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Original Research Paper

Laboratory investigation on the properties of asphalt mixtures modified with double-adding admixtures and sensitivity analysis

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ABSTRACT

In order to improve the high temperature stability and low temperature cracking resistance of asphalt mixtures, two varieties of admixtures (anti-rutting agent and lignin fiber) were selected and then combined. This is called double-mixture technology. A series of tests about pavement performance of base asphalt mixtures and asphalt mixtures with admixture of anti-rutting agent or lignin fiber were conducted. Meanwhile sensitivity analyses were used to study the influence of three factors (i.e., asphalt grade, aggregate type and gradation) on the high and low temperature performance and water stability of said asphalt mixtures. Test results indicated that the dynamic stability, residual stability, TSR and low temperature failure strain of asphalt mixtures have increased significantly with the additions of 0.40% anti-rutting agent and 0.36% lignin fiber. These results show that the high and low temperature and water stabilities of asphalt mixtures improve obviously. This supports the beneficial comprehensive effect of the double admixture. The problem of improving the asphalt mixtures performance with a single admixture is solved, in addition to also improving other pavement performance. Based on the sensitivity analysis, the most influential factors of dynamic stability, low temperature failure strain and TSR are the gradation, followed by asphalt grade and aggregate type.

1. Introduction

With the rapid growth of China's economy and transport demand, the phenomenon of overloading on some high grade highways of important transportation corridors is prominent, which caused severe rutting and low temperature cracking. These observed deficiencies affect the overall durability of asphalt pavement. Service life and quality of ride are closely related to rutting. Meanwhile, cracking will form in the

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asphalt pavement at low temperature. The presence of a large number of cracks causes the ingress of water from the road surface into the pavement structure, eventually leading to pavement cracks and potholes with the effect of vehicle load. Therefore, it is important to reduce rutting and low temperature cracks of asphalt pavement.

Many scholars studied how to improve the anti-rutting performance of asphalt pavement by material and structure. As for material, performance was improved by selecting high quality aggregates and modified asphalt, controlling asphalt content, gradation, adding polymer (Attaelmanan et al., 2011; Baghaee et al., 2015; Chee et al., 2014; Qadir, 2014) and anti-rutting agent (Hajj et al., 2013; Shafabakhsh and Ani, 2015; Ziari et al., 2015a,b). Specifically, high quality aggregates and modified asphalt improved the bond between aggregates and asphalt to enhance anti-rutting performance of asphalt mixtures. Higher coarse-to-fine aggregate ratios of asphalt mixtures of the same nominal size have better anti-rutting performance (Liu and Dai, 2004). Some researchers showed that asphalt mixtures added with high density polyethylene can effectively improve anti-rutting performance (Hui and Zhang, 2011; Li et al., 2010, 2014, 2015; Xiao et al., 2007; Ziari et al., 2015a,b).

In addition, fibers have a significant effect on the low temperature cracking resistance of asphalt mixture. Since the 1980s, American and some European countries have studied the application of fiber reinforced asphalt in order to meet the load requirements by heavy traffic on pavement materials. Research indicated that adding fibers to asphalt mixture could improve its fatigue resistance, low temperature cracking resistance, and decrease the probability of premature cracking. Based upon these researches, fibers were used in pavements of airports, bridges and toll stations (Ferrotti et al., 2014; Isla et al., 2015; Jafarifar et al., 2014; Park et al., 2015; Yao et al., 2013). When fibers are dispersed into a base asphalt mixture, the large superficial areas of the fibers become interfaces, which absorb a large amount of asphalt binder, so that the viscosity of asphalt mortar is enhanced and the softening point is raised along with the increased thickness of binder film on aggregate surface. As a result, stability at high temperatures of the fiber modified asphalt mixtures, and the ability of resisting water stripping of the interface between asphalt and aggregates were improved (Attaelmanan et al., 2011). Additional research also claimed that basalt fiber modified asphalt mixtures demonstrated better pavement performance (Fan et al., 2010).

The anti-rutting performance at high temperature of asphalt mixtures modified with anti-rutting agent is significantly improved, while the improvement of low temperature performance is much less obvious. On the contrary, the low temperature performance of asphalt mixtures modified with lignin fiber is significantly improved, while the improvement of high temperature performance is limited. Therefore, a single admixture cannot improve all the pavement performance of asphalt mixtures at the same time. Scholars found that adding lignin fiber and rubber powder simultaneously can improve the overall performance of asphalt mixtures (Chen and Xu, 2010; Lavasani et al., 2015; Park et al., 2015; Xiong et al., 2015). Double-adding technology (adding anti-rutting agent and lignin fiber simultaneously) is used in this paper to reduce rutting at high temperature and cracking at low temperature at the same time. With different composition of the mixtures, the effect of the two admixtures on anti-rutting performance at high temperature and anti-cracking at low temperature of asphalt mixtures was discussed. The purpose is to improve asphalt mixture performance, and to design asphalt mixtures which can be applied to a wide temperature range. At the same time, through sensitivity analyses of the influence of gradation, aggregate type and asphalt grade on the high and low temperature performance and water stability of asphalt mixtures modified with two admixtures (Ghabchi et al., 2014), the most influential factor can be found and controlled to improve the pavement performance of asphalt mixtures more effectively.

2. Materials and experimental plan

2.1. Materials

2.1.1. Asphalt

Shell 70# and Korea 90# were selected as heavy loading asphalt in this research. Their characteristics are as follows in Table 1. All the indexes of selected asphalts meet the demands of road petroleum asphalt.

2.1.2. Admixture

Lignin fiber and anti-rutting agent were selected as admixtures. Microstructure of lignin fiber is observed by electron microscopy at 200 times amplified. According to Fig. 1, lignin fibers have rough surface and flocculent structures. The coarse surface is beneficial to asphalt adhesiveness, while flocculent structures can absorb more asphalt. This improves dispersion of asphalt and bond effects, thus

Table 1 – Characteristics of Shell 70#-A asphalt binder and Korea 90#-AH asphalt binder.

Characteristic		Shell 70#-A		Korea 90#-AH	
		Measured value	Specified value	Measured value	Specified value
Penetration (25 °C, 100 g, 5 s) (0.2 mm)		71.0	60–80	86.3	80–100
Penetration index PI		−0.87	−1.0–1.0	−1.24	–
60 °C dynamic viscosity (Pa·s)		251	≥180	197.6	≥160
Softening point (°C)		46.7	≥46	45.5	≥45
Ductility (15 °C) (cm)		116.3	≥100	129.8	≥100
Density (15 °C) (g·cm^{-3})		0.98	–	1.011	–
TFOT (163 °C, 5 h)	Quality loss (%)	0.07	≤±0.8	0.55	≤±0.8
	Residual penetration ratio (%)	69.0	≥61	73.1	≥57
	Ductility (15 °C) (cm)	>100	≥15	>100	≥20

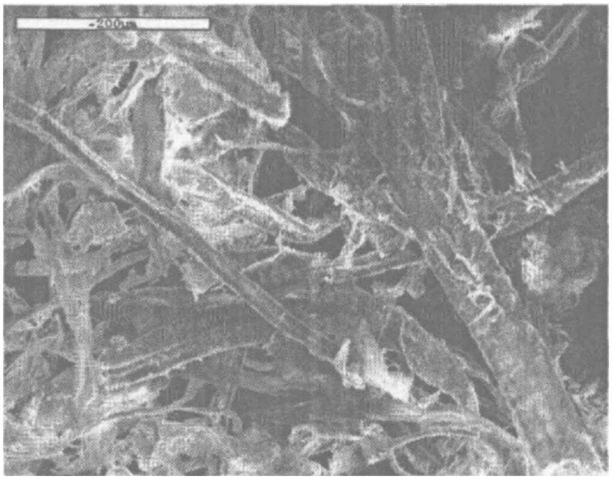

Fig. 1 – Microstructure of lignin fiber.

asphalt becomes more stable. In addition, lignin fibers have great heat resistance, which makes lignin fiber stable when mixed with asphalt mixture at high temperature (Zhang et al., 2012). Specific characteristics are listed in Table 2.

Anti-rutting agent is a black particle of 3 mm diameter, which can preserve at normal temperature. This kind of anti-rutting agent can improve asphalt viscosity, as well as aggregate adhesion and anti-stripping performance. Consequently, anti-rutting performance of asphalt pavement at high temperatures is improved, and the damage to the pavement which results from overloading traffic is reduced. Specific technical indicators are shown in Table 3.

2.1.3. *Aggregate and gradation*

Limestone and granite were selected as aggregates, and ground limestone was selected as mineral powder. AC-13, AC-16, AC-16S gradation were selected in the test. Among them, AC-13 and AC-16 were considered the median, and aggregate gradations were listed in Table 4.

AC-13, AC-16, limestone and Shell 70# asphalt were selected in pavement performance test. AC-13, AC-16, AC-16S, Shell 70# asphalt and Korea 90# asphalt, limestone and granite were selected in sensitivity test.

2.2. *Experimental plan*

2.2.1. *Determine the optimum asphalt aggregate ratio and content*

Adding lignin fibers and anti-rutting agent into asphalt mixtures makes asphalt mixtures become a composite multi-phase material whose structure is more complex. Fibers improve road performance of mixtures at appropriate content. Too many fibers will cause clustering, reduce workability and make it difficult to mix uniformly, which will adversely affect the performance. Anti-rutting agent improves road performance of mixtures at appropriate content too. Therefore, it is necessary to determine the optimum content of lignin fibers and anti-rutting agent, which will be introduced in following part. According to Marshall Test, the optimum asphalt aggregate ratio of AC-13 and AC-16 asphalt mixtures is 4.5% and 4.3%, respectively. Marshall Test results of AC-13 and AC-16 asphalt mixtures with optimum asphalt aggregate ratio are listed in Table 5.

Table 3 – Characteristics of anti-rutting agent.

Density (25 °C) ($g \cdot cm^{-3}$)	Melting point (°C)	Particle size (mm)
0.98	150–155	3–4

2.2.2. *Asphalt mixtures mixing*

Mixing temperature: according to the Standard Specification for Construction and Acceptance of Highway Asphalt Pavement, the heating temperature of 70# asphalt, 90# asphalt is 160 °C and 155 °C, respectively. Their mixing temperature is 165 °C, aggregate preheating temperature is 180 °C and compaction temperature is 125 °C. If asphalt mixtures are modified with just one admixture of anti-rutting agent or lignin fiber and double-adding admixtures, then the heating temperature of 70# asphalt is 165 °C, 90# asphalt is 160 °C, mixing temperature is 185 °C, aggregate preheating temperature is 180 °C and compaction temperature is 170 °C.

Mixing Order and Time: aggregates are mixed with base asphalt for about 90 s, then mixed with mineral which also lasts for 90 s. As for modified asphalt mixtures, admixtures such as fiber and anti-rutting agent are mixed with aggregate in sequence first for 90 s, then mixed with asphalt for 90 s and mixed with mineral for 90 s at last.

2.2.3. *Pavement performance test*

The pavement performance of base asphalt mixtures, asphalt mixtures modified with anti-rutting agent or lignin fiber and asphalt mixtures with double-adding admixtures (anti-rutting agent and lignin fiber) have been studied in this paper. Dynamic stability of high temperature rutting test, failure strain of low temperature bend test, residual stability of Immersion Marshall Test and TSR of Freeze-Thaw Split Test are selected to evaluate the high temperature performance, low temperature performance and water stability of asphalt mixtures, respectively. While these testing methods follow the Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering (JTG E20-2011).

0, 0.2%, 0.4%, 0.6% and 0.8% anti-rutting agents were added into base asphalt mixtures according to quality to evaluate the pavement performance and to determine the optimum content of anti-rutting agent. 0, 0.15%, 0.30% and 0.45% lignin fibers were added into base asphalt mixtures to determine the

Table 2 – Characteristics of lignin fiber.

Characteristic	Fiber length (mm)	Specific area ($m^2 \cdot g^{-1}$)	Ash content (%)	pH	Oil absorbency (%)	Water content (%)
Test result	<6	0.7322	11.40	7	6.47	2.20

Table 4 – Aggregate gradation of AC-13 and AC-16.

Sieve pore size (mm)		0.075	0.15	0.3	0.6	1.18	2.36	4.75	9.5	13.2	16	19
AC-13	Median	6.0	10.0	13.5	19.0	26.5	37.0	53.0	76.5	95.0	100.0	–
AC-16	Median	6.0	9.5	12.5	17.5	24.5	34.0	48.0	70.0	84.0	95.0	100.0
	S-gradation	5.0	7.0	9.0	11.0	17.0	26.0	48.0	74.0	90.0	96.0	100.0

Table 5 – Marshall Test results of AC-13 and AC-16 asphalt mixtures at optimum asphalt aggregate ratio.

Characteristic	Optimum asphalt aggregate ratio (%)	Bulk specific gravity	VV (%)	VFA (%)	Stability (kN)	Flow value (mm)
AC-13	4.5	2.417	4.54	69.09	13.11	3.35
AC-16	4.3	2.498	3.87	68.43	9.95	2.85
Recommended value	–	–	4–6	65–75	>8	2.0–4.5

optimum content of lignin fiber according to quality. The performance of asphalt mixtures modified with the optimum content of anti-rutting agent and lignin fiber were tested to evaluate the improvement of anti-rutting performance at high temperature and anti-cracking performance at low temperature of above mixtures.

2.2.4. *Sensitivity analysis*

AC-13, AC-16 and AC-16S gradations are selected. Limestone and granite are selected as aggregate type. 70# and 90# are selected as asphalt grade. The sensitivity of pavement performance made of asphalt mixtures modified with double-adding admixtures is analyzed through factor analysis method. Aggregate type, gradation and asphalt grade are selected as the three factors. Dynamic stability, failure strain at low temperature and TSR are selected to evaluate high temperature performance, low temperature performance and water stability of asphalt mixtures modified with double-adding admixtures. The change rate of dynamic stability, failure strain at low temperature and TSR caused by factor change can reflect the sensitivity of these performances to the influence of factor change.

3. Test results and analyses

3.1. *Pavement performance of asphalt mixture modified with anti-rutting agent*

Experiments show that the influence of anti-rutting agent on asphalt mixture at optimum asphalt aggregate ratio is very small. Therefore, the optimum asphalt aggregate ratio of asphalt mixtures modified with anti-rutting agent is same as that of base asphalt mixtures (Xiao et al., 2006). Tests of rutting, low temperature bend and water stability were done, when AC-13 and AC-16 asphalt mixtures modified with 0.2%, 0.4%, 0.6% and 0.8% anti-rutting agents at optimum asphalt aggregate ratio.

3.1.1. *Rutting test*

Fig. 2 shows the dynamic stability results of asphalt mixture added with different amount of anti-rutting agent under the condition that the mix design of base asphalt mixture was not changed.

It can be seen from Fig. 2 that dynamic stability of mixtures significantly increases with the increase of anti-rutting agent content, which indicates that anti-rutting agent can improve the dynamic stability of asphalt mixtures effectively. The dynamic stabilities of AC-13 asphalt mixtures modified with 0.2%, 0.4%, 0.6% and 0.8% anti-rutting agents are increased by 2.6, 7.5, 8.2 and 13.6 times, respectively, when compared with that of base asphalt mixtures. While dynamic stabilities of AC-16 asphalt mixtures modified with 0.2%, 0.4%, 0.6% and 0.8% anti-rutting agents are increased by 2.4, 7.7, 8.7 and 13.4 times compared with that of base asphalt mixtures, respectively, which is similar to the improvement of AC-13 asphalt mixtures. Furthermore, anti-rutting agent has a consistent effect on high temperature performance of asphalt mixtures.

Results show that the addition of anti-rutting agent can improve the dynamic stability of asphalt mixtures. The reason is that anti-rutting agent is a kind of composite material whose main components are high molecular polymer, natural asphalt and a kind of agent which can promote the fusion of anti-rutting agent and asphalt. Anti-rutting agent has dual modification effects on asphalt mixtures. First, anti-rutting agents are mixed with aggregates under dry conditions, part of anti-rutting agent is fused to the surface of aggregates as the mixing time is short, which can improve the bonding property of the aggregates equivalent to pre-modification of the aggregates. Next, the anti-rutting agents are mixed with aggregates under moist conditions and part of anti-rutting agent is dissolved or swollen in asphalt, resulting in an

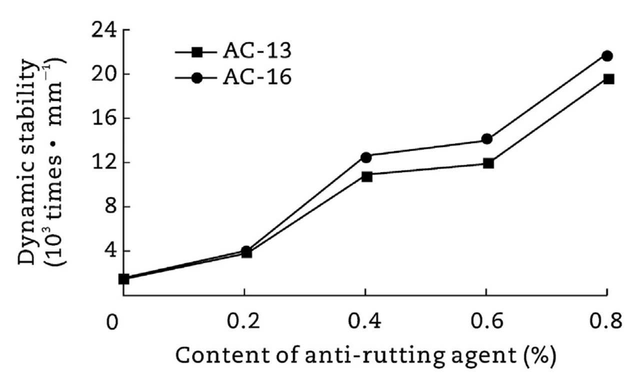

Fig. 2 – Relationship between dynamic stability and anti-rutting agent content.

increased softening point and viscosity, as well as decreasing sensitivity at high temperature. This is equivalent to modification of the asphalt.

3.1.2. *Low temperature bend test*

Results of failure strain at low temperature of base asphalt mixtures modified with different contents of anti-rutting agent are shown in Fig. 3.

It can be seen from Fig. 3 that the failure strain of AC-16 and AC-13 asphalt mixtures is increased gradually with the increase of anti-rutting agent. The failure strains of AC-13 and AC-16 asphalt mixtures modified with 0.6% anti-rutting agent are 2775.6 and 2585.6 με, respectively, which only increased by 1.4 and 1.3 times as opposed to the base asphalt mixture. This is because the anti-rutting agent will dissolve to some extent in asphalt during mixing, which make asphalt viscosity increase and is beneficial to bearing capacity and deformation resistance of asphalt mixtures. However, the failure strain decreases when the content of anti-rutting agent reaches 0.8%. Obviously, the anti-rutting agent can improve the low temperature performance of AC-13 and AC-16 asphalt mixtures, but the improvement effect is not obvious and subject to the agent content.

3.1.3. *Water stability test*

Immersion Marshall Test and Freeze-Thaw Split Test are selected to evaluate water stability of asphalt mixtures. The results of residual stability and TSR are shown in Figs. 4 and 5 respectively.

It can be seen from Figs. 4 and 5 that the anti-rutting agent has certain improvement on water stability of asphalt mixtures.

The residual stabilities of AC-13 asphalt mixtures modified with 0.2% and 0.4% anti-rutting agents are increased by 6% and 3%, respectively, when compared with base asphalt mixtures. While the residual stabilities of AC-13 asphalt mixtures modified with 0.6% and 0.8% anti-rutting agents are increased by 2.0% and 0.6%, respectively, when compared with base asphalt mixtures. The residual stabilities of AC-16 asphalt mixtures modified with 0.2%, 0.4% and 0.8% anti-rutting agents are increased by 7.0%, 3.8% and 3.7%, respectively, when compared with base asphalt mixtures. The residual stability of asphalt mixtures with 0.6% anti-rutting agent decreases by 0.8% compared with base asphalt mixtures. Fig. 4 indicates that the residual stability of both gradation types changes consistently with the increase of anti-rutting agent content.

TSR of AC-13 asphalt mixtures modified with 0.2%, 0.4%, 0.6% and 0.8% anti-rutting agents are increased by 17.1%, 17.9%, 17.3% and 6.7%, respectively, when compared with base asphalt mixtures. TSR of AC-16 asphalt mixtures modified with 0.2%, 0.4%, 0.6% and 0.8% anti-rutting agents are increased by 10%, 12%, 6% and 8%, respectively, when compared with base asphalt mixtures that show a trend of increasing first and then decreasing.

In summary, the water stabilities of AC-13 and AC-16 asphalt mixtures do not always increase with increased amounts of anti-rutting agent. Figs. 4 and 5 indicate that the residual stability and TSR show trends of initially increasing, and then decreasing with the increase of anti-rutting agent content. Thus anti-rutting agent has an optimum content to improve the water stability of asphalt mixtures.

3.1.4. *Determination of optimum content of anti-rutting agent*

Asphalt mixtures modified with anti-rutting agent have improved high temperature performance, water stability and other pavement performances except low temperature performance. The residual stability and TSR of asphalt mixtures show trends of initially increasing and then decreasing with the increase of anti-rutting agent content. So the optimum content of anti-rutting agent that mostly improved low temperature performance and water stability of asphalt mixtures is investigated in this paper.

Determination of optimum content of anti-rutting agent of AC-13 asphalt mixtures is as follows.

The relationship between failure strain and anti-rutting agent content is fitted by mathematical method described in Eq. (1) and Fig. 6.

$$Y_1 = -3.951X^3 + 36.752X^2 + 47.14X + 2007.1 \tag{1}$$

where X is the content of anti-rutting agent, Y_1 is failure strain, correlation coefficient R_1^2 is 0.9973.

The extreme value of the equation and the corresponding X are determined by mathematical method, which represents the content of anti-rutting agent corresponding to the maximum failure strain. The content of anti-rutting agent is 0.63% when the failure strain at low temperature achieved the peak value of 2775.33 με. According to the results of failure strain, the optimum content of this anti-rutting agent is determined as 0.63%.

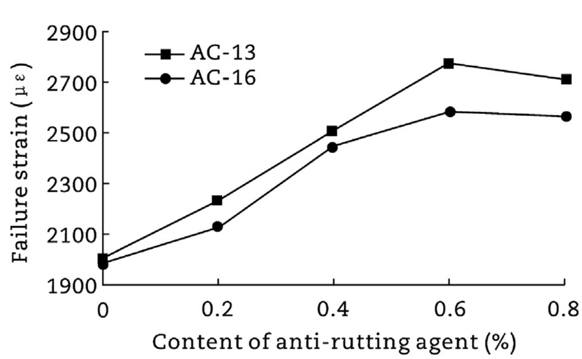

Fig. 3 – Relationship between failure strain and anti-rutting agent content.

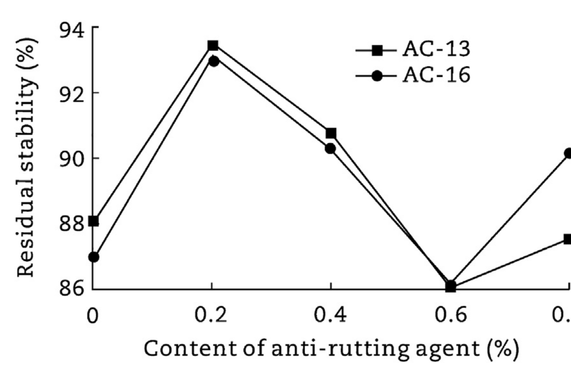

Fig. 4 – Relationship between residual stability and anti-rutting agent content.

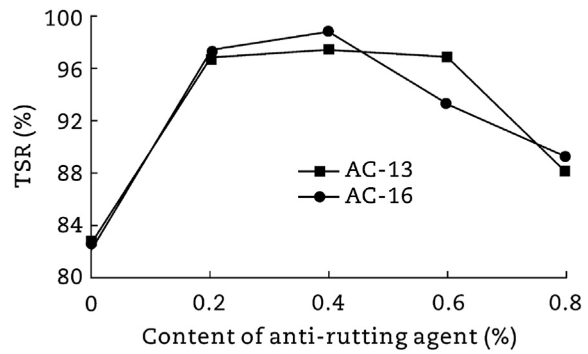

Fig. 5 – Relationship between TSR and anti-rutting agent content.

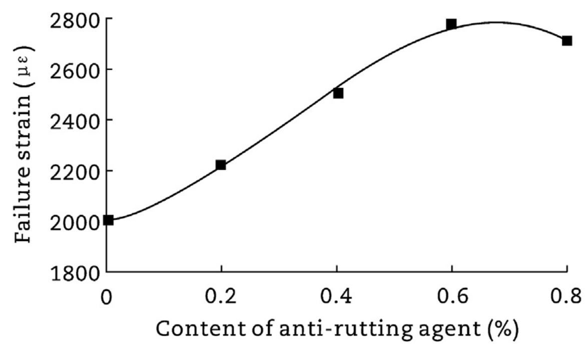

Fig. 6 – Change rule of failure strain at low temperature bend test of asphalt mixtures modified with anti-rutting agent.

The relationship between anti-rutting agent content and TSR of water stability is shown in Fig. 7.

The relationship between TSR and anti-rutting agent content is fitted by mathematical method described in Eq. (2).

$$Y_2 = 0.0531X^3 - 1.4768X^2 + 9.1018X + 82.876 \tag{2}$$

where Y_2 is TSR (%), correlation coefficient R_2^2 is 0.9701.

The extreme value of the equation and the corresponding X are determined by mathematical method. The content of anti-rutting agent is 0.39% when TSR achieved the highest value of 99.06%. According to the results of TSR, the optimum content of this anti-rutting agent is determined as 0.63%.

Therefore, the optimum content of anti-rutting agent is to be found between 0.39% and 0.63%.

The relationship between dynamic stability and anti-rutting agent content is shown in Fig. 8.

The relationship between dynamic stability and anti-rutting agent content is fitted by mathematical method described in Eq. (3).

$$Y_3 = 21.452X^3 - 170.66X^2 + 2272.7X + 1108.1 \tag{3}$$

where Y_3 is dynamic stability, correlation coefficient R_3^2 is 0.962.

When the content of anti-rutting agent is varied between 0.39% and 0.63%, the corresponding dynamic stability is 8648.4–14,016.6 times·mm^{-1}, far below the required stability value in hot area in summer.

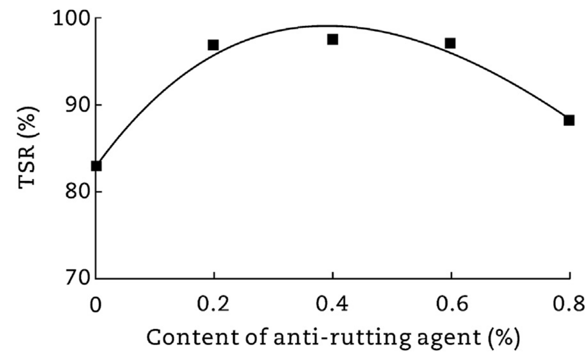

Fig. 7 – Relationship between TSR and anti-rutting agent content.

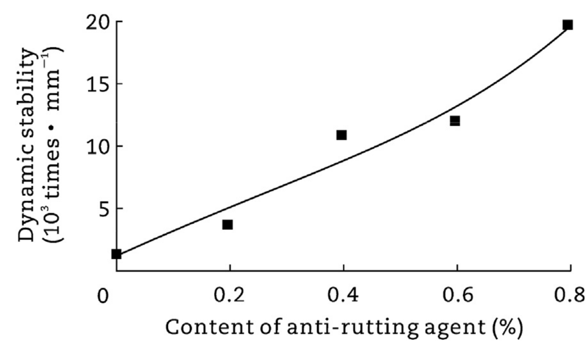

Fig. 8 – Relationship between dynamic stability of rutting test and anti-rutting agent content.

In summary, the optimum content of anti-rutting agent is around 0.39%–0.63%, when considering the high temperature performance, low temperature performance and water stability.

The optimum content range of anti-rutting agent of AC-13 asphalt mixtures is the same as AC-16. Thus, the AC-13 asphalt mixture is selected in the following research to represent both mixtures.

3.2. *Research on the road performance of asphalt mixture modified with lignin fiber*

Asphalt mixtures modified with lignin fibers have larger optimum asphalt content than base asphalt mixtures, since lignin fibers can absorb some asphalt. Different lignin fiber content can lead to different optimum asphalt aggregate ratio of asphalt mixtures. For convenience, optimum asphalt aggregate ratio of different asphalt mixtures types are listed in Table 6. AC-13 and AC-16 asphalt mixtures with optimum asphalt aggregate ratio with 0.15%, 0.30% and 0.45% lignin fibers are selected for rutting test, bend test at low temperature and water stability test. Marshall Test results of different asphalt mixture types are listed in Table 7.

3.2.1. *Rutting test*

The result of dynamic stability test of asphalt mixtures having different lignin fiber content is shown in Fig. 9, using the mixture ratio of base asphalt mixture.

Table 6 – Optimum asphalt aggregate ratio of different asphalt mixtures types.

Type	AC-13	AC-13 + 0.15%M	AC-13 + 0.30%M	AC-13 + 0.45%M
Optimum asphalt content/%	4.50	4.93	5.50	5.93
Type	AC-16	AC-16 + 0.15%M	AC-16 + 0.30%M	AC-16 + 0.45%M
Optimum asphalt content/%	4.30	4.82	5.36	5.74

Note: Letter M means lignin fiber, AC-13 + 0.15%M means adding 0.15% lignin fiber into AC-13 asphalt mixtures. The rests are as above.

Table 7 – Marshall Test results of different asphalt mixtures types.

Type	Optimum asphalt aggregate ratio (%)	Bulk specific density	Stability (kN)	Flow value (mm)	VV (%)	VFA (%)
AC-13	4.50	2.417	13.11	3.35	4.540	69.09
AC-13 + 0.15%M	4.93	2.414	17.39	3.38	4.362	70.46
AC-13 + 0.30%M	5.50	2.383	13.04	3.36	4.607	68.75
AC-13 + 0.45%M	6.07	2.419	15.41	3.58	3.261	82.00

Fig. 9 indicates that the addition of lignin fiber can improve the high temperature performance of AC-13 and AC-16 asphalt mixtures, but the effect is not highly noticeable. Dynamic stability of asphalt mixtures shows a trend of initially increasing, and then decreasing with the increases of lignin fiber. Dynamic stabilities of AC-13 and AC-16 asphalt mixtures are improved by 14% and 19%, respectively.

Lignin fiber has excellent heat resistance and oil absorption properties. In addition, compared with glass fiber and polyester fiber, lignin fiber has the peculiarities of small density and abundant porous which make the surface area of lignin fiber far greater than the others and makes oil absorption capacity reach 5–10 times the weight of its own. High temperature performance of asphalt mixtures modified with lignin fiber can be improved by dispersing lignin fibers into matrix asphalt mixtures. Lignin fiber can absorb large amounts of asphalt, and fiber with its surrounding structural asphalt coat on the aggregate surface so that the surface of asphalt film thickness, asphalt mortar viscosity and soften point increase. However, the dispersion uniformity of lignin fiber decreases with the increases of lignin fiber content so that the high temperature performance of asphalt mixtures decreases. Thus, the high temperature performance shows a trend of initially increasing and then decreasing with the increases of lignin fiber content.

3.2.2. *Low temperature bend test*

The result of failure strain at low temperature bent test is shown in Fig. 10.

Fig. 10 indicates that lignin fiber can improve the anti-cracking properties at low temperature of AC-13 and AC-16 asphalt mixtures, obviously. Failure strain at low temperature increases with the increases of lignin fiber content, and the maximum failure strain of AC-13 and AC-16 both can increase 2 times than before. The structure of lignin fiber in asphalt mixtures is three dimensional which increases the toughness of mixtures and reinforces the asphalt mixtures.

The above phenomenon can be explained by using the micro mechanical principle of composite materials. The strength of asphalt mixtures is positively correlated with the strength and content of fiber. The strength of asphalt mixture is improved when adding fiber to a certain extent, which is beneficial to the anti-cracking at low temperature. In addition, the "toughening" effect of mineral fiber is derived from the residual stress and strain fields and the micro cracks around the fiber matrix interface that result from the different material properties between fiber and mixtures. Therefore, fibers improve the anti-cracking at low temperature by improving the strength and toughness of asphalt mixtures.

3.2.3. *Water stability test*

Results of Immersion Marshall Test and Freeze-Thaw Split Test are shown in Figs. 11 and 12, respectively.

It can be seen from Figs. 11 and 12 that the water stabilities of AC-13 and AC-16 asphalt mixtures modified with lignin fibers are improved, but not obvious. The residual stability increases with the increases of lignin fiber content. The

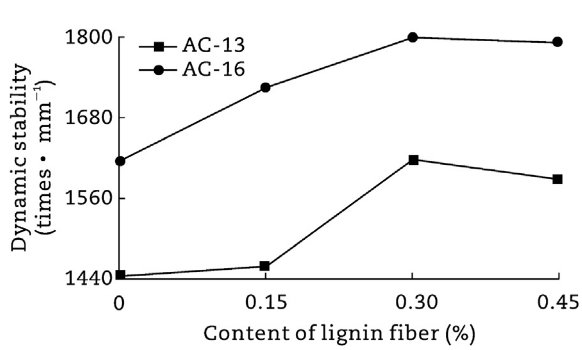

Fig. 9 – Relationship between dynamic stability and lignin fiber content.

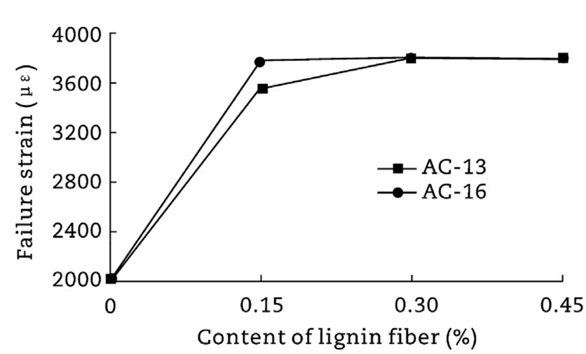

Fig. 10 – Relationship between failure strain and lignin fiber content.

maximum increases of residual stability and TSR are only about 4%.

This is because the optimum asphalt contents of AC-16 and AC-13 asphalt mixtures modified with lignin fiber are increased to certain degree, so that the thickness of asphalt film that attached on the surface of aggregates is also increased and the space among mixtures is reduced. Because the content of the internal structural asphalt increases with adding lignin fiber, the interfacial action between structural asphalt and aggregates is more severe which is beneficial to the stability of the asphalt mixtures. With the increases of lignin fiber content, the dispersion properties of fiber is restricted, and the optimum asphalt content increases slightly, so that mixtures are difficult to be compacted and the void age of mixtures is increasing. And as a result of adding too much fiber, there may be a part of the fiber will be dispersed to the interface between the asphalt and aggregates, and the bonding area between asphalt and aggregates is decreased. Therefore, the water stability is decreased.

3.2.4. *Determination of optimum content of lignin fiber*

The above analysis indicates that the failure strain at low temperature of asphalt mixtures modified with lignin fiber shows a trend of initially increasing and then decreasing with the increases of lignin fiber content. Improvements of high temperature performance and water stability of asphalt mixtures modified with lignin fiber are not obvious. Therefore, the optimum content of lignin fiber that mostly improved low temperature performance of asphalt mixtures is selected in this paper.

The strain energy at low temperature is selected to evaluate the low temperature performance of asphalt mixtures. Strain energy represents the energy consumption of the specimen from the loading to the damage, which is an ideal index for the comprehensive consideration of the strength and strain of the mixture.

The fitting equation between the fiber content which is range from 0.15% to 0.45% and the strain energy of asphalt mixtures modified by lignin fiber is shown in Eq. (4) and Fig. 13.

$$Y_4 = -2.1238X_1^3 + 12.224X_1^2 - 4.2238X_1 + 130 \tag{4}$$

where X_1 is the content of lignin fiber, Y_4 is strain energy, correlation coefficient R_4^2 is 1.

The extreme value of the equation is determined by mathematical method and the corresponding X_1 is 0.37%.

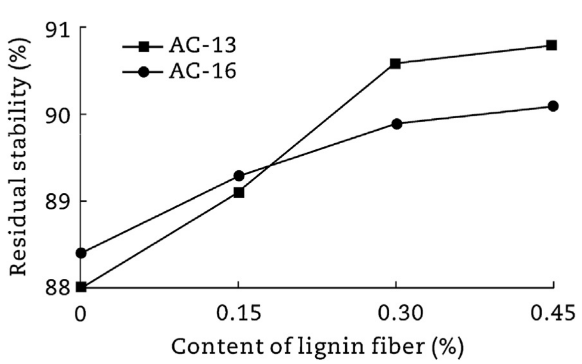

Fig. 11 – Relationship between residual stability and lignin fiber content.

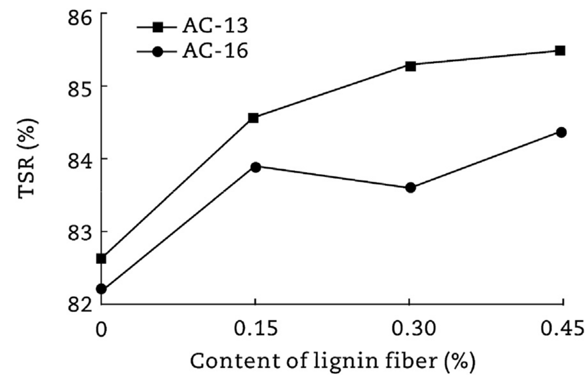

Fig. 12 – Relationship between TSR and lignin fiber content.

At the same time, other indicators of low temperature bend test should also be considered to determine the optimum content of lignin fiber. Overall, the optimum content of lignin fiber is determined to be 0.36%.

The optimum content of lignin fiber of AC-13 asphalt mixtures is the same as AC-16. Thus, 0.36% content of lignin fiber is selected as the optimum content of lignin fiber of AC-13 asphalt mixtures to facilitate research.

3.3. *Research on pavement performance of asphalt mixtures modified with double-adding admixtures*

Based on the above discussion, the optimum contents of anti-rutting agent and lignin fiber are 0.39%–0.63% and 0.36%, respectively, that mostly improves the performance of asphalt mixtures. Consequently, the optimum contents of anti-rutting agent and lignin fiber of double-adding admixtures are selected as 0.40% and 0.36%, respectively. AC-13 + 0.4% K + 0.36%M and AC-16 + 0.4%K + 0.36%M are selected for pavement performance test which compared with the results of asphalt mixtures only modified with anti-rutting agent or lignin fiber.

In order to ensure the accuracy and consistency of the research on asphalt mixtures modified with double-adding admixtures, the optimum asphalt contents of AC-13 + 0.4% K + 0.36%M, AC-16 + 0.4%K + 0.36%M and AC-16S + 0.4% K + 0.36%M are 5.4%, 5.1% and 5.3%, respectively, which are determined by Marshall Test. The optimum asphalt content of

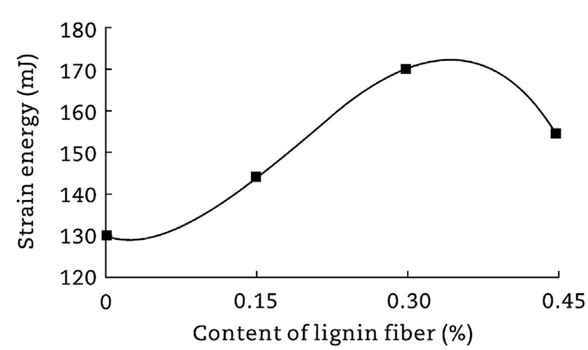

Fig. 13 – Relationship between strain energy and lignin fiber content.

mixtures modified with double-adding admixtures is less than lignin fiber modified asphalt mixtures. This indicates that kind of anti-rutting agent can reduce the asphalt content. The possible reason is that this anti-rutting agent has similar cementitious effect as asphalt, replacing part of the asphalt in the mixture.

3.3.1. *Rutting test*

Results of dynamic stability at rutting test are shown in Fig. 14.

It can be seen from Fig. 14 that the dynamic stabilities of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 8.4 and 7.9 times, respectively, compared with base asphalt mixtures, which indicates that double-adding admixtures have similar improvement effect on stabilities at high temperature of different gradation types of asphalt mixtures. The dynamic stabilities of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 11.2% and 1.0%, respectively, compared with asphalt mixtures modified with only anti-rutting agent, which indicates that anti-rutting agent plays an important role in improving the high temperature performance of asphalt mixture. The dynamic stabilities of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 7.3 and 6.8 times, respectively, compared with asphalt mixtures modified with only lignin fiber. This indicates that lignin fiber can improve the high temperature stability of asphalt mixtures, however, the effect is not obvious.

3.3.2. *Low temperature bend test*

Results of failure strain at low temperature bend test are shown in Fig. 15.

It can be seen from Fig. 15 that the failure strains of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 2.1 and 2.0 times, respectively, compared with base asphalt mixtures, which indicates that improvements in the low temperature performance of different gradation types of asphalt mixtures modified with double-adding admixtures are similar. The failure strains of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 3% and 1%, respectively, compared with asphalt mixtures modified with only lignin fiber, which indicates that lignin fiber plays a key role in improving the low temperature performance of asphalt

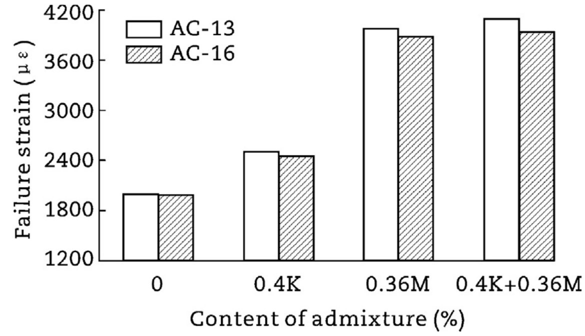

Fig. 15 – Failure strains of different types of asphalt mixtures.

mixtures. The failure strains of AC-13 and AC-16 asphalt mixtures modified with double-adding admixture, to a certain degree, are improved by 64% and 61%, respectively, compared with asphalt mixtures modified with only anti-rutting agent. This indicates that anti-rutting agent can significantly improve the stability of asphalt mixtures at high temperature, unlike it insignificant effect on low temperature performance.

3.3.3. *Water stability test*

Results of water stability test are shown in Figs. 16 and 17.

It can be seen from Figs. 16 and 17 that the residual stabilities of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 8.3% and 5.6% compared with base asphalt mixtures and 5.1% and 1.8% compared with asphalt mixtures modified with only anti-rutting agent; and are improved by 6.4% and 3.8% compared with asphalt mixtures modified with only lignin fiber, respectively. TSRs of AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures are improved by 9.4% and 12.7% compared with base asphalt mixtures and 8.3% and 10.6% compared with asphalt mixtures modified with only lignin fiber; and are reduced by 7.7% and 6.7% compared with asphalt mixtures modified with only anti-rutting agent, respectively.

Though anti-rutting agent and lignin fiber can both improve the water stability of asphalt mixtures, the above analyses show that asphalt mixtures modified with double-adding admixtures have better water stability than asphalt mixtures modified by only anti-rutting agent or lignin fiber.

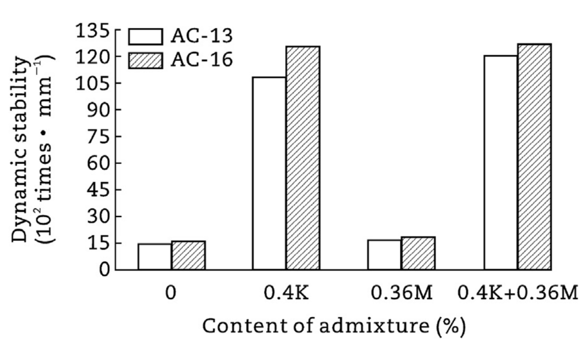

Fig. 14 – Dynamic stabilities of different types of asphalt mixtures (K means anti-rutting agent, and M means lignin fiber).

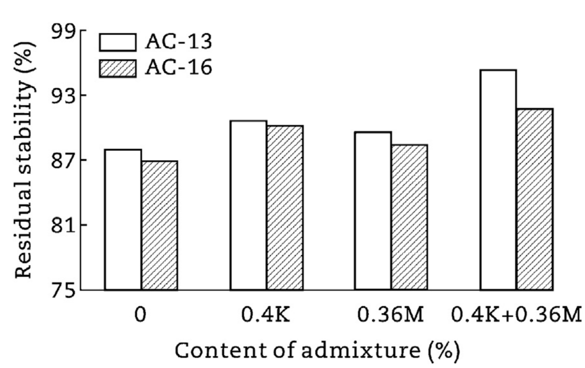

Fig. 16 – Residual stabilities of different types of asphalt mixtures.

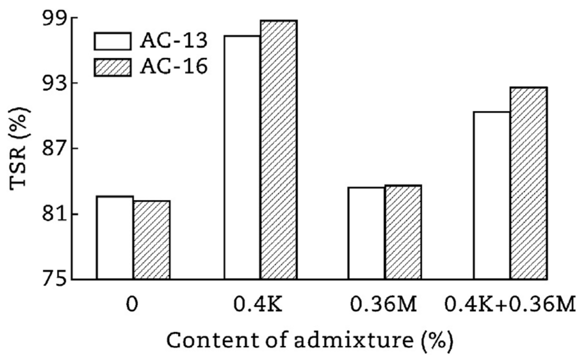

Fig. 17 – TSRs of different types of asphalt mixtures.

Above all, double-adding admixtures can improve high temperature performances, low temperature performances and water stabilities of AC-13 and AC-16 asphalt mixtures more significantly than the improvements made just by anti-rutting agent or lignin fiber.

4. Sensitivity analysis on pavement performance of asphalt mixtures modified with double-adding admixtures

Sensitivity analysis is a quantitative method utilized to study the influence of several factors on one, or a set of key indicators. The essence of the method is to explain the law of the key indicators by changing the numerical value of relevant variables. In this paper, the main factors that affect the high and low temperature performance and water stability of asphalt mixtures modified with double-adding admixtures are studied by sensitivity analysis from material composition.

With respect to material constitution, junior factors that affect the properties of asphalt mixtures modified with double-adding admixtures were selected as gradation, aggregate type and asphalt grade. Dynamic stability, failure strain at low temperature and TSR were selected as maternal factors. The change rate of maternal factors indicates the influence of junior factors on the sensitivity of corresponding maternal factors. Then the most sensitive junior factors of corresponding maternal factors can be found and controlled in order to improve the properties of asphalt mixtures modified with double-adding admixtures effectively. The change rate of factors is determined by Eq. (5).

$$CF = \frac{MF_1 - MF_0}{MF_0} \tag{5}$$

where CF is the factor of change rate, MF_1 is the maternal factors values after changes, and MF_0 is the maternal factors values before changes.

In sensitivity analysis, AC-13, AC-16 and AC-16S were selected as three gradation types, Shell 70# and Korea 90# were selected as asphalts, limestone and granite were selected as aggregate types. There are eight combinations based on three said factors are as follows: AC-13 + li. + 70#, AC-16 + li. + 70#, AC-13 + gr. + 70#, AC-16 + gr. + 70#, AC-13 + li. + 90#, AC-16 + li. + 90#, AC-13 + gr. + 90#, AC-16 + gr. + 90#. In addition, the pavement performance of AC-16S + li. + 70# modified with double-adding admixtures should be tested to compare with the asphalt mixtures of eight said combinations. AC-13 + li. + 70# means AC-13 (gradation), limestone (aggregate type) and 70# asphalt (asphalt grade); AC-16 + gr. + 90# means AC-16 (gradation), granite (aggregate type) and 90# asphalt (asphalt grade).

4.1. *Sensitivity analysis on one factor*

The sensitivity analysis on one factor (e.g. gradation) means fixing the two factors of aggregate type and asphalt grade, and changing the other one of gradation to calculate the change rate of dynamic stability, failure strain at low temperature and TSR.

4.1.1. *Change rate of maternal factors with the change of gradation type*

The aggregate type and asphalt grade are fixed and then the gradation type is changed, the change rates of maternal factors are shown in Table 8.

The change rate ranges of dynamic stability, failure strain at low temperature and TSR of asphalt mixtures modified with double-adding admixtures caused by the change of gradation type are 1.1%–21.9% and 1.1%–17.9%, 1.5%–5.0% and 1.5%–

Table 8 – Change rates of maternal factors caused by the change of combinations.

Combination	Change rate of dynamic stability (%)	Change rate of failure strain (%)	Change rate of TSR (%)
AC-13 + li. + 70# → AC-16 + li. + 70#	5.4	−3.3	2.4
AC-16 + li. + 70# → AC-13 + li. + 70#	−5.1	3.4	−2.4
AC-13 + gr. + 70# → AC-16 + gr. + 70#	20.3	−3.2	0.8
AC-16 + gr. + 70# → AC-13 + gr. + 70#	−16.9	3.3	−0.8
AC-13 + li. + 90# → AC-16 + li. + 90#	1.1	−3.9	2.2
AC-16 + li. + 90# → AC-13 + li. + 90#	−1.1	4.0	−2.2
AC-13 + gr. + 90# → AC-16 + gr. + 90#	20.7	−3.1	3.4
AC-16 + gr. + 90# → AC-13 + gr. + 90#	−17.2	3.2	−3.4
AC-13 + li. + 70# → AC-16S + li. + 70#	21.9	1.5	−1.1
AC-16S + li. + 70# → AC-13 + li. + 70#	−17.9	−1.5	1.1
AC-16 + li. + 70# → AC-16S + li. + 70#	15.6	5.0	−3.4
AC-16S + li. + 70# → AC-16 + li. + 70#	−13.5	−4.7	3.6

Note: "+" or "−" means that pavement performance of mixture is improved or weakened, respectively.

Table 9 – Change rate of TSR with the change of aggregate type.

Combination	Change rate of TSR (%)
AC-13 + gr. + 70# → AC-13 + li. + 70#	19.1
AC-13 + li. + 70# → AC-13 + gr. + 70#	−16.0
AC-13 + gr. + 90# → AC-13 + li. + 90#	21.0
AC-13 + li. + 90# → AC-13 + gr. + 90#	−15.6
AC-16 + gr. + 70# → AC-16 + li. + 70#	18.5
AC-16 + li. + 70# → AC-16 + gr. + 70#	−17.4
AC-16 + gr. + 90# → AC-16 + li. + 90#	17.0
AC-16 + li. + 90# → AC-16 + gr. + 90#	−14.5

4.7%, 0.8%–3.6% and 0.8%–3.4%, respectively. So, gradation type is not the main factor to the improvement of low temperature performance of mixtures. In addition, gradation type does not significantly improve the water stability of mixtures.

Conclusions can be drawn by analyzing Table 8.

(1) When the gradation changes as AC-13 → AC-16, AC-13 → AC-16S and AC-16 → AC-16S, the change rate of dynamic stability is positive, which means increasing grain size, or adopting the S gradation type is good for stability of asphalt mixtures at high temperature. The reason is that when the size increases, the extrusion force and friction force between aggregates of asphalt mixtures increase so that the dynamic stability and stability at high temperature of asphalt mixtures are improved.

(2) When the gradation changes as AC-16 → AC-13, AC-16S → AC-13 and AC-16S → AC-16, the change rate of failure strain at low temperature is positive, which is opposite to the change at high temperature. The reason for this is that, when cracks appear, the force is transferred through aggregate particles in the process of bending at low temperature, crack propagation and diffusion through the mixture of solid material. During the transfer, the finer gradation hinder, cracks so that the crack extension distance and diffusion energy increase. As a result, the failure strain is also increased. On the contrary, during the process of crack transfer, the crack transfer quickly between aggregates and failure strain is decreased if the size of aggregate particle is large.

(3) When the gradation changes as AC-13 → AC-16, AC-16S → AC-13 and AC-16S → AC-16, the change rate of TSR is positive and the change rate of TSR becomes minus when the change occurs in the opposite direction. Results show that there is no certain rule between gradation type and water stability of asphalt mixtures, and the gradation type has no significant influence on the water stability of asphalt mixtures.

4.1.2. *Change rate of TSR with the change of aggregate type*

The gradation and asphalt grade are fixed and then the aggregate type is changed. The change rates of TSR caused by the change of combinations are shown in Table 9. Aggregate gradation and asphalt grade that influence the high and low temperature performance are considered in this study. The influence of aggregate type on change rates of dynamic stability and failure strain at low temperature is not shown in Table 9.

When aggregates change from granite to limestone, the range of improvement on water stability is between 17% and 21%. The differences in water stability between different asphalt mixtures are small which shows that an acid or alkali aggregate is a key factor to water stability and the influence of gradation and asphalt grade is small. When aggregates change from limestone to granite, the water stability of mixtures is weakened, to the same range of change as improvement.

4.1.3. *Change rate of maternal factors with the change of asphalt grade*

The gradation and aggregate type is fixed, and the asphalt grade is changed. The change rates of maternal factors caused by the change of combinations are shown in Table 10.

When asphalts change from 90# to 70#, the improvement range of dynamic stability is between 0.5% and 6.1%. Asphalt grade is one of the factors that affect the stability of asphalt mixtures at high temperature, but it is no more influential than gradation type to dynamic stability of the mixture. As a result, the stability at high temperature is influenced by both the gradation, especially the crowding effect between coarse aggregates and the asphalt grade.

When the asphalts change from 70# to 90#, the increase range of failure strain at low temperature of asphalt mixtures modified with double-adding admixtures is between 3.6% and 37.3%. When the asphalts change from 90# to 70#, the decrease range of failure strain at low temperature of asphalt mixtures modified with double-adding admixtures is

Table 10 – Change rates of maternal factors caused by the change of asphalt grade.

Combination	Change rate of dynamic stability (%)	Change rate of failure strain (%)	Change rate of TSR (%)
AC-13 + li. + 70# → AC-13 + li. + 90#	−1.8	37.3	0.0
AC-13 + li. + 90# → AC-13 + li. + 70#	1.8	−27.2	0.0
AC-16 + li. + 70# → AC-16 + li. + 90#	−5.7	36.5	−0.2
AC-16 + li. + 90# → AC-16 + li. + 70#	6.1	−26.7	0.2
AC-13 + gr. + 70# → AC-13 + gr. + 90#	−0.8	3.6	0.5
AC-13 + gr. + 90# → AC-13 + gr. + 70#	0.8	−3.5	−0.5
AC-16 + gr. + 70# → AC-16 + gr. + 90#	−0.5	3.7	3.3
AC-16 + gr. + 90# → AC-16 + gr. + 70#	0.5	−3.6	−3.2

between 3.3% and 27.2%. These phenomena show that, although the change of asphalt grade is same, the low temperature variation of the mixture is significantly different due to the effect of aggregate types, i.e. the performance of limestone is better than granite. One possible reason is that good alkalinity of limestone is beneficial to the adhesion between asphalts and aggregates at low temperature, so that bending performance at low temperature of asphalt mixtures is improved.

The TSR change ranges of asphalt mixtures modified with double-adding admixtures are 0–3.3% and 0–3.2%, respectively. This indicates that asphalt grade has little effect on water stability of asphalt mixtures.

Single factor analysis is carried out on the basis of the eight scheme. The influence of junior factors on maternal factors is reflected by the absolute value of maternal factors. The results of different types of changes based on single factor analysis are shown in Table 11.

It can be seen from Table 11 that the most important factor to high temperature stability of asphalt mixtures modified with double-adding admixtures is gradation, and the influence caused by asphalt grade is stronger than gradation type only in the AC-13 + li. + $70^{\#}$ and AC-16 + li. + $90^{\#}$ combinations. Therefore, the most important factors that influence anti-cracking performance at low temperature and water stability are asphalt grade and aggregate type, respectively.

Based on the analysis, some conclusions of influence on the properties caused by single factor can be drawn.

(1) The influence on high temperature stability of asphalt mixtures achieve a maximum value when aggregate sizes increase and the gradation type changes to S. Asphalt grade has a certain influence on the dynamic stability of asphalt mixture, but it is not as significant as the change of gradation.
(2) Asphalt grade changing from low to high has greatest influence on the low temperature performance, the low temperature strain of asphalt mixture can be improved effectively. The influence on low temperature performance of asphalt mixtures caused by gradation is no more significant than that caused by asphalt grade.
(3) The most influential factor of water stability is alkaline aggregate type. When alkaline limestone is used, the water stability of the mixture is obviously improved. The influence on water stability is small with the change of gradation and asphalt grade.

4.2. *Sensitivity analysis on dual factors*

The sensitivity analysis on dual factors means fixing any one factor, such as gradation, aggregate type and asphalt grade, and changing the other two factors in order to study the change to the maternal factors. From the single factor analysis, the influence on high and low temperature performance of asphalt mixtures caused by aggregate type can be neglected, and the influence on water stability caused by gradation and asphalt grade is not significant. Therefore, only the gradation and asphalt grade are taken into consideration

Table 11 – Influence of maternal factors sensitivity caused by single factors.

Combination	Sort on the influence of maternal factors sensitivity caused by junior factors		
	Sort on dynamic stability sensitivity	Sort on failure strain sensitivity	Sort on TSR sensitivity
AC-13 + li. + $70^{\#}$	Gradation AC-13 → AC-16S > gradation AC-13 → AC-16 > asphalt grade	Asphalt grade > gradation AC-13 → AC-16 > gradation AC-13 → AC-16S	Aggregate > gradation AC-13 → AC-16 > gradation AC-13 → AC-16S > asphalt grade
AC-16 + li. + $70^{\#}$	Gradation AC-16 → AC-16S > gradation AC-16 → AC-13 > asphalt grade	Asphalt grade > gradation AC-16 → AC-16S > gradation AC-16 → AC-13	Aggregate > gradation AC-16 → AC-16S > gradation AC-16 → AC-13 > asphalt grade
AC-13 + gr. + $70^{\#}$	Gradation > asphalt grade	Asphalt grade > gradation	Aggregate > gradation > asphalt grade
AC-16 + gr. + $70^{\#}$	Gradation > asphalt grade	Asphalt grade > gradation	Aggregate > asphalt grade > gradation
AC-13 + li. + $90^{\#}$	Asphalt grade > gradation	Asphalt grade > gradation	Aggregate > gradation > asphalt grade
AC-16 + li. + $90^{\#}$	Asphalt grade > gradation	Asphalt grade > gradation	Aggregate > gradation > asphalt grade
AC-13 + gr. + $90^{\#}$	Gradation > asphalt grade	Asphalt grade > gradation	Aggregate > gradation > asphalt grade
AC-16 + gr. + $90^{\#}$	Gradation > asphalt grade	Asphalt grade > gradation	Aggregate > gradation > asphalt grade

Note: The gradation change of the first two combinations includes AC-13, AC-16 and AC-16S, while the gradation of the other four combinations includes AC-13 and AC-16. And limestone and granite are selected as aggregate. The asphalt grades are $70^{\#}$ and $90^{\#}$.

when studying the influence on high/low temperature performance in sensitivity analysis on dual factors.

Change rates of maternal factors of relevant schemes using the same aggregate type, but changing the gradation and asphalt grade are shown in Table 12. Also the change patterns of high temperature performance, low temperature performance and water stability caused by dual factors were analyzed respectively.

4.2.1. *High temperature performance*

The change ranges of dynamic stabilities caused by the change of gradation and asphalt grade are 0.7%–21.4% and 0.6%–17.6%, respectively.

When the combination scheme changes from AC-13 + gr. + 90# to AC-16 + gr. + 70#, the maximum increase of dynamic stability is 21.4%. This means that high temperature performance of mixtures is optimally improved. The stability at high temperature of AC-16 is better than AC-13, and 70# asphalt grade gives better high temperature performance than 90# asphalt grade. So, with both the changes, the stability at high temperature of mixtures can be improved at utmost.

For AC-13 + gr. + 90#, when the gradation changes as AC-13 → AC-16, asphalt grade changes as 90# → 70# and dual factors change as AC-13 → AC-16 and 90# → 70#, the changes of dynamic stability are 20.7%, 0.8% and 21.4%, respectively. This indicates that the improvement on stability at high temperature caused by dual factors is more significant than one single factor.

The dynamic stability is increased by 0.6% which is the minimum value when the combination scheme changes as AC-16 + li. + 90# → AC-13 + li. + 70#.

4.2.2. *Low temperature performance*

The ranges of failure strain at low temperature caused by dual factors (gradation and asphalt grade) are 0.3%–42.0% and 0.3%–29.6%, respectively.

When the combination scheme changes as AC-16 + li. + 70# → AC-13 + li. + 90#, the failure strain at low temperature is increased by 21.4%, which means the low temperature performance of mixtures is improved to the greatest degree. The failure strain at low temperature increases when the gradation changes from AC-16 to AC-13, and asphalt grade changes from 70# to 90#. With both the changes, the change rate of failure strain at low temperature is increased at utmost, which means the low temperature performance of asphalt mixtures is also improved to the greatest degree.

When the combination scheme changes as AC-13 + gr. + 70# → AC-16 + gr. + 90#, the failure strain at low temperature is increased by 0.6% which is the minimum value.

4.2.3. *Water stability*

The changes of TSR caused by dual factors are 0.3%–4.1% and 0.3%–3.9%, respectively. This indicates that the influence on water stability of asphalt mixtures from gradation and asphalt grade is limited. The water stability of asphalt mixtures only changes significantly when the aggregate type changes, which is similar to the influence caused by the change of single factor without gradation and asphalt grade.

Some conclusions based on above analysis can be drawn.

(1) The stability at high temperature is improved, to a certain degree, when the gradation changes from AC-13 to AC-16, the asphalt grade changes from 90# to 70#, and the stability decreases when the change occurs in the opposite direction. The cracking resistance at low temperature is improved, to a certain degree, when the gradation changes from AC-16 to AC-13, the asphalt grade changes from 70# to 90#, and the crack resistance decreases when the change occurs in the opposite direction.
(2) The water stability of asphalt mixtures is improved when the aggregate changes from granite to limestone, and the water stability decreases when the change occurs in the opposite direction.
(3) The high and low temperature performance of asphalt mixtures are improved at utmost when dual factors change toward the direction that is good for asphalt mixtures while changes in the opposite direction decrease these performances to the greatest degree. When one factor changes towards the improved direction, and the other factors changes towards the decreased direction, the improvement of high or low temperature performances reaches the minimum value while the decrease of these performances reaches the minimum value when changes in the opposite directions occur.

5. Conclusions

Through tests of high temperature performance, low temperature performance, water stability and sensitivity analysis

Table 12 – Change rate of pavement performance caused by the change of gradation type and asphalt grade.

Combination	Change rate of dynamic stability (%)	Change rate of failure strain (%)	Change rate of TSR (%)
AC-13 + li. + 70# → AC-16 + li. + 90#	−0.6	32.0	2.2
AC-16 + li. + 90# → AC-13 + li. + 70#	0.7	−24.2	−2.2
AC-16 + li. + 70# → AC-13 + li. + 90#	−6.8	42.0	−2.4
AC-13 + li. + 90# → AC-16 + li. + 70#	7.3	−29.6	2.4
AC-13 + gr. + 70# → AC-16 + gr. + 90#	19.7	0.3	4.1
AC-16 + gr. + 90# → AC-13 + gr. + 70#	−16.5	−0.3	−3.9
AC-16 + gr. + 70# → AC-13 + gr. + 90#	−17.6	7.0	−0.3
AC-13 + gr. + 90# → AC-16 + gr. + 70#	21.4	−6.6	0.3

of AC-13 and AC-16 base asphalt mixtures, AC-13 and AC-16 asphalt mixtures modified with just anti-rutting agent or lignin fiber, and AC-13 and AC-16 asphalt mixtures modified with double-adding admixtures, some main conclusions are made as follows.

(1) High and low temperature performances of AC-13 and AC-16 asphalt mixtures modified with anti-rutting agent or lignin fiber have been improved. High temperature performance is dramatically improved, while the improvement of low temperature performance is slight, and only when adding anti-rutting agent into asphalt mixtures. On the contrary, when just adding lignin fiber into mixtures, low temperature performance is significantly improved while improvement of high temperature performance is not significant. Adding both admixtures can improve high and low temperature performances and water stability, simultaneously.

(2) There is an optimum content of anti-rutting agent and lignin fiber in the mixture. The optimum content of anti-rutting agent in AC-13 and AC-16 asphalt mixtures modified with only anti-rutting agent is 0.39%–0.63%. The optimum content of lignin fiber in AC-13 and AC-16 asphalt mixtures modified with only lignin fiber is 0.36%. The optimum content of double-adding admixtures in AC-13 and AC-16 asphalt mixtures is 0.4% anti-rutting agent and 0.36% lignin fiber, when high and low temperature performances and water stability of asphalt mixtures can be greatly improved.

(3) Some main conclusions from the factor analysis are made as follows. ①The most influential factor to the high temperature stability of asphalt mixtures modified with double-adding admixtures is gradation, and the influence of asphalt grade and aggregate type on the stability of high temperature is not obvious. ②The most influential factor to the anti-cracking performance at low temperature of asphalt mixtures modified with double-adding admixtures is asphalt grade, and the influence of gradation and aggregate type on low temperature crack resistance is slight. ③The most important factor affecting water stability of asphalt mixtures modified with double-adding admixtures is aggregate type, and the effect of asphalt grade and gradation on water stability is not noteworthy.

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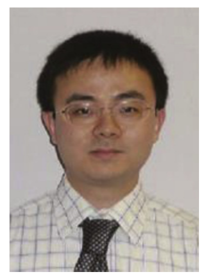

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