulsion mixture (CBEM) technology that can be used without decreasing in-service performance. This review also aims to provide a practical guide for the manufacture of bitumen emulsion and the design procedure of CBEM for the road pavements industry. Finally, it can be suggested that CMA is a crucial technique for pavement construction, as it provides acceptable performance alongside energy-saving and ecological objectives.

Keywords: Asphalt mixtures; bitumen emulsion; cold mix asphalt; cold bitumen emulsion mixture; energy consumption and emissions; hot mix asphalt.

1. Introduction

A plethora of modern-day expectations and needs rely on road pavement networks. As such, they must provide efficient and safe transportation, economic and environmental sustainability, and convenient modes of travel that are both accessible and reliable. Sustainable developments refer to the ethical and conscious consumption of natural resources to curb global warming and air contamination. An increase in such sustainability can be achieved by using perfected designs and procedures alongside a prepensed choice of construction material and techniques. Unfortunately, during the manufacture of hot mix asphalt (HMA), a considerable amount of energy (fossil fuels) is emitted, in addition to the release of pollutant gases, as a result of drying and heating large quantities of aggregates and bitumen at elevated temperatures around 170 ℃. Approximately 300,000 British thermal units (BTU's) are required to dry and heat aggregates in order to produce one tonne of HMA, this process consuming around 7.6-11.4 litres of fossil fuels and 2.5-3.5 therms of natural gas [1]. A cleaner approach to the production of asphalt mixtures requires a reduction in processing temperature. If this can be achieved and the production and processing of these bituminous mixtures carried out within ambient temperatures, whilst simultaneously retaining similar, or even superior levels of engineering behaviour, the economic and environmental gains and therefore incentive for use, would be substantial. For these reasons, the development of new construction technology is of paramount importance in order to provide a suitable alternative to HMA [2].

Scientific and technical institutions have developed several new practical techniques and solutions most notably, cold mix asphalt (CMA). This mix is manufactured and spread at lower temperatures (ambient temperature) than HMA, requiring less energy to reduce bitumen viscosity than HMA [3, 4]. CMA also significantly reduces factory fumes and emissions, providing better working environments for production staff and operators [5-12]. Regarding cold bitumen emulsion mixture (CBEM) technology, this considered the more desirable type of CMA, emulsified bitumen is used at ambient temperatures, whereas pure bitumen is used for producing HMA at elevated temperatures, 140–160 ℃ [13, 14]. CBEM has a wide range of production temperatures as it is usually manufactured at ambient temperatures under different environmental conditions without heating for both aggregates and bitumen [15].

Even though CBEM techniques have several advantages when compared to HMA regarding ecological, production and economic objectives, it is not without fault [16-19]. These include weak early strength, high voids ratios and an increased curing time required to reach full strength. Because of these, various manufacturing and enhanced approaches to the production these mixtures are currently under development.

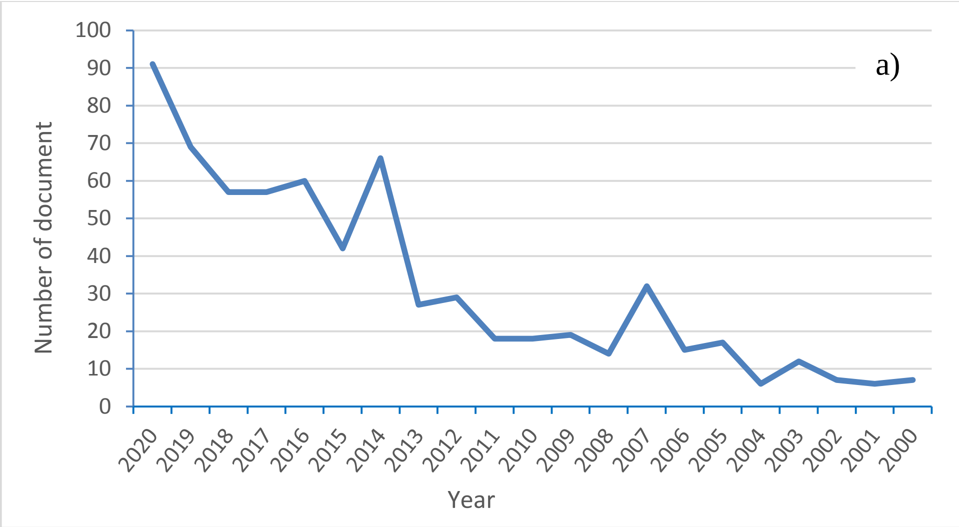
A review of current extensive research studies has revealed noteworthy advances in the development of emulsion, design methods, laboratory mix designs, fabrication techniques, curing, compaction processes and the mix development of CMA and CBEM. However, to date, there is no comprehensive research on CMA's or CBEM's that fully addresses these issues. This study aims to explain current emulsion technology, design procedures, and material processing and enhancements conducted to improve the performance characteristics of CBEM, whilst also identifying future challenges and obstacles related to the CBEM industry, identified, recommended and/or highlighted by recent studies.

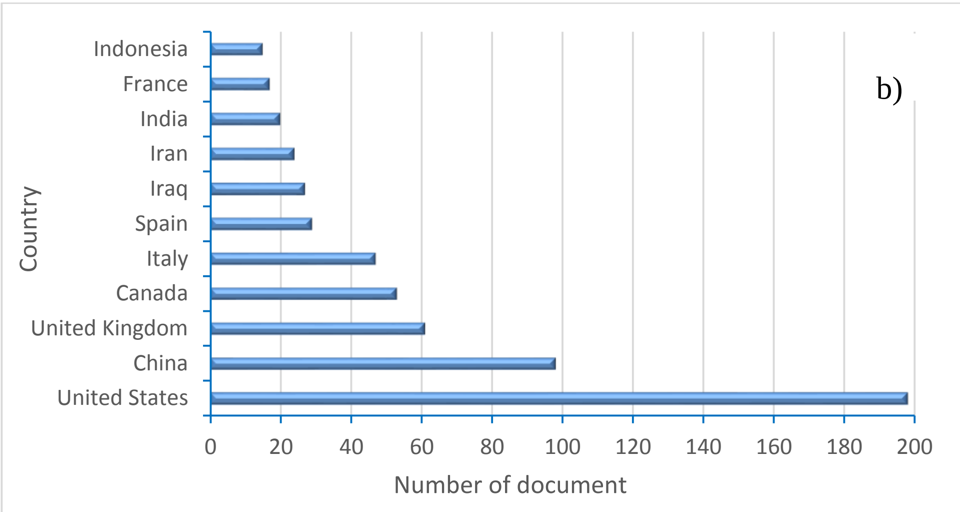
2. Systematic review and research methodologies

This paper will describe engineering parameters, their up-to-date development, challenges and solutions concerning CBEM through reviewing:

- Emulsified bitumen technologies,
- CBEM design procedures,
- CBEM production processes,
- Curing regimes and,
- Performance enhancement of CBEM.

An extensive review of CMA in terms of emissions and energy savings due to asphalt mixture manufacturing processes used by the road pavement industry have been surveyed. According to Scopus databases, a universally accepted database [1, 20, 21] and when using ‘cold mix asphalt’ as keywords [22], 779 documents were published between 1971 and 2020. Round about 140 articles, prioritizing relevant research, were selected for detailed assessment. Figure 1 lists the numbers of publications and document types considered in this paper. As emulsion and design procedures play a significant role in the development of CBEM, a thorough review relating to emulsified bitumen composition, classification, quality, production, types and grade as well as widely implemented design procedures, were presented while investigating the above. Key development, barriers and the potential of CMA outlined by selected publications, have aimed to provide a state-of-the-art source related to sustainable pavement materials research, that can be readily evidenced.





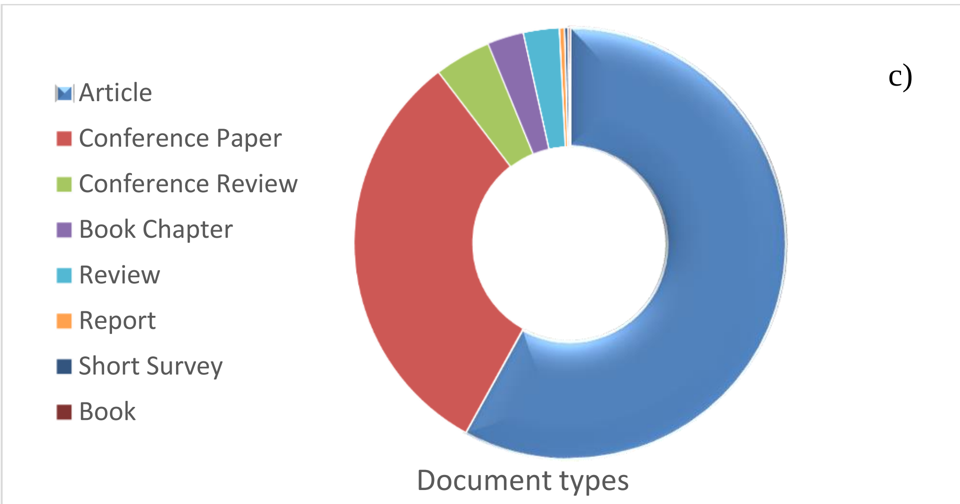


Figure 1. Number of documents by year, b) Number of documents by country, and c) Types of documents (graphs sourced from Scopus, accessed on 20 May 2021).

3. Types of cold mix asphalt

As a response to worldwide concerns surrounding global warming, the road pavement industry is committed to searching for alternative, energy-efficient technologies to HMA [23-25]. An effective solution is the use of CMA technology as it allows mixing, laying and the compaction of bituminous mixtures without heating. Cold mix asphalt is a mixture comprised of aggregate with a reduced viscosity asphalt binder [26]. It is produced by emulsifying bitumen in water prior to mixing with the aggregate at ambient temperatures [27, 28]. At the emulsification step, the bitumen is less viscous, the mix easier to work and compact. The emulsion breaks after a specific amount of water has evaporated, the cold mixture, ideally, taking on the properties of HMA [29]. Various types of CMA have been developed as detailed below.

3.1. Cold lay macadam

Cold lay macadam is a bituminous mix that consists of aggregate with reduced viscosity asphalt (cutback bitumen), using flux oil or solvent [30]. Flux oil contains a non-volatile measure of petroleum to dilute the hard bitumen to the required consistency [31]. The efficiency of this mixture mainly relies on the evaporation rate of the flux oil due to weather conditions and pavement service [26, 31]. Several types of flux oil are used in cold lay macadam such as gas oil, white spirit, kerosene and creosotes [32]. This mixture is usually used for surface dressing, base courses, macadam mixtures and filling for temporary reinstatement work. Because of the low stiffness of this mix due to the flux oil, it is not used as frequently, replaced instead with HMA mixtures [33]. In addition to this, cold lay macadam is considered uneconomical and environmentally unfriendly due to the use of solvents [34].

3.2. Grave emulsion mixtures

Grave emulsion (emulsion stabilised aggregate) mixtures have been used mostly in warm and dry regions due to its high susceptibility to moisture damage [35]. In grave emulsion mixtures, dense gradation aggregate is mixed with pre-wetting water then mixed with a medium setting emulsion which is considered the main binder [26]. It is classified as a dense-graded emulsified mixture, used for base courses and as an overlay to strengthen deteriorating pavements and to re-profile old roads. It can also be used as a wearing course for low trafficked pavements [36, 37]. Typically, these mixtures need to be laid directly after mixing which can be challenging due to the distance between the site and the manufacturing plant. As such, it has been modified using flux oil, which allows the mix to be stockpiled for many days before laying [26]. Unfortunately, this modification causes a reduction in stiffness because it softens the bitumen and increases the curing period. This mixture can be distinguished from other types of CMA by the thin films of binder that coat the aggregate particles as a result of the low bitumen content, one of its weaknesses [35, 36].

3.3. Foamed asphalt mixture

An alternative cold process uses foamed asphalt as a binder in to manufacture CMA. Foamed asphalt is produced by blending hot liquid asphalt with water-derived steam, plus a surfactant [26, 38]. The asphalt expands to about 15 times its volume during the rapid boiling of the water, resulting in foam which is then stabilised using surfactants. The asphalt is then mixed with aggregates while it is still in a foamed state, and due to the increased size of the binder, a high degree of coating is achieved. Normally, asphalt consists of about 97% of the foam mass, water and foamed agent comprising 2% and 1% respectively [39].

3.4. Cold bitumen emulsion mixture (CBEM)

Cold bitumen emulsion mixture (CBEM) is the most popular type of CMA mixture. It is used to create a bituminous mixture produced by mixing bitumen emulsion with mineral aggregates [18]. The CBEM industry is interested in using either virgin aggregate or RAP (Reclaimed Asphalt Pavement) or both together to gain an optimum gradation. With CBEM, less energy consumption and fewer emissions are considered as the main advantages compared with HMA [12, 40]. However, in common with other CMA mixtures, CBEM has weaknesses such as insignificant early stiffness, an extended period of curing and high level of voids ratios, considered substandard to HMA [19]. In contrast to HMA, CBEM requires up to 24 months, in some cases, to attain its eventual strength and related characteristics [41, 42]. Because of this, CBEM has been restricted to reinstatement works, low traffic volume pavements and footways [34, 36, 37, 43, 44]. Doyle et al. [45] reported that due to the long period of curing required for CBEM to gain its peak strength after paving and compaction, it has restricted use for heavy traffic load roads. It is also considered highly sensitive to rainfall when at an early age [46]. Therefore, using CBEM as a structural layer is limited, especially in the UK but it can be used for heavily trafficked pavements when overlaid by at least 4 cm of HMA [47]. In general, open or semi-dense aggregate gradation is used to produce CBEM to create better aeration within the high air void mixture, something which helps the evaporation of trapped water and reduces curing time [41]. Different gradations have been used in the preparation of CBEM, such as dense gradation and continuous or gap graded gradations [36, 47-49]. In addition to gradation, the characteristics of CBEM depend on the characteristics and type of the bitumen emulsion, pre-wetting water, the curing process, compaction effort and additives used [36].

Different countries employ and are developing CBEM for road works, including France and the USA [37]. However, this mixture is not preferred for road-work use in other countries due to wet and cold climates, and because of weaknesses such as weak early strength, long curing periods and high levels of voids. This makes it vital to develop an effective technique to enhance and tailor the behaviour of this mixture to industrial needs, whilst improving in-site service life and minimizing mixture difficulties. It can then ultimately serve as an alternative to HMA under all weathers and without the aforementioned limitations. As CBEM is a niche area, a substantial amount of effort is required to develop and use this low carbon technology in place of HMA on a larger scale. The following sections will review emulsion technology, design procedures, materials processing, and enhancements designed to improve the performance characteristics of CBEM that have been conducted to date. Further challenges related to the strength of CBEM are also identified, research recommendations highlighted.

4. Performance characteristics of CBEM

Research carried out to examine CBEM's characteristics have identified its main problems and have proposed methods of mitigation. Thanaya [50] stated that CBEM is comparable to HMA regarding engineering properties. Similarly, Robinson [51] observed that the indirect tensile stiffness modulus of CBEM gradually improves over 10 months, to meet the requirements of 600 MPa, its stiffness developed to approximately 800 MPa after 2 years. Thanaya [50] proposed that CBEM is appropriate for light to medium traffic load pavements when the creep slopes of such mixtures were considered for this work. Brown and Needham [52] noted that adding Ordinary Portland Cement (OPC) to CBEM has positive effects as the mix without OPC, fails at less than 1000 cycles in the unconfined mode of Repeated Load Axial Tests.

Despite the significant beneficial environmental and economic impacts of CBEM, this mixture is still significantly underutilised worldwide because of the complexities involved in the design and behaviour evaluation of the product [53]. Road pavement companies understandably prefer to use construction materials that perform their proposed design roles directly after construction. Serfass et al. [54] showed that CBEM is an evolutive material, especially in its early age, when the early bond is low, building up progressively. This behaviour is attributed to the potential combination of various aspects, such as the reactivity between aggregates and emulsion, binder film coalescence, the presence of water and cohesion development [55].

Rapid developments of bitumen emulsion production techniques, have helped to overcome some of the other mixture issues in terms of low binder film thickness, binder stripping and poor aggregate coating. Thanaya [36] observed that insufficient binder coating is mainly related to coarse aggregates because of the low compacting between emulsion and aggregates, while the emulsion is flocculated on the fines portion. Due to the reduced binder viscosity of CBEM, Thanaya [36] suggested that such mixes might suffer from binder stripping and drainage during storage and compaction. In addition, Staples [56], stated that the CBEM does not meet UK Standards as it has a significantly lower elastic modulus than that required, even after 18 months of curing, because of the high voids ratio of this mixture.

In summary, it has been observed from the literature that there are several difficulties to overcome if CBEM is to be used as a fully integrated structure in pavement construction [36, 57, 58]. These difficulties arise during the manufacturing stages and the service life of this mixture. It is concluded that curing time and weather conditions are the key factors to consider if CBEM is to achieve full curing on site, a process which can take between 2 – 24 months [59]. As such, cold, humid and rainy weather is considered incompatible with reductions in CBEM curing time.

4.1. Bitumen Emulsion Technology

Bitumen is manufactured in different types and grades, ranging from hard and brittle solids to thin liquids. The bitumen used for road works is normally in the middle of these two extremes. Although paving bitumen is a solid, or semi-solid material at ambient temperatures, it can be readily liquefied by heating, adding a petroleum solvent, or emulsifying it in water [36, 60]. Heating bitumen during HMA production, is used to liquefy said bitumen to enable it to coat the aggregates and retain efficacy during transport, laying down and compaction. After that, the bitumen cools and regains its viscosity. This and other binding properties that make it an effective paving material [31]. In addition to heating, petroleum solvents such as kerosene and naphtha are added to the base bitumen to make it liquid, the resultant product called cutback bitumen. The cutback cures and the binding properties of the bitumen are restored when the solvent evaporates. Bitumen emulsion is produced by milling the bitumen into minuscule particles and spreading it in water with a chemical emulsifier [31, 61]. Emulsions are considered efficient and used in road works when the chemical emulsifier is retained by the bitumen after evaporating the water into the atmosphere.

Emulsion was first industrialized and used in road works in the 1920s [61], its use limited to some spray applications and dust palliatives [31]. Developments regarding the use of bitumen emulsions in pavement engineering was relatively slow, restricted by the type of emulsions available and a lack of information as to how emulsion should be used. Nowadays, due to the continuous developments of new emulsion grades and types, coupled with developed construction equipment and practices, a range of choices are available [62]. The European Asphalt Pavement Association [63] reported that the United States is the biggest in bitumen emulsions consumer averaging 2,300 000 tonnes per annum.

4.1.1. Bitumen emulsions composition and classification

In general, bitumen emulsions comprise three main constituent parts: bitumen, water and an emulsifying agent [64]. On some occasions, the bitumen emulsion may include other ingredients such as stabilisers, coating improvers, antistrips or break control agents. Mixing bitumen and water using chemical additives and highly specialised equipment, is conducted under carefully controlled conditions [31, 65].

Bitumen is the main component of bitumen emulsion and in most cases it comprises 50% to 75% of the emulsion. Bitumen grade, or hardness, significantly affects the produced emulsions which are normally manufactured with bitumen in the 40-250 penetration grade [26, 61, 66].

Occasionally, environmental conditions may require a harder or softer base bitumen [67]. In any case, the chemical compatibility of the emulsifying agent with the bitumen is an essential factor to consider when manufacturing a stable emulsion. Bitumen principally consists of large hydrocarbon molecules [31]. The complex interaction of these molecules makes it practically impossible to perfectly predict the behaviour of the bitumen to be emulsified meaning that quality control is necessary when manufacturing bitumen emulsion [30].

The second component of bitumen emulsion is water which contains minerals that affect the manufacture of stable bitumen emulsions [67]. Consequently, drinking water might not be perfect for the manufacture of bitumen emulsion. The benefit of calcium and magnesium ions in water is to form a stable cationic emulsion which usually requires the addition of calcium chloride for improved storage stability. These ions, however, have a negative impact on the anionic emulsion due to magnesium salts and water-insoluble calcium which are generated in the reaction with potassium salts and water-soluble sodium that are commonly utilized as chemical emulsifiers [30]. In contrast, carbonate and bicarbonate anions can stabilise the anionic bitumen emulsion because of their buffering influence, but these anions destabilise the cationic emulsion by reacting with water-soluble amine hydrochloride emulsifiers. Accordingly, water containing particulate materials and impure water is not preferred for the manufacture of emulsions as they disrupt the proportion of the emulsion ingredients that can negatively influence behaviour or result in untimely breaking.

Emulsifiers are surface-active agents, or surfactants, that have a significant impact on the properties of bitumen emulsions [68, 69]. The emulsifiers have a very important role in controlling breaking time due to their ability to keep the bitumen droplets in a stable condition [36]. Emulsifying agents such as clays and soaps were used in the early days of bitumen emulsion manufacturing but because of an increasing demand for bitumen emulsion, other effective emulsifiers were sourced, with a range of emulsifying agents now being commercially available. Fatty acids such as lignins, tall oils and rosins, which are wood-product derivatives, are considered the most anionic emulsifiers [70]. Anionic emulsifiers are saponified (turned into soap) via reactions with sodium hydroxide or potassium hydroxide. Fatty amines are the most common cationic emulsifiers such as imidazolines, amidoamines and diamines [36], these transformed into soap by reacting with acid, generally hydrochloric. Fatty quaternary ammonium salts are another type of emulsifying agent that is utilised to produce cationic emulsions. These types of emulsifiers are adequate and stable cationic emulsifiers as they are water soluble salts and do not need the addition of acid.

Bitumen emulsions are categorized into three types: anionic, cationic, and non-ionic [61], both anionic and cationic types the most widely applied in the pavement industry and for maintenance. Categorisation by type, refers to the electrical charges surrounding the bitumen particles. The anode pole becomes positively charged while the cathode pole becomes negatively charged when these two poles are submerged into a fluid where an electric current is introduced. If this electric current is passed through a bitumen emulsion containing negatively charged particles of bitumen, these particles will move to the anode, thus the emulsion is classified as anionic [36]. In contrast, positively charged bitumen particles will migrate to the cathode, the emulsion identified as cationic. Neutral bitumen particles do not move to either pole, the in emulsion in this case, classified as non-ionic [31, 71].

Emulsions are also classified based on the speed with which bitumen droplets consolidate and return to bitumen. This is related to the rate at which the emulsion becomes unstable and breaks after coating the aggregates. This classification is simplified and standardised by adopting the terms RS (rapid-setting), MS (medium-setting) and SS (slow-setting) [65]. The RS emulsion has little of no ability to mix with aggregates, the MS emulsion seem to mix with coarse aggregates, while SS emulsion prefers to mix with coarse and fine aggregates. In addition to this labelling, bitumen emulsions are identified by using different letters and numbers that indicate their viscosity and the hardness of the base bitumen in accordance with BS EN 13808 [72]. The letter “C” at the beginning of the emulsion type indicates that it is cationic. A second letter “B” indicates the binder content. Occasionally, in the case of an added polymer, the third letter included is “P” and also if the emulsion contents flux (more than 2%), this is the fourth component indicated by the letter “F”. The first number that follows the letter “C” is related to the percentage of binder content in the bitumen emulsion [29]. The other number at the end refers to the breaking rate, this ranging from 1 (fastest breaking rate) to 7 (slowest breaking rate). For instance, C50BPF3 refers to a cationic emulsion with 50% based bitumen, that contains a polymer and more than 2% flux, with a class 3 breaking rate [73].

Anionic bitumen emulsions are identified based on the British Standard Institution [74] using three elements. The first element refers to the type of emulsion, for example, ‘A’ for anionic emulsion. The next part represents the stability or breaking value, this ranging from 1 to 4, where the higher value refers to a slow breaking rate. The last component of the code indicates the bitumen content in the emulsion. For example, A1-60 is an anionic emulsion with rapid breaking and 60% emulsion-based bitumen.

4.1.2. Bitumen Emulsion Quality

Several factors influence the manufacture, storage and behaviour of bitumen emulsions [31, 60, 65, 73]. These factors have significant effects including:

- The base bitumen chemical properties, hardness, quality and particle size in the emulsion.
- Emulsifying agent type, concentration and properties.
- The temperature and pressure used during manufacturing.
- Emulsion particles’ ionic charge.

- The order in which ingredients are added.
- Use of additives such as chemical modifiers and polymers.

4.1.3. Production of the Emulsion

The main equipment to produce bitumen emulsion consists of a mechanical colloid mill with a high-speed rotor (about 1000-6000 rotations per minute) to split the bitumen into very small droplets [26, 29]. A heated bitumen container, emulsifier solution container, pumps and flow-metering gauges are also required.

In general, bitumen emulsion has very small droplet sizes of about 0.001 to 0.010 millimetres, these droplet sizes affected by the intensity of the mechanical energy that is provided by the mill. The bitumen and chemical emulsifier solutions are introduced into the colloid mill using separate pumps [60].

Prior to the emulsification process, the bitumen and water are heated individually to the desired temperatures [30]. The bitumen and water containing the emulsifier, is pumped into the colloid mill where it is separated into very small droplets. If the emulsion temperature, is higher than the boiling point of water when it leaves the mill, a heat exchanger must be applied to cool the bitumen down [60]. The emulsion is then usually fed into bulk storage containers. Flow meters are usually used to accurately proportion the bitumen and chemical emulsifier solution. To control proportioning, the temperatures of the bitumen and emulsifier solution on entering the mill, and the discharge temperature should be monitored. Bitumen particle size is an essential parameter when producing a stable emulsion [29, 36].

4.1.4. Emulsion Breaking and Curing

If the bitumen emulsion is used as a binder to the aggregates in road works, on top of ensuring the emulsion performs optimally, the water should be separated and evaporated from the emulsion. This separation is called “breaking” [36]. Depending on what the bitumen emulsion will be used for, it is formulated to break by one of two breaking mechanisms: chemical and evaporative. The evaporation mechanism is mainly performed for slow-setting emulsion grades, whilst the chemical mechanism is used for breaking medium-setting and rapid-setting grades. The breaking time of rapid-setting emulsion is considerably shorter than the time needed for medium and slow-setting emulsions. The type and concentration of emulsifier also have an essential role to play in breaking the emulsion. Other factors, explained below, can also control the rate of breaking [26]. To meet the specific requirements for the use of bitumen emulsions in the pavement industry, and to obtain the best outcomes, it is essential to control all these factors.

Curing includes the development of bitumen engineering characteristics. To do this, complete evaporation and absorption of water must be achieved. The particles of bitumen emulsion should join and bond to the intended surface [75, 76]. Petroleum solvents can be used in some bitumen emulsions to help in the mixing and coating process, however, the time taken to cure will be influenced by the quantity and type of the solvents used [60].

The breaking and curing times of bitumen emulsions are affected by several factors including [29, 36]:

- Aggregate water content: Although wet aggregate may help in the coating process, it tends to increase the curing time needed for evaporation.
- Water absorption: A rough-textured and porous mix reduces the breaking period due to the absorption of emulsion water.
- Environmental conditions: Water evaporation rates are affected by temperature, humidity and wind velocity.

- Mechanical pressure: slow-moving pressure from the compactors during the compaction stage forces the water to leave the mixture, this helping cohesion, curing and stability.
- Surface area: Increasing the aggregate surface area (when more fine aggregate used), can shorten the breaking time of the bitumen emulsion.

4.1.5. Selecting the Appropriate Emulsion Type and Grade

The correct selection of type and grade of bitumen emulsion as per its intended use, offers superlative bituminous mixture performance. There are several applications of bitumen emulsion such as a plant mix (central or mixed-in-place), recycled mix, prime coat, fog seal, slurry seal, micro surfacing or chip seal. After selection, other project variables must then be taken. The environmental conditions expected during construction and geographical location are significant considerations while aggregate type, gradation and availability are other factors that affect emulsion selection [26, 55, 77].

The above sub-sections have addressed the current information available regarding bitumen emulsion, reflecting the continuous need for emulsion performance enhancement, emulsion classification, emulsion best practice applications, and identification of the mechanisms of adhesion. Ongoing research on the above issues is designed to, and will hopefully, overcome the shortcomings of CBEMs.

4.2. Design procedure

Bituminous mixtures are complex materials, which generally comprise bitumen, different aggregate gradations and air voids. In the flexible pavements industry, such materials are commonly used because of the quality of bond possible between bitumen and aggregates [78]. However, different failure modes such as cracking, segregation and rutting can appear on the surface of flexible pavements because of heavier than anticipated traffic, the effect of moisture and variations in temperature. Failures happen because the shear and tensile strength of asphalt mixtures are weak [79]. Addressing these distresses, or at least delaying future pavement deterioration, can be achieved by using an optimal design, one that provides strong and durable flexible pavements.

A mix design procedure is required for CBEM research. It is necessary that trial mixtures be manufactured in the lab to establish the grade and percentage of emulsion and various mixture properties i.e. workability, water sensitivity, stability and strength [36]. Different design procedures are suggested for CBEM by road pavement authorities and research organizations because there is no universally accepted design method [59, 75, 80, 81]. Most of these procedures are modifications of American design procedures (Asphalt Institute or AASHTO) [31]. The following sections summarise different design methods for CBEM that encompass the main design procedures, namely: Asphalt Institute design procedures, the design procedure of the Ministry of Public Work, Republic of Indonesia, Nikolaides' design procedure and the Nynas test procedures [36]. These procedures may be used as guides for developing mix design method templates, reflecting local materials and conditions.

4.2.1. Asphalt Institute Design Procedures

Asphalt Institute Manual Series No.14, MS-14 [68] has standardised two design methods for emulsified bitumen aggregate cold mixtures. One procedure uses a modified Haveem Method, the other the Marshall Method. These procedures serve as guides for developing mix design method templates reflecting the use of local materials and local conditions. The Marshall method for emulsified bitumen aggregate cold mixture design was established through research conducted at Illinois University. This design method is defined in the manual series MS-14 and has been adopted by the current study. The design procedure includes [26, 31, 71]:

- Aggregate selection: Aggregates meeting the requirements of British Standards, are among those suitable for bitumen emulsion mixtures. For the gradations containing coarse and fine aggregates, drying or aeration prior to mixing and compaction may be required.
- Bitumen emulsion: Different types of bitumen emulsions are used to produce bitumen emulsion mixtures. Empirical formulas are used to as starting point for the design of trial emulsions and residual bitumen contents. These formulas are based on the percentage of aggregate passing sieve No. 4 (4.75 millimetres) and in most cases, provide a satisfactory starting point.
- Coating and adhesion testing: The initial assessment of each bitumen emulsion selected for mixture design, is carried out through coating and adhesion tests. Pre-wetting water is combined with the trial emulsion determined above. A coating test is used to evaluate the capacity of the bitumen emulsion to coat the aggregate particles and to decide the optimum pre-wetting water content. The coating is visually estimated as satisfactory or unsatisfactory for the intended use of the pre-wetting water in the mix.
- Optimum total liquid quantity at compaction: Optimum total liquid quantity at compaction can be determined from compacted specimens according to the maximum dry density of CBEMs.
- Optimum residual bitumen content: Determine optimum residual bitumen content for the selected aggregate grading.

The Asphalt Institute, in association with the Asphalt Emulsion Manufacturers Association (AEMA), published a new manual on asphalt emulsion in 1997. This manual is the Basic Asphalt Emulsion Manual (MS-19), 3rd edition [69]. It is based on MS-14 and includes modifications. Firstly, if the degree of coating of aggregate particles when using only bitumen emulsion is within an acceptable range, there no need for pre-wetting water to be involved.

Secondly, the optimum total liquid content at compaction has no requirements compared with MS-14. However, prepared mixes must be air-dried until neither too wet nor too dry for compaction. In addition, the compacted mixes are conditioned by keeping them in their compaction moulds, in the oven, at a temperature of 60 °C for 2 days. This is followed with additional compaction with a 178 kN static load for one minute, applied at the same temperature, using a double plunger at each side of the specimen.

4.2.2. Design Procedure of Ministry of Public Works of Indonesia

Thanaya [36] described the design procedure that was adopted by the Ministry of Public Works in Indonesia in 1990. In this procedure, open-graded and dense-graded mixture gradations with bitumen emulsion are covered based on AASHTO with specific modifications in terms of national and regional conditions in Indonesia. The Marshall design procedure [68] was modified based on stability testing and used when specimens are tested at ambient temperature. As such, it is not recommended to pre-condition specimens by submersing them in water at 60 °C for 30 minutes.

4.2.3. Nikolaides Design Procedure

In 1990, Nikolaides developed a hybrid design procedure by combining both the American Standard and the Ministry of Public Works Republic of Indonesia procedures [82]. In this procedure, rutting behaviour is characterised by controlling the maximum acceptable asphalt content [31]. The maximum allowable value of residual asphalt content is judged based on permanent deformation performance. Consequently, the relationship between the creep stiffness coefficient and the residual asphalt content is required to specify this value (maximum residual bitumen content). Nikolaides [83] specified that the creep stiffness coefficient is determined by the static creep test which is applied for one-hour using a static load (0.1 MPa) at 40 °C. The stiffness modulus of bituminous mixtures can be determined at any loading time for a specific test of any asphalt content.

4.2.4. Nynas Test Procedures

The Nynas Company designed three tests which are only utilized during storage or prior to laying down of loose mixtures. These tests are identified as run-off, wash-off and workability tests [26]. A funnel with a mesh size of less than 2 mm at the bottom, is prepared in the run-off test and a loose bitumen emulsion mixture (500 g) is placed into the funnel. The run-off value refers to the amount of bitumen which runs off in 30 minutes. The wash-off test is then performed immediately after the run-off test while the mixture is still in the funnel. 200ml of water is poured over the mixture and both the wash water and any wash-off bitumen are collected and measured. Lastly, the workability test is performed using a Nynas workability tester. In this test, a small part of the top of loose stored CBEM is scaped off during storage, or just before placing, and used to measure the maximum force required to shear off this part [36].

Based on the limited design procedures above, design parameters can be divided into two primary categories: globally agreed with parameters (e.g. the nominal aggregate size, gradation types), and global parameters that are not agreed (such as pre-wetting water content, air voids limits, mechanical properties, curing protocols and emulsion characteristics). The next step is to establish global specifications limits for the agreed parameters, for example, identification of the nominal maximum aggregate size: 19, 14, 12.5, 9.5, or 4.75 mm. Further investigations are required locally to identify correct specification limits, for instance, the appropriate base asphalt binder in the emulsion for a hot climate is 40-60, while for a cold climate, it is 100-150.

The current challenges in adapting a globally accepted design procedure for CBEM include a wide range of mixing materials, the effect of climatic on mix curing, and a unified curing protocol.

4.3. Processing Stages

There are three different process stages in the preparation of CBEMs where the bitumen emulsion is expected to perform different functions [36, 84], namely:

- Stage 1: The emulsion, during mixing with the aggregates, must coat both fine and coarse aggregate particles uniformly and stay stable at the same time.
- Stage 2: During storage and laying-down of CBEMs, the bitumen emulsion must retain its efficacy and be partially set, or broken, to resist moisture and rain. CBEMs must not be drained (due to the low viscosity of the bitumen emulsion) after blending with the aggregates.
- Stage 3: During the compaction process, the emulsion must break quickly and return to its original base bitumen. In most cases, bitumen emulsions require a relatively long time of curing to allow volatiles to evaporate leading to full breakage and thus achieving optimal performance.

4.4. Curing CBEM's

Curing is one of the most important requirements for CBEM [85]. As mentioned before, the performance of CBEM is directly related to the properties of the materials used in the mix and the curing condition [27, 35, 36, 46, 86, 87]. Curing is defined as the process whereby the compacted mixtures discharge water through either evaporation, particle charge repulsion or pore-pressure induced flow paths [27]. The consequent reduction in the mixture's water content helps develop the strength of the CBEM. Roberts et al. [88] reported that the cold mix tensile strength increases considerably by increasing curing temperature from 23 °C to 60 °C. Bocci et al. [89] found a substantial development in the performance of cold mixtures as curing time and curing temperature increase; curing for 14 days at 20 °C is equivalent to 7 days at 40 °C. Full curing may take between two months and two years in the field [50, 90, 91]. Bocci et al. [87] demonstrated that CBEM's require a set curing time to develop required mechanical properties such as strength and stiffness, as can be seen in Figure 2.

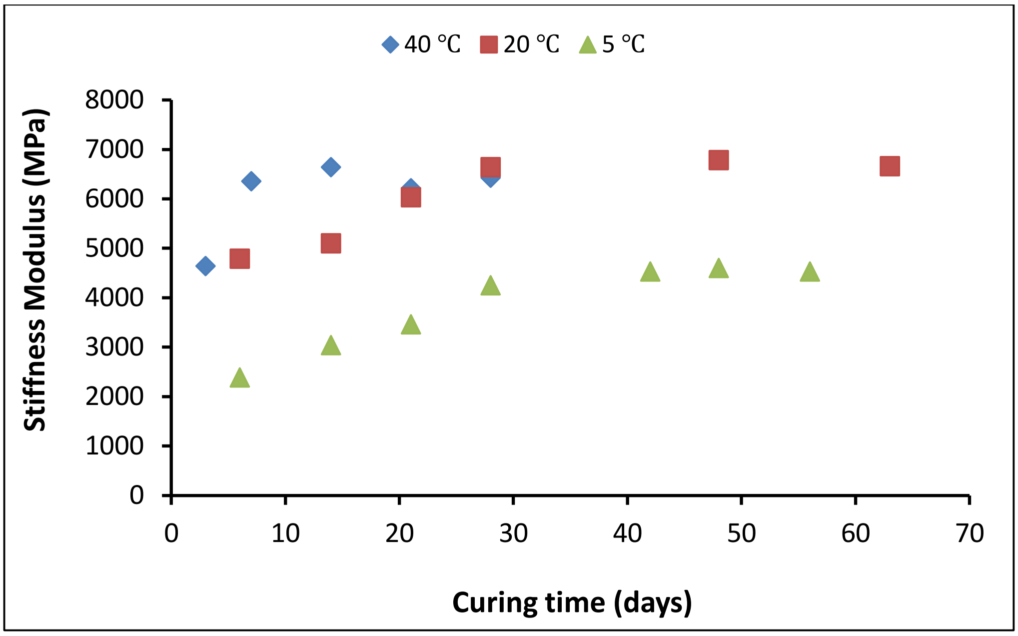


Figure 2. Effects of curing and temperature on the ITSM of bitumen emulsion mixtures [87]

Jenkins [27] found that curing temperature is a major factor in mixture preparation as moisture and temperature are dependent factors that affect moisture evaporation rates. Moisture can impede emulsion distribution, compaction and the workability of the mixture whilst also increasing the curing period and decreasing the strength and density of the compacted mixtures. Serfass et al. [54] suggested that assessing cured cold mixtures in the lab is necessary, however replicating exact field curing conditions is complicated and, above all, time-consuming, implying that an accelerated curing process is necessary. this suggests that the curing procedure should be as short as possible, and that bitumen ageing should be avoided.

Serfass et al. [54] found that the moisture content of small samples evaporates quickly at any temperature, taking longer for larger samples. In addition to curing time, at high temperatures (for example 60 °C), samples dry too quickly, this causing cracking in large samples. In the field, cold mixtures are rarely considered to be completely dry. The moisture content of such mixtures has often been found to be between 0.5% to 1.5% in the roads in temperate climates. In consequence, to obtain cold mixtures without deterioration to the specimens, it has been recommended that such specimens should be cured for 14 days at 35 °C to 40 °C. This procedure does not damage the samples [92]. 35 °C to 40 °C was selected because it is realistic and below the bitumen softening point.

Kim et al. [93] found a direct relationship between strength and moisture loss, this evident at higher temperatures over curing time. This is true for CBEMs that have inert fillers such as limestone filler, as at high temperatures of curing, water evaporates easily. In the case of active fillers such as cementitious material, a positive externality is gained because cement hydration reactions require the presence of water; the use of cementitious material accelerates the emulsion curing process by reducing the amount of free water [31, 35, 49, 94].

4.5. Enhancement of CBEM

About 95% of roads around the world have been paved using hot mix asphalt (HMA) as the main material [95]. However, HMA is considered environmentally disadvantageous as it requires a considerable amount of energy to heat the bitumen alongside the aggregates, generating CO_2 emissions during manufacture, laying down and compaction [96, 97]. A variety of asphalt roadway design techniques have been created to eliminate, or reduce, emissions and save energy in terms of the flexible paving industry [98-100]. One of these techniques is CBEM defined as an asphalt mix of asphalt emulsion and aggregates, blended at ambient temperature [101]. The following advantages can be achieved using CBEM:

- CBEM is independent of environmental conditions.
- It can be prepared on-site or off-site.
- It is considered an eco-friendly technology throughout all construction stages, minimizing energy consumption, emissions and toxic fumes.
- It is a cost-effective option for paving or repairing rural roads where the hot mix plant is some distance away.

However, CBEM has been assessed as a secondary mixture in comparison to HMA, based on its engineering properties i.e. an extended curing time required to attain optimum behaviour and its low early stiffness [102]. Low-quality bituminous mixtures and inadequate design can mean inefficient flexible pavement. Different studies have been conducted to investigate and improve the performance of CBEMs. Several tactics have been investigated such as incorporating various types of materials and applying different preparation techniques. Ibrahim and Thom [103] studied the influence of curing and compaction types and concluded that an increase in curing time develops the indirect tensile stiffness modulus. CBEM is generally identified to have weak early stiffness, extended curing times and high air voids [104]. Therefore, such a mixture tends to be comparatively low quality in comparison to a hot mixture. Consequently, CBEM is limited regarding road pavement application. Several studies using a range of procedures and techniques, have been performed to address the poor performance of CBEMs.

4.5.1. Compaction enhancement

The mechanical properties of CBEMs are mainly affected by compaction, as suitable compaction is required for optimum performance. Increasing compaction efforts leads to an improvement in the bitumen emulsion / aggregate combination if 20 mm aggregate maximum size granite is used [52]. Thanaya [36] stated that applying heavy compaction (120 revolutions, 240 kPa, 2° angle of gyration) reduces and adapts void ratios to within the specification limits rather than medium compaction (80 revolutions, 240 kPa, 2° angle of gyration). The aim of compaction is to obtain a void content of between 5% to 10%, something which can be achieved by performing 240 gyrations, this categorised as extra heavy compaction [36]. The application of heavy compaction is crucial when attempting to achieve bitumen emulsion breaking and to ensure that CBEMs strengthen properly [50]. The excessive quantity of liquids in cold mixes reduces the compaction benefit and prevents mixes from obtaining their acceptable air voids, leading to reduced strength. Serfass et al. [54] described the relationship between stiffness modulus and compaction of CBEMs, as shown in Figure 3.

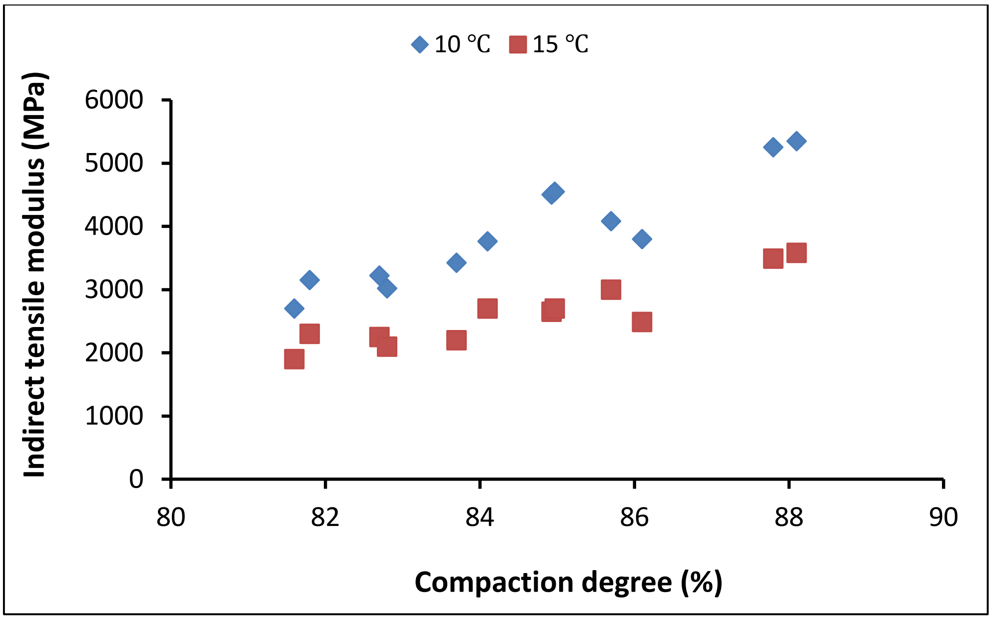


Figure 3. Effect of compaction on the indirect tensile stiffness [54]

4.5.2. Polymers enhancement

Khalid and Eta [105] carried out a laboratory investigation to study the impact of polymer enhanced emulsions on the mechanical properties of emulsified bitumen macadam. Dense graded binder course and close graded surface course were used as aggregate grading with a cationic emulsion containing 65% base bitumen of 100-penetration grade. They concluded that Styrene-Butadiene-Styrene (SBS) and Ethylene Vinyl Acetate (EVA) polymers have positive effects on the modification of bitumen emulsion as they enhance stiffness and reduce permanent deformation of CBEMs. In addition, the fatigue resistance of 4% SBS and 6% EVA modified CBEMs, developed approximately 45 and 35 times, respectively, in comparison with the fatigue resistance of unmodified CBEMs. In further research, polyvinyl acetate was added to a rapid-setting emulsified bitumen to develop the compressive strength of the CBEM [106]. Two mixing methods were applied where in the first method, the aggregates were mixed using bitumen-polyvinyl acetate, and in the second, the aggregates were coated by a diluted polyvinyl acetate-emulsion. As a result of the improvement in void content, the second method achieved a 31% improvement in compressive strength. More recently, Xu et al. [107] used an enhanced polymer-modified emulsifier in a bituminous mixture finding that the performance of the mixture was in agreement with the specification requirements in terms of water damage, rutting and cracking resistance.

4.5.3. Cement enhancement

Additives can play a crucial role in controlling the mechanical characteristics of bituminous mixtures with reference to water susceptibility, rutting and fracture resistance, and stiffness. Some of these additives are used as a filler replacement in the mix such as cement and lime [108]. Cement can be technically defined as a material that when mixed with other non-cohesive particles, produces a hard mass. Fine powders such as Portland, slag, pozzolanic and high alumina generate strong and durable binding materials because of the hydration processes involved [109]. The use of cement in bituminous mixtures is not a new technique. Terrel and Wang [110] carried out one of the first studies that used cement in emulsion-treated mixtures, concluding that the use of cement as an activator in bitumen emulsion mixtures, can accelerate the development rate of the resilient modulus due to the accelerated rate of curing. This means that Ca2+ ions from the cement neutralised the anionic chemical emulsifier thus allowing the bitumen emulsion droplets to coalesce and adhere to the aggregates. This helps to break the emulsion quickly and absorb water from the mixture thus decreasing curing times [111]. Head [112] found that adding 1% OPC (Ordinary Portland Cement) as a modifier to CMA, increases the Marshall stability by 300% when compared with untreated mixtures. Dardak [113] reported that 50% of bituminous layer thickness can be reduced by using OPC improved CMA as a result of stability developments (200% to 300%). Li et al. [114] stated that cement-bitumen emulsion has less sensitivity to temperature, longer fatigue life and better developed toughness. Brown and Needham [52] evaluated the effects of incorporating OPC into bitumen emulsion mixtures finding that the stiffness moduli (Figure 4) was enhanced due to the increased pH which helps the emulsion to break.

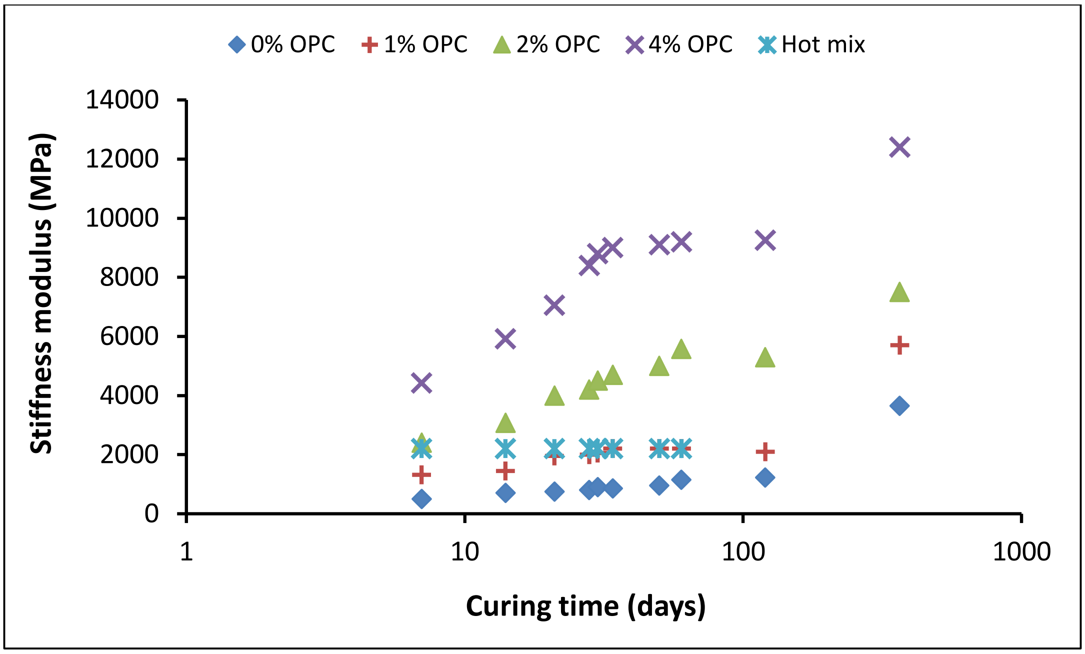


Figure 4. Effect of the OPC on stiffness modulus of bitumen emulsion mixtures [52]

The type of cement used can significantly increase the strength of CBEMs [36]. Thanaya [36] found Rapid Setting Cement (RSC) gave a higher rate of increase in strength in comparison to the OPC. The stiffness of CBEMs modified with RSC was about 2000 MPa to 2500 MPa after a few weeks of curing, while the unmodified mixtures needed 16 weeks to achieve the same stiffness values. This behaviour can be explained as the RSC behaving as an active filler in CBEMs, causing an increase in their pH.

Oruc et al. [46] and Oruc et al. [115] conducted experimental studies to evaluate the addition of 0% to 6% OPC as a filler replacement to emulsified asphalt. These results showed significant developments in the mechanical properties of mixtures modified with a higher percentage of OPC, as presented in Figure 5.

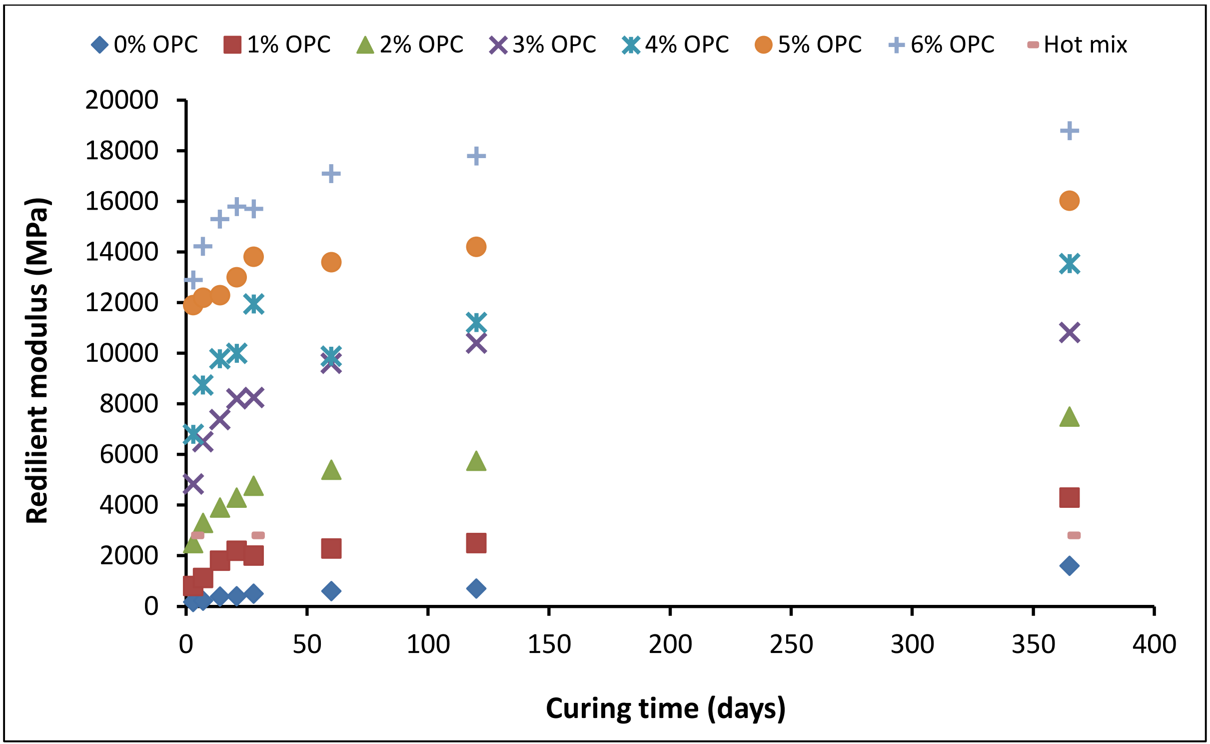


Figure 5. Effect of cement on resilient modulus of the emulsified asphalt mixtures [46].

Wang and Sha [116] found that the cement in cement asphalt emulsion mixtures can improve the microhardness of their interface. García et al. [94] applied various percentages of cement to test the mechanical properties of CBEMs that were cured at different levels of environmental humidity (35%, 70% and 90%) RH. Specimens cured at 90% relative humidity, had a slower hardening time than those cured at low relative humidity. It was also demonstrated that the incorporation of cement into bituminous mixtures resulted in changes in the pH of the emulsion, allowing it to break quickly.

Al-Hdabi et al. [117] studied the effect of replacing all the conventional mineral filler with OPC to improve a gap-graded CBEM based on a cement-treated mixture. The results indicated that substantial developments were gained in engineering properties, moisture sensitivity resistance and temperature effects resistance. Fang et al. [118] investigated the use of rapid hardening cement to accelerate the development of the mechanical properties of cement bitumen emulsion and obtain a better understanding of the role of cement in such mixtures. After one day of curing mixtures with calcium sulphoaluminate and calcium aluminate cement, the mechanical properties were comparable to those mixed using Portland cement after 7 days of curing. In addition, Shanbara et al. [119] investigated the effect of OPC on Cold mix mechanical properties through laboratory tests. An important enhancement in stiffness modulus values of mixtures containing OPC, was observed compared to the control mixture.

It can therefore be concluded that OPC has been widely used in the development of CBEMs. However, cement production is a very energy-intensive process and therefore environmentally harmful [120]. To manufacture of 1 tonne of cement involves the consumption of 1.5 tonnes of quarry material, 5.6 GJ of energy and 0.9 tonnes of CO_2 emissions. According to O'Rourke et al. [121], 5% of total global carbon dioxide CO_2 emissions are generated by the cement industry. Ravikumar et al. [122] stated that the recent awareness of the ecological impact of using cement in construction, is encouraging researchers and industrial companies to use waste and by-product materials as a replacement, or partial replacement, for cement.

4.5.4. Waste and by-products materials enhancement

The use of waste and by-product materials in the production of CBEMs, is one way to enhance their mechanical properties and durability, this also producing economic and ecological benefits [19, 123-125]. The economic benefits are evident through the low, or essentially the gratis cost of production. Ecological benefits manifest through the elimination of the need for expensive waste disposal as these materials contain toxic ingredients that can be hazardous to both biodiversity and human health when disposed of in lakes, streams or landfills. These materials have cementitious and pozzolanic properties depending on their reactions [126, 127]. The materials that generate cementitious compounds when they react with water, are called cementitious materials [128]. The materials that do not have cementitious properties, but when used with cement or any other cementitious materials, react to form cementitious compounds, are called pozzolanic.

Earlier investigations have shown that the use of cementitious materials in CBEMs have positive effects in terms of engineering properties. Unfortunately, such materials have two main drawbacks: their ecological effect and cost. As such the use of waste and industrial by-products materials in CBEM construction, is reasonable for technical, economic and ecological reasons as explained earlier [129]. Thanaya [36] conducted a study using various waste materials to develop the engineering properties of CBEMs. His findings revealed that red porphyrin sand, synthetic aggregates made from sintering quarry fines and crushed glass, can be used and still allow acceptable stiffness values. The use of steel slag was considered risky as it leads to an expansion in volume in wet conditions and crumb rubber results in cracks in the early stages of compaction. Thanaya et al. [104] also found that the stiffness of CBEMs modified using pulverised fly ash as a filler, is comparable to hot mixtures at full curing conditions thus confirming it is suitable to use. Ground Granulated Blast Furnace Slag (GGBS) has been used with bitumen emulsion in CBEMs comprised of recycled aggregates, their stiffness and strength developed when GGBS was added in high humidity conditions.

Al-Hdabi et al. [49] used Waste Fly Ash (WFA) as a filler replacement in cold-rolled asphalt (CRA) to enhance its engineering properties and resistance to moisture damage. Silica fume, a by-product material, was also used as a modifier to enhance the durability and engineering properties of the CRA. The findings determined that in addition to an enhancement in resistance to moisture damage, there was a substantial enhancement in stiffness modulus and uniaxial creep tests. Nassar et al. [130] used binary and ternary blended fillers (BBF and TBF) to enhance the mechanical properties of CBEMs. For the BBF, fly ash and GGBS were used, silica fume (SF) added to the BBF to obtain TBF. Based on measurement of the enhanced durability and mechanical properties of CBEMs, the TBF was found to be more suitable than BBF for CBEMs manufacture. Furthermore, it is suggested that adding SF to BBF in bitumen emulsion mixtures, increases the formation of hydration products caused by the bitumen emulsion. Dulaimi et al. [101] developed a new cold asphalt concrete mixture for a binder course by incorporating a new binary blended filler material produced from high calcium fly ash and a fluid catalytic cracking catalyst (FC3R), instead of the traditional limestone filler. It was proved that using such materials facilitated a significant development in resistance to fatigue cracking and rutting in CBEMs.

Recently, Dulaimi et al. [102] applied a waste alkaline NaOH solution as an activator in a binary blended filler, to create an alkali-activated binary blended cementitious filler (ABBCF). This was to develop a new fast-curing and environmentally friendly CBEM for the binder course. Considerable improvements were observed in terms of moisture sensitivity and engineering characteristics. Progressive curing with ABBCF was responsible for the high-water damage resistance. Using ABBCF means that the stiffness moduli of conditioned mixtures have greater values than un-conditioned mixtures, these better than the result for the reference mixes, as shown in Figure 6.

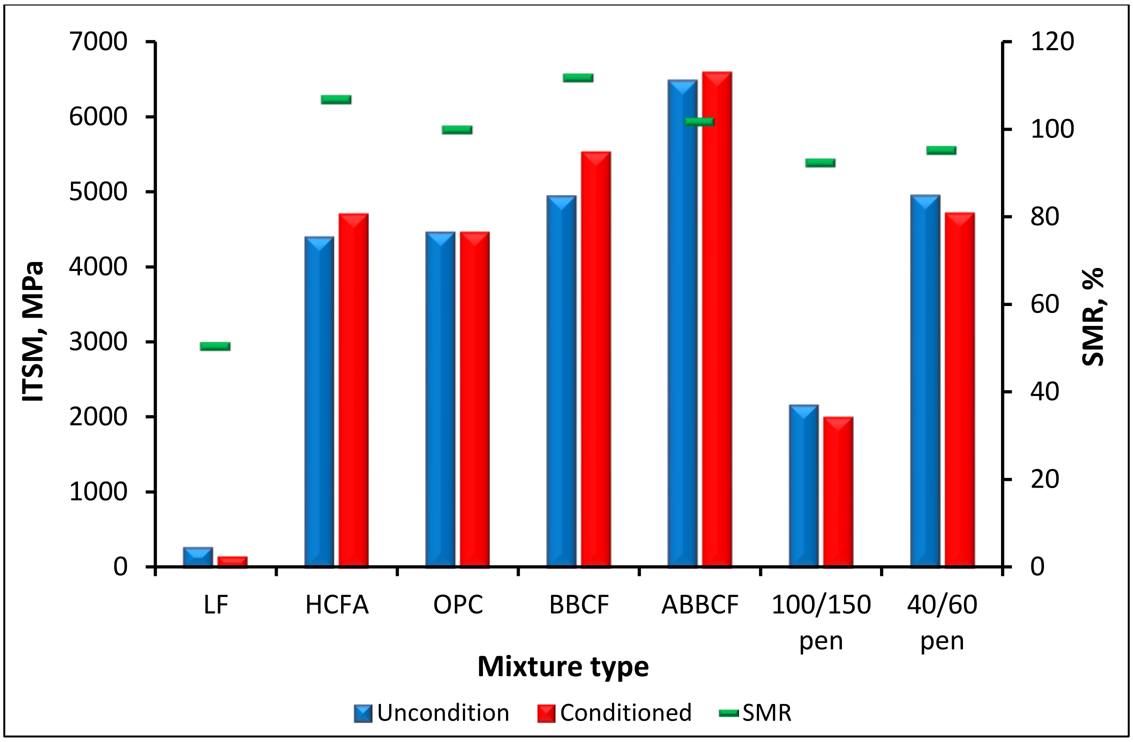


Figure 6. Water sensitivity performance results [85]

More recently, a new cementitious material containing a calcium carbide residue and ground-granulated blast-furnace slag has been developed by Dulaimi et al. [123] to replace traditional mineral limestone filler and produce new cold asphalt emulsion mixtures (CAEMs). The generation of cementitious products such as ettringite, Portlandite and C-S-H gel was responsible for improvements in both mechanical and durability properties. As seen in Figure 7, these products enabled improvements in stiffness at an early age.

It is worth mentioning that a range of research studies have shown that CBEM has positive engineering characteristics in terms of cracking, rutting, and durability properties, in comparison to HMA. However, almost all these studies were undertaken in labs [55, 131-135], a small number of field studies performed to draw comparisons between CBEM and HMA [136, 137]. Therefore, there is the need to carry out works which can examine and consolidate its superiority in service as a heavily trafficked pavement layer. It is encouraging that these field-based publications prove that the use of CBEMs is continuing to grow.

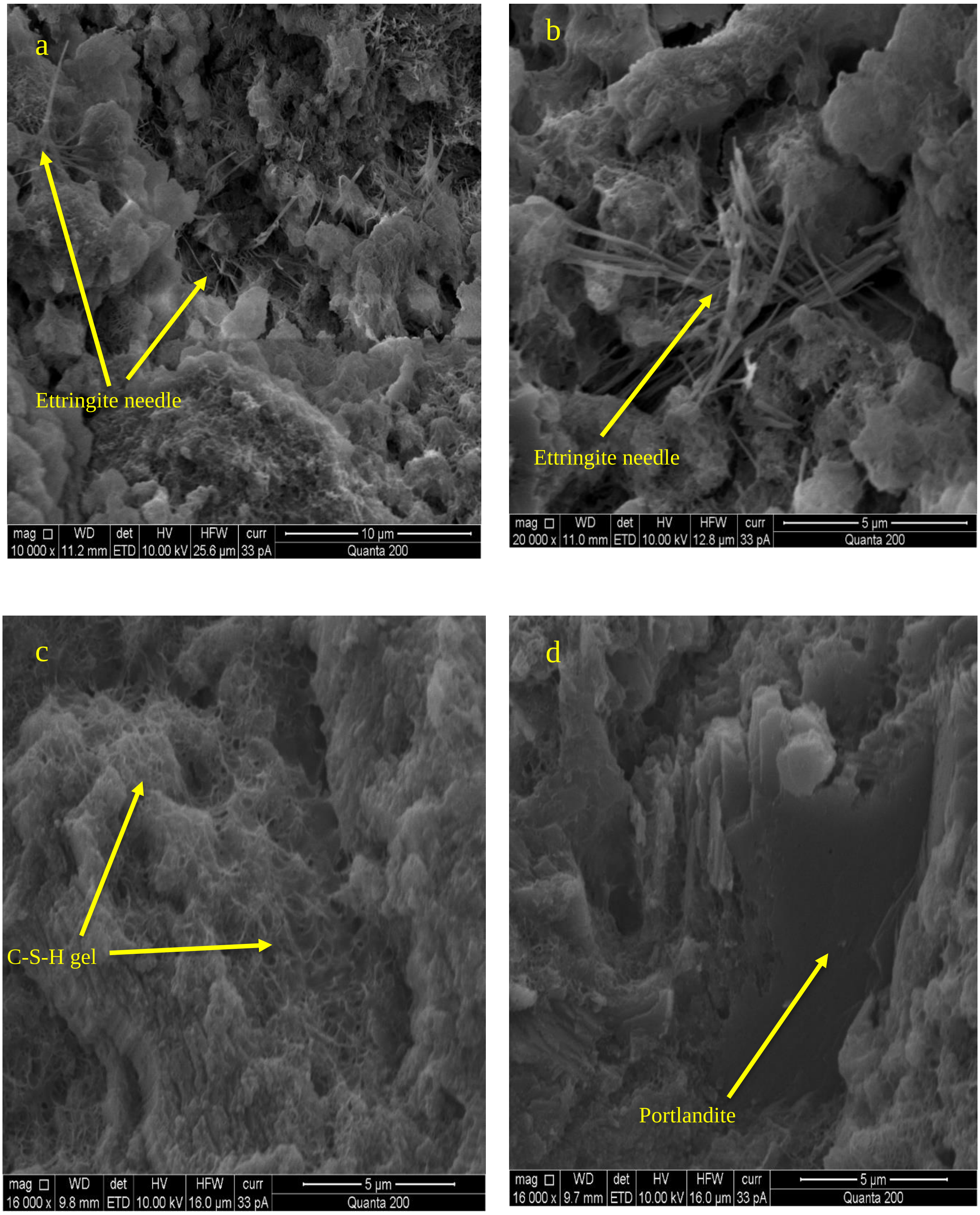


Figure 7. Morphology details of microstructures: (a) and (b) morphology of BBF at 3 days, (c) and (d) morphology of BBF at 28 days [123]

4.5.5. Fibre enhancement

Several techniques have been applied in order to improve flexible pavements. During bituminous mixture manufacturing, stiffness and cohesion can be developed by the addition of fibres [138-142]. This is an effective technique to enhance pavement behaviour when they do not meet traffic, climate and pavement structural requirements. Reinforcing said pavements, can develop their life by improving cracking and rutting resistance [143, 144]. Shanbara et al. [140] studied the effect of using natural hemp (HEM), jute (JUT), coir (COI)) and synthetic glass (GLS) fibres on the rutting performance of CBEM at 60 ℃ against conventional (CON) CBEM and HMA mixtures, as shown in Figure 8. Including these types of fibres as reinforcing materials, has the potential to enhance the overall pavement strength, and to develop cohesion and durability [145]. These fibres have a range of desirable properties and are used to reinforce other materials which also require such properties [146-150]. There is a good possibility of developing the bond and tensile strength of hot and cold mixes by using fibres that have better tensile strength, as opposed to bituminous mixes alone [151]. The main objectives of using fibres as reinforcing materials in pavement construction are to develop the tensile strength and provide more strain resistance to fatigue cracking and permanent deformation of the resulting mixtures [152]. Draining down of bituminous mixes is prevented by using fibres, rather than polymers, during all pavement construction stages [153, 154]. In addition, fibres improve the viscosity of bituminous mixtures [148], resistance to rutting [155-157], stiffness modulus [158], moisture susceptibility [148] and retard reflection cracking for pavements [159, 160]. The modification of bituminous mixtures with additives has also been shown to minimize permanent deformation and increase durability [161-164].

To date, a variety of laboratory studies have been carried out to assess the impact of synthetic and natural fibres on the engineering performance of asphalt mixes in terms of hot and cold mix asphalt. The findings of such investigations all agree that fibres have a positive effect on the behaviour of asphalt mixes [147, 153, 165, 166]. The behaviour of reinforced asphalt mixes is mostly affected by fibre type, surface texture, length, diameter and content [152, 153, 165, 166]. Bueno et al. [167] investigated the use of fibre to enhance the mechanical properties of cold emulsion, densely graded, emulsified bituminous mixtures. Ferrotti et al. [145] carried out experimental research reinforcing CBEM with three types of fibres, cellulose, glass-cellulose and nylon-polyester-cellulose, at two different contents (0.15% and 0.30%). The reinforced mixtures were tested at different curing times (1 day, 7 days, 14 days and 28 days) and conditions (dry and wet). The results revealed that the mixture reinforced with 0.15% cellulose fibre, had showed a comparable, or even better performance than the conventional mixture.

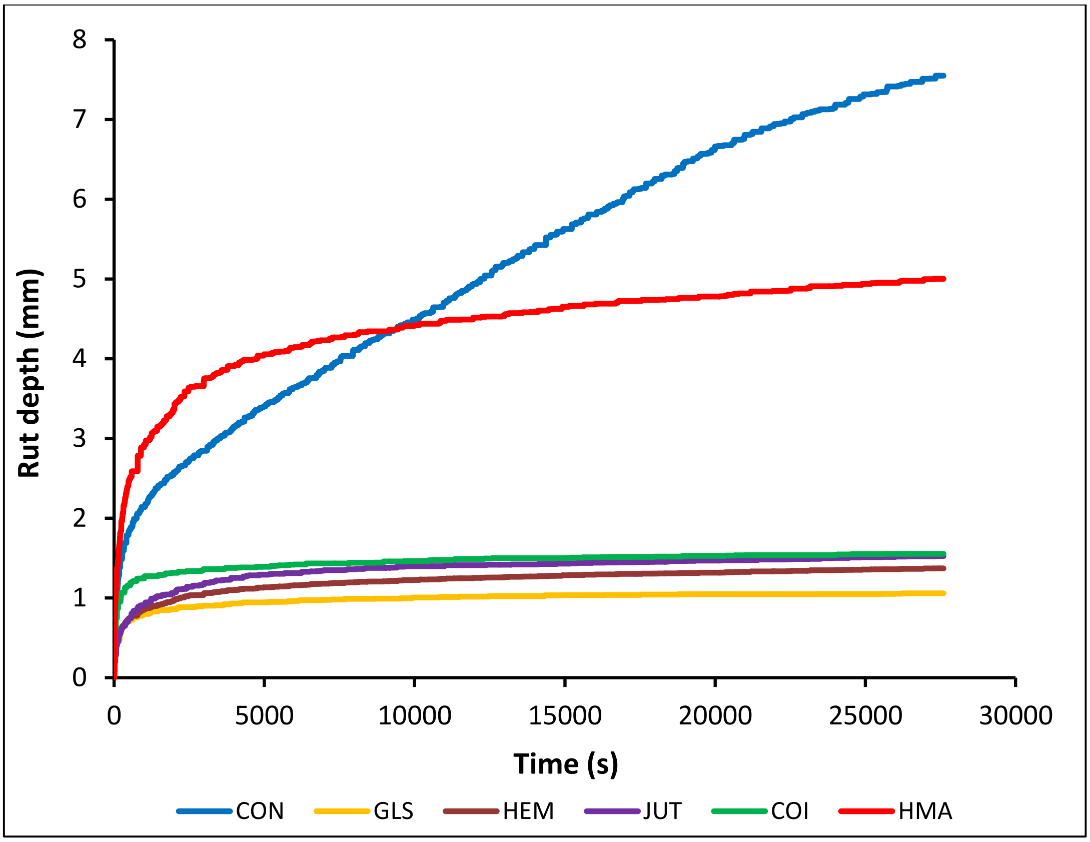


Figure 8. Rutting of different mixtures at 60 ℃ [121]

4.5.6. Ultrasound technique enhancement

A new, modified bitumen emulsion has been developed using a novel technology to reduce the size of the bitumen droplets and make them more uniformly distributed. Ultrasound technology was used to produce a new micro-bitumen emulsion [30]. The outcome revealed a reduction in the viscosity of the newly treated emulsion by 28% in comparison to conventional emulsions. Mean particle size dropped by 85% compared to the untreated emulsion, the particle size distribution curve more uniform and closer to the mean value. The effect of the sonicated bitumen emulsion on the performance of the cold bitumen emulsion mixture was studied in terms of indirect tensile stiffness modulus. The enhancement in ITSM was approximately 70% compared to the conventional mixture with untreated emulsion [30].

5. Summary and conclusions

CBEM boasts a profusion of advantages such as low emissions, cost-effectiveness, safe application, easy production and efficacy in cold weather. However, these mixtures also have some drawbacks in terms of their lower mechanical performance and long curing time, this prompting extensive research to overcome these shortcomings. This review also sheds light on previous studies designed to enhance the behaviour of CBEMs. Some procedures have been applied to improve the engineering characteristics of these mixes to make them environmentally friendly, economical and sustainable alternatives to traditional hot mix asphalt mixtures as there is no need to heat huge amounts of aggregates and bitumen in comparison to conventional hot mix asphalt mixtures. Nevertheless, low early stiffness and extended curing times required to obtain the final strength of CBEMs after compaction, have been highlighted as the crucial obstructions to a wide range of applications. The status of CBEMs can be described as follows:

1. To date, there is no globally accepted mix design procedure because of a variety of factors.
2. There are significant attempts to upgrade CBEM in terms of rutting and cracking resistance, while fatigue and abrasion resistance remain under development.
3. Sustainable materials are playing a vital role in the improvement of CBEMs. Although the addition of OPC in CBEMs has some advantages as suitable strength can be achieved in a short period of time, OPC is not a green material and can harmfully impact the environment. The use of waste and industrial by-product materials in CBEMs is usually promoted for two reasons; economic advantages and environmental sustainability.
4. Reinforcing bituminous mixtures using natural and synthetic fibres has been considered one of the key methods of enhancing the engineering properties of these mixtures to combat possible faults.
5. The ongoing development of bitumen emulsions in terms of base asphalt binders, additives, and particle size distribution, is resulting in the further development of CBEMs.

To conclude, it is of paramount importance that the road pavement industry incentivises CBEM plants through providing support for further research and technology. Ultimately, it is steps such as these that will effectively lay the foundation for the future of a more sustainable road pavement industry and a more ecological world as a whole.

Acknowledgements

Permission for copyrighted graphics, images, tables and/or figures have been secured.

References

[1] Thives, L.P. and Ghisi, E., *Asphalt mixtures emission and energy consumption: A review.* Renewable and Sustainable Energy Reviews, 2017. 72: p. 473-484.

[2] Dulaimi, A., Shanbara, H.K., Jafer, H. and Sadique, M., *An evaluation of the performance of hot mix asphalt containing calcium carbide residue as a filler.* Construction and Building Materials, 2020. 261: p. 119918.

[3] Shanbara, H.K., Ruddock, F., Dulaimi, A. and Atherton, W. *Cold and hot asphalt pavements modelling*. in *Bearing Capacity of Roads, Railways and Airfields*. 2017.

[4] Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L., *A Novel Cold Asphalt Concrete Mixture for Heavily Trafficked Binder Course.* International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 2015. 9(15): p. 734-738.

[5] Hurley, G.C. and Prowell, B.D., *Evaluation of Aspha-Min zeolite for use in warm mix asphalt.* NCAT report, 2005(05-04).

[6] Hurley, G.C. and Prowell, B.D., *Evaluation of Sasobit for use in warm mix asphalt.* NCAT report, 2005. 5(6): p. 1-27.

[7] Hurley, G.C. and Prowell, B.D., *Evaluation of Evotherm for use in warm mix asphalt.* NCAT report, 2006. 2: p. 15-35.

[8] Prowell, B.D., Hurley, G.C. and Crews, E., *Field performance of warm-mix asphalt at national center for asphalt technology test track.* Transportation Research Record, 2007. 1998(1): p. 96-102.

[9] Wasiuddin, N.M., Selvamohan, S., Zaman, M.M. and Guegan, M.L.T.A., *Comparative laboratory study of sasobit and aspha-min additives in warm-mix asphalt.* Transportation Research Record, 2007. 1998(1): p. 82-88.

[10] Shanbara, H.K., Dulaimi, A., Ruddock, F. and Atherton, W. *The linear elastic analysis of cold mix asphalt by using finite element modeling*. in *The Second BUiD Doctoral Research Conference*. 2016.

[11] Shanbara, H.K., Ruddock, F. and Atherton, W., *Stresses and Strains Distribution of a Developed Cold Bituminous Emulsion Mixture Using Finite Element Analysis.* Science and Technology Behind Nanoemulsions, 2018: p. 9.

[12] Dulaimi, A., Nageim, H.A., Ruddock, F. and Seton, L., *Laboratory Studies to Examine the Properties of a Novel Cold-Asphalt Concrete Binder Course Mixture Containing Binary Blended Cementitious Filler.* Journal of Materials in Civil Engineering, 2017. 29(9).

[13] Querol, N., Barreneche, C. and Cabeza, L.F., *Method for controlling mean droplet size in the manufacture of phase inversion bituminous emulsions.* Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2017. 527: p. 49-54.

[14] Shanbara, H.K., Ruddock, F. and Atherton, W., *Predicting the rutting behaviour of natural fibre-reinforced cold mix asphalt using the finite element method.* Construction and Building Materials, 2018. 167: p. 907-917.

[15] Shanbara, H.K., Shubbar, A., Ruddock, F. and Atherton, W., *Characterizing the Rutting Behaviour of Reinforced Cold Mix Asphalt with Natural and Synthetic Fibres Using Finite Element Analysis*, in *Advances in Structural Engineering and Rehabilitation*. 2020, Springer. p. 221-227.

[16] Shanbara, H.K., Ruddock, F. and Atherton, W. *Improving the Mechanical Properties of Cold Mix Asphalt Mixtures Reinforced by Natural and Synthetic Fibers*. in *International Conference on Highway Pavements & airfield Technology*. 2017.

[17] Dulaimi, A., Al Nageim, H., Hashim, K., Ruddock, F. and Seton, L. *Investigation into the stiffness improvement, microstructure and environmental impact of a novel fast-curing cold bituminous emulsion mixture*. in *Eurasphalt and Eurobitume Congress, European Asphalt Pavement Association (EAPA) and Eurobitume, Brussels, Belgium*. 2016.

[18] Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L., *Assessment the Performance of Cold Bituminous Emulsion Mixtures with Cement and Supplementary Cementitious Material for Binder Course Mixture*, in *The 38th International Conference on Cement Microscopy*. 2016: Lyon, France.

[19] Al Nageim, H., Dulaimi, A., Ruddock, F. and Seton, L., *Development of a new cementitious filler for use in fast-curing cold binder course in pavement application*, in *The 38th International Conference on Cement Microscopy*. 2016: Lyon, France. p. pp. 167-180.

[20] Wasim, M., Vaz Serra, P. and Ngo, T.D., *Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction – a review.* International Journal of Construction Management, 2020: p. 1-9.

[21] Wasim, M., Ngo, T.D. and Law, D., *A state-of-the-art review on the durability of geopolymer concrete for sustainable structures and infrastructure.* Construction and Building Materials, 2021. 291: p. 123381.

[22] Scopus. *Scopus analyze search results*. 2021 20th May 2021]; Available from: https://www.scopus.com/results/results.uri?sort=plf-f&src=s&nlo=&nlr=&nls=&sid=2a76eff24c093f1b211839e818d37f43&sot=b&sdt=cl&cluster=scopubyr%2c%222021%22%2cf&sl=31&s=TITLE-ABS-KEY%28Cold+mix+asphalt%29&origin=resultslist&zone=leftSideBar&editSaveSearch=&txGid=937269e31cb6f71c5e58fb0d2e0609c5.

[23] Dinis-Almeida, M., Castro-Gomes, J., Sangiorgi, C., Zoorob, S.E. and Afonso, M.L., *Performance of warm mix recycled asphalt containing up to 100% RAP.* Construction and Building Materials, 2016. 112: p. 1-6.

[24] Vaitkus, A., Čygas, D., Laurinavičius, A., Vorobjovas, V. and Perveneckas, Z., *Influence of warm mix asphalt technology on asphalt physical and mechanical properties.* Construction and Building Materials, 2016. 112: p. 800-806.

[25] Shanbara, H.K., Ruddock, F. and Atherton, W., *Rutting prediction of a reinforced cold bituminous emulsion mixture using finite element modelling.* Procedia engineering, 2016. 164: p. 222-229.

[26] Al-Hdabi, A., *HIGH STRENGTH COLD ROLLED ASPHALT SURFACE COURSE MIXTURES*, in *Department of Civil Engineering*. 2014, Liverpool John Moores University: Liverpool

[27] Jenkins, K.J., *Mix design considerations for cold and half-warm bituminous mixes with emphasis of foamed bitumen*. 2000, Stellenbosch: Stellenbosch University.

[28] Shanbara, H.K., Ruddock, F. and Atherton, W., *A viscoplastic model for permanent deformation prediction of reinforced cold mix asphalt.* Construction and Building Materials, 2018. 186: p. 287-302.

[29] Al-Busaltan, S., *Development of New Cold Bituminous Mixtures for Road and Highway Pavements*, in *School of Built Environment*. 2012, Liverpool John Moores University: Liverpool

[30] Herez, M., *Development of a New High Performance Cold Mix Asphalt*, in *Department of Civil Engineering*. 2019, Liverpool John Moores University: Liverpool.

[31] Dulaimi, A., *DEVELOPMENT OF A NEW COLD BINDER COURSE EMULSION ASPHALT*, in *Department of Civil Engineering*. 2017, Liverpool John Moores University: Liverpool

[32] Nicholls, J.C., *Asphalt surfacings*. 1998: CRC Press.

[33] Robinson, R. and Thagesen, B., *Road engineering for development*. 2004: CRC Press.

[34] Leech, D., *Cold bituminous materials for use in the structural layers of roads.* Transport Research Laboratory, Project Report, 1994. 75.

[35] Needham, D., *Developments in bitumen emulsion mixtures for roads*. 1996, University of Nottingham Nottingham.

[36] Thanaya, I., *Improving the performance of cold bituminous emulsion mixtures (CBEMs) incorporating waste materials*. 2003.

[37] Ojum, C.K., *The design and optimisation of cold asphalt emulsion mixtures*. 2015, University of Nottingham.

[38] Kuna, K.K., *Mix Design Considerations and Performance Characteristics of Foamed Bitumen Mixtures (FBMs)*. 2014, University of Nottingham: Nottingham, UK.

[39] Al-Busaltan, S., *Development of New Cold Bituminous Mixtures for Road and Highway Pavements*. 2012, Liverpool John Moores University.

[40] Jain, S. and Singh, B., *Cold mix asphalt: An overview.* Journal of Cleaner Production, 2021. 280: p. 124378.

[41] Nikolaides, A.F., *Design of dense graded cold bituminous emulsion mixtures and evaluation of their engineering properties*. 1983, University of Leeds.

[42] Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L., *Microanalysis of Alkali-Activated Binary Blended Cementitious Filler in a Novel Cold Binder Course Mixture*, in *The 38th International Conference on Cement Microscopy*. 2016: Lyon, France.

[43] Liebenberg, J. and Visser, A., *Towards a mechanistic structural design procedure for emulsion-treated base layers.* Journal of the South African Institution of Civil Engineering= Joernaal van die Suid-Afrikaanse Instituut van Siviele Ingenieurswese, 2004. 46(3): p. 2-9.

[44] Gómez-Meijide, B. and Pérez, I., *A proposed methodology for the global study of the mechanical properties of cold asphalt mixtures.* Materials & Design, 2014. 57: p. 520-527.

[45] Doyle, T.A., McNally, C., Gibney, A. and Tabaković, A., *Developing maturity methods for the assessment of cold-mix bituminous materials.* Construction and Building Materials, 2013. 38: p. 524-529.

[46] Oruc, S., Celik, F. and Akpinar, M.V., *Effect of cement on emulsified asphalt mixtures.* Journal of Materials Engineering and Performance, 2007. 16(5): p. 578-583.

[47] Ibrahim, H.E.-S.M., *Assessment and design of emulsion-aggregate mixtures for use in pavements*. 1998, University of Nottingham.

[48] Al-Busaltan, S., Al Nageim, H., Atherton, W. and Sharples, G., *Mechanical Properties of an Upgrading Cold-Mix Asphalt Using Waste Materials.* Journal of materials in civil engineering 2012. 24(12): p. 1484-91.

[49] Al-Hdabi, A., Al Nageim, H., Ruddock, F. and Seton, L., *Development of sustainable cold rolled surface course asphalt mixtures using waste fly ash and silica fume.* Journal of materials in civil engineering, 2014. 26(3): p. 536-543.

[50] Thanaya, I.N.A., *Review and recommendation of cold asphalt emulsion mixtures CAEMS design.* Civil Engineering Dimension, 2007. 9(1): p. pp. 49-56.

[51] Robinson, H. *Thin asphalt surfacings using cold mix technology*. in *PERFORMANCE AND DURABILITY OF BITUMINOUS MATERIALS. PROCEEDINGS OF THE SECOND EUROPEAN SYMPOSIUM ON PERFORMANCE AND DURABILITY OF BITUMINOUS MATERIALS, LEEDS, APRIL 1997*. 1997.

[52] Brown, S. and Needham, D., *A study of cement modified bitumen emulsion mixtures.* Asphalt Paving Technology, 2000. 69: p. 92-121.

[53] Khalid, H.A. *Assessing the potential in fatigue of a dense wearing course emulsified bitumen macadam*. in *PERFORMANCE TESTING AND EVALUATION OF BITUMINOUS MATERIALS PTEBM'03. PROCEEDINGS OF THE 6TH INTERNATIONAL RILEM SYMPOSIUM HELD ZURICH, SWITZERLAND, 14-16 APRIL 2003*. 2003.

[54] Serfass, J.-P., Poirier, J.-E., Henrat, J.-P. and Carbonneau, X., *Influence of curing on cold mix mechanical performance.* Materials and structures, 2004. 37(5): p. 365-368.

[55] Nassar, A., *Enhancing the performance of cold bitumen emulsion mixture using supplementary cementitious*, in *Department of Civil Engineering*. 2016, University of Nottingham: Nottingham.

[56] Staples, P.R., *COLD EMULSION MACADAM PERFORMANCE TRIALS FOR FOOTWAY SURFACING IN LEICESTERSHIRE.* 1997. 123(3): p. 174-177.

[57] Gómez-Meijide, B., Pérez, I. and Pasandín, A.R., *Recycled construction and demolition waste in cold asphalt mixtures: Evolutionary properties.* J. Cleaner Prod., 2016. 112: p. 588.

[58] Fang, X., Garcia, A., Winnefeld, F., Partl, M.N. and Lura, P., *Impact of rapid-hardening cements on mechanical properties of cement bitumen emulsion asphalt.* Mater. Struct, 2016. 49: p. 487.

[59] Al Nageim, H., Al-Busaltan, S.F., Atherton, W. and Sharples, G., *A comparative study for improving the mechanical properties of cold bituminous emulsion mixtures with cement and waste materials.* Construction and Building Materials, 2012. 36: p. 743-748.

[60] Read, J. and Whiteoak, D., *The Shell Bitumen Handbook - Fifth Edition*. 2003, London. UK.

[61] Salomon, D., *Transportation research circular E-C102: Asphalt emulsion technology.* Transportation Research Board, Washington, DC, 2006: p. 1-24.

[62] Manual, A.B.A.E., *Manual series no. 19 (ms-19).* Asphalt Institute, 1979.

[63] European Asphalt Pavement Association. *The Use Of Bitumen Emulsion In Europe*. 2015 12/04/2018]; Available from: http://www.eapa.org/publications.php?c=73.

[64] Needham, D., *Developments in bitumen emulsion mixtures for roads*. 1996, University of Nottingham: Nottingham,UK.

[65] Thanaya, I.N.A., *Improving the performance of cold bituminous emulsion mixtures incorporating waste materials*. 2003, University of Leeds, UK.

[66] Salomon, D.R., *Asphalt emulsion technology*. 2006: Transportation research board.

[67] James, A., *Overview of asphalt emulsion.* Transport Research Circulary Number E-C102, Asphalt Emulsion Technology, 2006: p. 1-15.

[68] Asphalt Institute, *Asphalt Cold Mix Manual, Manual Series No. 14 (MS-14), 3rd Edition, Lexington, Kentucky 4, USA*. 1989.

[69] Asphalt Institute, *Basic Asphalt Emulsion Manual, Manual Series No. 19 (MS-19), 4th Edition., Lexington, Kentucky, USA*. 2008.

[70] Read, J. and Whiteoak, D., *The Shell Bitumen Handbook*. 2003, 5th Edition, London, UK: Thomas Telford Publishing.

[71] Thanaya, I., *Improving the performance of cold bituminous emulsion mixtures (CBEMs): incorporating waste*. 2003, University of Leeds.

[72] European Committee for Standardization, *BS EN 13808: Bitumen and bituminous binders - Framework forspecifying cationic bituminous emulsions, British Standards Institution, London, UK*. 2013.

[73] Al-Busaltan, S., *Development of New Cold Bituminous Mixtures for Road and Highway Pavements.* PhD Thesis, School of Built Environment, Liverpool John Moores University, 2012.

[74] British Standard Institution, *BS 434-1: Bitumen and road emulsions - Part 1: Specification for anionic bitumen road emulsions, UK*. 2011.

[75] Jenkins, K.J., *Mix design considerations for cold and half-warm bituminous mixes with emphasis on foamed asphalt*. 2000, University of Stellenbosch, Stellenbosch: South Africa.

[76] Serfass, J., Poirier, J., Henrat, J. and Carbonneau, X., *Influence of Curing on Cold Mix Mechanical Performance*, in *the 6th International RILEM Symposium on Performance testing and Evaluation of Bituminous Materials*. 2004, RILEM Publications: Zurich, Bagneux. p. 81-87.

[77] Ojum, C.K., *The Design and Optimisation of Cold Asphalt Emulsion Mixtures*. 2015, University of Nottingham: Nottingham, UK.

[78] Wu, S., Ye, Q. and Li, N., *Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers.* Construction and Building Materials, 2008. 22(10): p. 2111-2115.

[79] Mahrez, A. and Rehan, K.M., *Fatigue characteristics of stone mastic asphalt mix reinforced with fiber glass.* International Journal of the Physical Sciences, 2010. 5(12): p. 1840-1847.

[80] Nageim, H.A., Al-Busaltan, S.F., Atherton, W. and Sharples, G., *A comparative study for improving the mechanical properties of cold bituminous emulsion mixtures with cement and waste materials.* Constr. Build. Mater., 2012. 36: p. 743.

[81] Al-Hdabi, A., Nageim, H.A., Ruddock, F. and Seton, L., *Enhancing the mechanical properties of gap graded cold asphalt containing cement utilising by-product material.* J. Civ. Eng. Archit., 2013. 7: p. 916.

[82] Thanaya, I.N.A., *Review and Recommendation of Cold Asphalt Emulsion Mixtures Design.* Civil Engineering Dimension, 2007. 9(1. Indonesia).

[83] Nikolaides, A.F., *A new design method for dense cold mixtures*. 1994: Proceedings of the first European symposium on performance and durability of bituminous materials. University of Leeds.

[84] Taylor, M.B., *Assessment of Cold Mix Emulsions*, in *Proceedings of the 2nd European Symposium on Performance and Durability of Bituminous Materials, University of Leeds, Zurich. Aedificatio Publishers, 399-408*. 1997.

[85] Thom, N., *Principles of pavement engineering*. 2008, London: Thomas Telford Limited.

[86] Niazi, Y. and Jalili, M., *Effect of Portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion.* Construction and Building Materials, 2009. 23(3): p. 1338-1343.

[87] Bocci, M., Grilli, A., Cardone, F. and Graziani, A., *A study on the mechanical behaviour of cement–bitumen treated materials.* Construction and building materials, 2011. 25(2): p. 773-778 %@ 0950-0618.

[88] Roberts, F.L., Engelbrecht, J.C. and Kennedy, T.W., *Evaluation of Recycled Mixtures Using Foamed Asphalt.* Transportation Research Record No. 968, 1984.

[89] Bocci, M., Virgili, A. and Colgrande, S., *A study of the Mechanical Characteristics of Cold Recycled Bituminous Concretes*. 2002, University of Nottingham: Proceeding of 4th European Symposium on Performance of Bituminous and Hydraulic Materials in Pavement. p. 227-235.

[90] Santucci, L.E., *Thickness Design Procedure for Asphalt and Emulsified Asphalt Mixes*, in *The 4th International Conference on Structural Design of Asphalt Pavements*. 1977, Transportation Research board: Michigan, USA. p. 424-456.

[91] Leech, D., *Cold bituminous materials for use in the structural layers of roads*. 1994, Transport Research Laboratory: Wokingham, United Kingdom.

[92] Lanre, O.O., *A Study on The Development of Guidelines for The Production of Bitumen Emulsion Stabilised Raps for Roads in The Tropics*, in *Depatment of Civil Engineering*. 2010, University of Nottingham: Nottingham, United Kingdom.

[93] Kim, Y., Im, S. and Lee, H.D., *Impacts of Curing Time and Moisture Content on Engineering Properties of Cold In-Place Recycling Mixtures Using Foamed or Emulsified Asphalt.* Journal of Materials in Civil Engineering, 2011. 23(5): p. 542-553.

[94] García, A., Lura, P., Partl, M.N. and Jerjen, I., *Influence of cement content and environmental humidity on asphalt emulsion and cement composites performance.* Materials and Structures, 2013. 46(8): p. 1275-1289.

[95] Arabani, M. and Kamboozia, N., *The linear visco-elastic behaviour of glasphalt mixture under dynamic loading conditions.* Construction and Building Materials, 2013. 41: p. 594-601.

[96] Al-Hdabi, A., Al Nageim, H. and Seton, L., *Superior cold rolled asphalt mixtures using supplementary cementations materials.* Construction and Building Materials, 2014. 64: p. 95-102.

[97] Yuliestyan, A., García-Morales, M., Moreno, E., Carrera, V. and Partal, P., *Assessment of modified lignin cationic emulsifier for bitumen emulsions used in road paving.* Materials & Design, 2017. 131: p. 242-251.

[98] Jamshidi, A., Hamzah, M.O., Kurumisawa, K., Nawa, T. and Samali, B., *Evaluation of sustainable technologies that upgrade the binder performance grade in asphalt pavement construction.* Materials & Design, 2016. 95: p. 9-20.

[99] Al-Mansoori, T., Garcia, A., Norambuena-Contreras, J. and Artamendi, I., *Self-healing properties of asphalt mixtures with embedded capsules*, in *Advances in Materials and Pavement Prediction*. 2018, CRC Press. p. 551-555.

[100] Al-Mansoori, T., Micaelo, R. and Garcia, A., *Characterization of polymer capsules used for self-healing asphalt pavements*, in *Functional Pavement Design*. 2016, CRC Press. p. 1167-1174.

[101] Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L., *New developments with cold asphalt concrete binder course mixtures containing binary blended cementitious filler (BBCF).* Construction and Building Materials, 2016. 124: p. 414-423.

[102] Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L., *High performance cold asphalt concrete mixture for binder course using alkali-activated binary blended cementitious filler.* Construction and Building Materials, 2017. 141: p. 160-170.

[103] Ibrahim, H. and Thom, N. *The Effect of Emulsion-Aggregate Mixture Stiffness on both Mixture and Pavement Design*. in *PERFORMANCE AND DURABILITY OF BITUMINOUS MATERIALS. PROCEEDINGS OF THE SECOND EUROPEAN SYMPOSIUM ON PERFORMANCE AND DURABILITY OF BITUMINOUS MATERIALS, LEEDS, APRIL 1997*. 1997.

[104] Thanaya, I.N.A., Forth, J.P. and Zoorob, S.E., *A laboratory study on cold-mix, cold-lay emulsion mixtures.* Proceedings of the Institution of Civil Engineers, 2009(1): p. 47-55.

[105] Khalid, H.A. and Eta, K.E., *Structural Support Values for Emulsified Bitumen Macadams in Highway Reinstatement*, in *The 2nd European Symposium on Performance and Durability of Bituminous Materials*. 1997, Aedificatio Publishers, Zurich: University of Leeds. p. 307- 326.

[106] Chávez-Valencia, L.E., Alonso, E., Manzano, A., Pérez, J., Contreras, M.E. and Signoret, C., *Improving the compressive strengths of cold-mix asphalt using asphalt emulsion modified by polyvinyl acetate.* Construction and Building Materials, 2007. 21(3): p. 583-589.

[107] Xu, S.F.X., Zhao, Z.C., Xu, Y. and Wang, X.X., *Mixture Design and Performance Evaluation of Cold Asphalt Mixture Using Polymer Modified Emulsion.* Advanced Materials Research, 2015. 1065-1069: p. 760-765.

[108] Abdel-Wahed, T. and Al Nageim, H., *Investigating the effects of cement and cement kiln dust as a filler on the mechanical properties of cold bituminous emulsion mixtures.* International Journal of Civil Engineering and Technology, 2016. 7(1): p. 441-453 %@ 0976-6308.

[109] O’Flaherty, C.A., *Highways the Location, Design, Construction and Maintanance of Road Pavements*. 2007, Butterworth Heinemann, USA.

[110] Terrel, R.L. and Wang, C.K., *Early curing behavior of cement modified asphalt emulsion mixtures*, in *Association of Asphalt Paving Technologists (AAPT) Conference*. 1971, Transportation Research Board: Washington, USA. p. 108-125.

[111] Schmidt, R.J., Santucci, L.E. and Coyne, L.D., *Performance characteristics of cement-modified asphalt emulsion mixes*, in *Association of Asphalt Paving Technologists (AAPT) Conference*. 1973, Transportation Research Board: Washington, USA. p. 300–319.

[112] Head, R.W., *An informal report of cold mix research using emulsified asphalt as a binder*, in *Association of Asphalt Paving Technologists (AAPT) Conference*. 1974, Transportation Research Board: Washington, USA. p. 110-131.

[113] Dardak, H., *Performance of different mixes of sand emulsion in Indonesia*, in *1st World Congress on Emulsion*. 1993: Paris. p. 4-12.

[114] Li, G., Zhao, Y., Pang, S.S. and Huang, W., *Experimental study of cement-asphalt emulsion composite.* Cement and Concrete Research, 1998. 28(5): p. 635-641.

[115] Oruc, S., Celik, F. and Aksoy, A., *Performance of cement modified dense graded cold-mix asphalt and establishing mathematical model.* Indian Journal of Engineering & Materials Sciences, 2006. 13.

[116] Wang, Z. and Sha, A., *Micro hardness of interface between cement asphalt emulsion mastics and aggregates.* Materials and Structures, 2010. 43(4): p. 453-461.

[117] Al-Hdabi, A., Al Nageim, H. and Seton, L., *Performance of gap graded cold asphalt containing cement treated filler.* Construction and Building Materials, 2014. 69: p. 362-369.

[118] Fang, X., Garcia, A., Winnefeld, F., Partl, M.N. and Lura, P., *Impact of rapid-hardening cements on mechanical properties of cement bitumen emulsion asphalt.* Materials and Structures, 2016. 49(1): p. 487-498.

[119] Shanbara, H.K., RuddocN, F., Atherton, W. and Nassir, N.A., *Mechanical Properties of Ordinary Portland Cement Modified Cold Bitumen Emulsion Mixture.* International Journal of Civil and Environmental Engineering, 2018. 12(5): p. 576-581.

[120] Schneider, M., Romer, M., Tschudin, M. and Bolio, H., *Sustainable cement production—present and future.* Cement and Concrete Research, 2011. 41(7): p. 642-650.

[121] O'Rourke, B., McNally, C. and Richardson, M.G., *Development of calcium sulfate–ggbs–Portland cement binders.* Construction and Building Materials, 2009. 23(1): p. 340-346.

[122] Ravikumar, D., Peethamparan, S. and Neithalath, N., *Structure and strength of NaOH activated concretes containing fly ash or GGBFS as the sole binder.* Cement and Concrete Composites, 2010. 32(6): p. 399-410.

[123] Dulaimi, A., Shanbara, H.K. and Al-Rifaie, A., *The mechanical evaluation of cold asphalt emulsion mixtures using a new cementitious material comprising ground-granulated blast-furnace slag and a calcium carbide residue.* Construction and Building Materials, 2020. 250: p. 118808.

[124] Abduljabbar, N., Al-Busaltan, S. and Dulaimi, A., *Evaluating the mechanical properties of thin asphalt overlay incorporating reed ash.* IOP Conference Series: Materials Science and Engineering, 2021. 1067(1): p. 012077.

[125] Abduljabbar, N., Al-Busaltan, S., Dulaimi, A. and Al Jawad, O., *EVALUATING OF AGING BEHAVIOR OF THIN ASPHALT OVERLAY MODIFIED WITH SUSTAINABLE MATERIALS.* The International Journal of Pavement Engineering & Asphalt Technology, 2020. 21(1): p. 162-173.

[126] Al-Khafaji, Z.S., Al Masoodi, Z., Jafer, H., Dulaimi, A. and Atherton, W., *The Effect Of Using Fluid Catalytic Cracking Catalyst Residue (FC3R)" As A Cement Replacement In Soft Soil Stabilisation.* International Journal Of Civil Engineering Technology Volume, 2018. 9: p. 522-533.

[127] Jafer, H.M., Majeed, Z.H. and Dulaimi, A., *Incorporating of Two Waste Materials for the Use in Fine-Grained Soil Stabilization.* Civil Engineering Journal, 2020. 6(6): p. 1114-1123.

[128] Shubbar, A.A.F., Atherton, W., Jafer, H.M., Dulaimi, A.F. and Al-Faluji, D. *The Development of a New Cementitious Material Produced from Cement and GGBS*. 2017. BUiD.

[129] Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L., *Performance Analysis of a Cold Asphalt Concrete Binder Course Containing High-Calcium Fly Ash Utilizing Waste Material.* Journal of Materials in Civil Engineering, 2017. 0(0).

[130] Nassar, A.I., Mohammed, M.K., Thom, N. and Parry, T., *Mechanical, durability and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler.* Construction and Building Materials, 2016. 114: p. 352-363.

[131] Shanbara, H.K., Dulaimi, A. and Al-Mansoori, T., *Studying the mechanical properties of improved cold emulsified asphalt mixtures containing cement and lime.* IOP Conference Series: Materials Science and Engineering, 2021. 1090(1): p. 012006.

[132] Dulaimi, A., Shanbara, H.K. and Al-Mansoori, T., *A Novel Emulsion-Based Mixture (EBM) Containing Ground Granulated Blast-Furnace Slag and Waste Alkaline Ca(OH)2 Solution.* IOP Conference Series: Materials Science and Engineering, 2021. 1090(1): p. 012037.

[133] Al-Khafaji, R., Dulaimi, A., Sadique, M. and Aljsane, A., *Application of Cement Kiln Dust as Activator of Ground Granulated Blast Slag for Developing A Novel Cold Mix Asphalt.* IOP Conference Series: Materials Science and Engineering, 2021. 1090(1): p. 012029.

[134] Sajjad, A.-M., Shakir, A.-B. and Hassan Al, N., *Characterizing Cold Bituminous Emulsion Mixtures Comprised of Palm Leaf Ash.* Journal of Materials in Civil Engineering, 2019. 31(6): p. 04019069.

[135] Nassar, A.I., Mohammed, M.K., Thom, N. and Parry, T., *Mechanical, durability and microstructure properties of cold asphalt emulsion mixtures with different types of filler.* Constr. Build. Mater., 2016. 114: p. 352.

[136] Redelius, P., Östlund, J.-A. and Soenen, H., *Field experience of cold mix asphalt during 15 years.* Road Materials and Pavement Design, 2015. 17(1): p. 223-242.

[137] Day, D., Lancaster, I.M. and McKay, D., *Emulsion cold mix asphalt in the UK: A decade of site and laboratory experience.* Journal of Traffic and Transportation Engineering (English Edition), 2019. 6(4): p. 359-365.

[138] Wu, S.-P., Liu, G., Mo, L.-t., Chen, Z. and Ye, Q., *Effect of fiber types on relevant properties of porous asphalt* Transactions of Nonferrous Metals of China, 2006. 16: p. 791-795.

[139] Wu, J., *The Influence of Mineral Aggregates and Binder Volumetrics on Bitumen Ageing*, in *Department of Civil Engineering*. 2009, The University of Nottingham: Nottingham, United Kingdom.

[140] Shanbara, H.K., Ruddock, F. and Atherton, W., *A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibres.* Construction and Building Materials, 2018. 172: p. 166-175.

[141] Shanbara, H.K., *EFFECT OF CARBON FIBER ON THE PERFORMANCE OF REINFORCED ASPHALT CONCRETE MIXTURE.* Muthanna Journal of Engineering and Technology (MJET), 2011. 1(1): p. 39-51.

[142] Shanbara, H.K., Musa, S.S. and Dulaimi, A., *The effect of polypropylene fibres on the tensile performance of asphalt mixtures for road pavements.* IOP Conference Series: Materials Science and Engineering, 2020. 888.

[143] Abiola, O.S., Kupolati, W.K., Sadiku, E.R. and Ndambuki, J.M., *Utilisation of natural fibre as modifier in bituminous mixes: A review.* Construction and Building Materials, 2014. 54: p. 305-312.

[144] Shanbara, H.K., Ruddock, F. and Atherton, W. *Evaluation of rutting potential in cold bituminous emulsion mixture using finite element analysis*. in *Bearing Capacity of Roads, Railways and Airfields*. 2017.

[145] Ferrotti, G., Pasquini, E. and Canestrari, F., *Experimental characterization of high-performance fiber-reinforced cold mix asphalt mixtures.* Construction and Building Materials, 2014. 57: p. 117-125.

[146] Xiong, R., Fang, J., Xu, A., Guan, B. and Liu, Z., *Laboratory investigation on the brucite fiber reinforced asphalt binder and asphalt concrete.* Construction and Building Materials, 2015. 83: p. 44-52.

[147] Yang, J.M., Kim, J.K. and Yoo, D.Y., *Effects of amorphous metallic fibers on the properties of asphalt concrete.* Construction and Building Materials, 2016. 128: p. 176-184.

[148] Fakhri, M. and Hosseini, S.A., *Laboratory evaluation of rutting and moisture damage resistance of glass fiber modified warm mix asphalt incorporating high RAP proportion.* Construction and Building Materials, 2017. 134: p. 626-640.

[149] Fu, Z., Shen, W., Huang, Y., Hang, G. and Li, X., *Laboratory evaluation of pavement performance using modified asphalt mixture with a new composite reinforcing material.* International Journal of Pavement Research and Technology, 2017.

[150] Jaskuła, P., Stienss, M. and Szydłowski, C., *Effect of Polymer Fibres Reinforcement on Selected Properties of Asphalt Mixtures.* Procedia Engineering, 2017. 172: p. 441-448.

[151] Xue, Y. and Qian, Z., *Development and performance evaluation of epoxy asphalt concrete modified with mineral fiber.* Construction and Building Materials, 2016. 102: p. 378-383.

[152] Abtahi, S.M., Sheikhzadeh, M. and Hejazi, S.M., *Fiber-reinforced asphalt-concrete – A review.* Construction and Building Materials, 2010. 24(6): p. 871-877.

[153] Chen, H., Xu, Q., Chen, S. and Zhang, Z., *Evaluation and design of fiber-reinforced asphalt mixtures.* Materials & Design, 2009. 30(7): p. 2595-2603.

[154] Park, P., El-Tawil, S., Park, S.-Y. and Naaman, A.E., *Cracking resistance of fiber reinforced asphalt concrete at −20°C.* Construction and Building Materials, 2015. 81: p. 47-57.

[155] Fazaeli, H., Samin, Y., Pirnoun, A. and Dabiri, A.S., *Laboratory and field evaluation of the warm fiber reinforced high performance asphalt mixtures (case study Karaj – Chaloos Road).* Construction and Building Materials, 2016. 122: p. 273-283.

[156] Mirabdolazimi, S.M. and Shafabakhsh, G., *Rutting depth prediction of hot mix asphalts modified with forta fiber using artificial neural networks and genetic programming technique.* Construction and Building Materials, 2017. 148: p. 666-674.

[157] Tanzadeh, J. and Shahrezagamasaei, R., *Laboratory Assessment of Hybrid Fiber and Nano-silica on Reinforced Porous Asphalt Mixtures.* Construction and Building Materials, 2017. 144: p. 260-270.

[158] Tabaković, A., Braak, D., van Gerwen, M., Copuroglu, O., Post, W., Garcia, S.J. and Schlangen, E., *The compartmented alginate fibres optimisation for bitumen rejuvenator encapsulation.* Journal of Traffic and Transportation Engineering (English Edition), 2017.

[159] Doh, Y.S., Baek, S.H. and Kim, K.W., *Estimation of relative performance of reinforced overlaid asphalt concretes against reflection cracking due to bending more fracture.* Construction and Building Materials, 2009. 23(5): p. 1803-1807.

[160] Fallah, S. and Khodaii, A., *Reinforcing overlay to reduce reflection cracking; an experimental investigation.* Geotextiles and Geomembranes, 2015. 43(3): p. 216-227.

[161] Moghaddam, T., B.,, Karim, M., R., and Abdelaziz, M., *A review on fatigue and rutting performance of asphalt mixes.* Academic Journals, 2011. 6(4): p. 670-682.

[162] Vaitkus, A., Čygas, D., Laurinavičius, A. and Perveneckas, Z., *Analysis and evaluation of possibilities for the use of warm mix asphalt in Lithuania.* The Baltic Journal of Road and Bridge Engineering, 2009. 4(2): p. 80-86.

[163] Zaumanis, M., Poulikakos, L.D. and Partl, M.N., *Performance-based design of asphalt mixtures and review of key parameters.* Materials & Design, 2018. 141: p. 185-201.

[164] Zhang, Y. and Leng, Z., *Quantification of bituminous mortar ageing and its application in ravelling evaluation of porous asphalt wearing courses.* Materials & Design, 2017. 119: p. 1-11.

[165] Saeid, H., Saeed, A. and Mahdi, N., *Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement.* Construction and Building Materials, 2014. 53: p. 680-691.

[166] Guoming, L., Weimin, C. and Lianjun, C., *Investigating and optimizing the mix proportion of pumping wet-mix shotcrete with polypropylene fiber.* Construction and Building Materials, 2017. 150: p. 14-23.

[167] Bueno, B.d.S., Silva, W.R.d., Lima, D.C.d. and Minnete, E., *Engineering Properties of Fiber Reinforced Cold Asphalt Mixes.* Journal of Environmental Engineering, 2003. 129: p. 952-955.

Highlights

CBEMs have several ecological and economic benefits.

Laboratory data show an equal or better performance of CBEM compared to HMA.

The laboratory behaviour investigations on CBEM are not conclusive.

The application of waste materials in CMA improves sustainability.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dr. Anmar Dulaimi