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# Laboratory evaluation of pavement performance using modified asphalt mixture with a new composite reinforcing material

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**Abstract**

As a new way of modifying asphalt or asphalt mixture, composite modification has obvious effects. In order to improve the performance of asphalt pavement in a simple, fast and efficient way, a new kind of composite reinforcing material (CRM) is used in this study. The Marshall Immersion test, the freeze–thaw splitting test and low-temperature bending test were conducted to evaluate the pavement performance of the asphalt mixture with different CRM contents. Test results show that the pavement performance of modified asphalt mixtures is better than unmodified asphalt mixture. When the CRM content increases, resistance to rutting at a high temperature increases significantly, low temperature cracking resistance and moisture damage resistance first rise and then fall. In consideration of other pavement performance, such as dynamic stability (DS), indirect tensile strength ratio (TSR) and maximum tensile strain, the suggested optimal CRM dosage is 5.9‰ to 7.9‰.


*Keywords:* Highway engineering; Asphalt mixture; Composite reinforcing material; High temperature stability; Water stability; Low temperature cracking resistance

## 1. Introduction

The performance of asphalt pavements is strongly affected by the properties of asphalt mixture. With the growth of traffic, the harsh condition of high temperature and heavy axle load, there has been a higher requirement for asphalt concrete performance. In view of this situation, the modification technology to asphalt or asphalt mixture has been studied and improved. The most commonly used modification technology is to add various additives to asphalt or asphalt mixture. Single additive was used in the past but with varied improvement on pavement performance. Composite modifiers, such as composite admixtures with fiber and polymer, composite admixtures with natural asphalt and fiber, have attracted more attention. Since various components of composite modifiers are used each targeting the improvement of a certain performance, the overall road performance has been improved greatly. However, most of the studies so far focus on the single modification, and research on the composite reinforcement is still in its early stage despite of the increasing demand for its application to highway engineering.

## 2. Literature review of asphalt mixture additive

So far, the modification materials that are applied into asphalt and asphalt mixture are mainly of three kinds: high-molecular polymer, mineral filter and liquid modifier. Further, high-molecular polymer can be also divided into

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thermoplastic elastomer (TPE), rubber and resin. Mineral filter includes diatomite, nano materials, carbon black, fibers, etc. Those materials have different modification effects on pavement performance when added into asphalt mixtures. Many scholars and experts at home and abroad have done extensive research on all kinds of materials. The authors talk about those additives including rubber powder [1,2], polyethylene (PE) [3–5], lignin fibers, basalt fiber [6,7] have a significantly improved effect on rutting resistance of asphalt mixture at high temperatures, but not very good in anti-fatigue performance or water stability or low-temperature cracking. There are also some mineral filters have a relatively good performance when used in asphalt mixtures, but the modification effect is limited, such as rock asphalt [8], basalt fiber [9], bio-char [10]. Although additives are various, no one is very good at improving the pavement performance including rutting-resistance, deformation-resistance, anti-fatigue performance, water stability, low-temperature cracking.

Since different modification materials primarily modify a certain performance, it is hard to satisfy every aspect of pavement performance. Thus, the combined use of multiple modification materials has attracted the attention of researchers [11]. Using both the tacky property of polypropylene (PP) fiber at a temperature around its melting point and the high modulus of glass fiber is a possible way to modify asphalt concrete, such that the reinforced product got higher stability and lower flow [12]. Combining crumb rubber and Lignin fiber can improve the overall road performance of rubber asphalt mixture [13]. Double-adding technology (adding anti-rutting agent and lignin fiber simultaneously) is used in this paper to reduce rutting at high temperatures and cracking at low temperatures at the same time which can improve the pavement performance [11]. When diatomite and polyacrylate (PAE) are used together to modified asphalt mixture, the high temperature performance and the moisture damage resistance are enhanced simultaneously [14]. Research has showed that the addition of Nano-$TiO_2$/$SiO_2$ can boost the asphalt rheological characteristics and improve the asphalt mixture's rutting and fatigue resistance [15].

The modification effect of different additives on asphalt or asphalt mixtures is different. With the research of over years, it is found that lignin fibers added into asphalt mixture can absorb asphalt and make the asphalt film attached to aggregate thick, and make the connection between asphalt and aggregate more stable. Natural asphalt, of which production process is simple, is very compatible with petroleum asphalt, and is significant in improving the anti-rutting performance and water damage resistance, and as a modifier in road construction has a wide range of application advantages. Polymer modified material are various, such as natural rubber (NR), styrene butadiene rubber (SBR), styrene–butadienestyrene (SBS), polyethylene (PE), polyvinyl chloride (PVC), etc. Those materials widely used in modifying asphalt and asphalt mixture. The polymer, lignin fiber and natural asphalt have special features in modifying asphalt mixture separately. However, making the three materials into a new composite material and evaluating its effects on the performance of modified asphalt mixture is rarely studied. In this paper, the composite reinforcing material (CRM) is made from polymers, lignin fibers and natural asphalt by a special process. A series of laboratory tests about this CRM asphalt mixture are conducted to illustrate the effect on, and characteristics of, the modified asphalt mixture. This paper provides mix design method, laboratory tests and discussion on results for its application in asphalt pavement.

## 3. Materials and experiments

### 3.1. Materials

#### 3.1.1. Asphalt binders

The Shell heavy traffic road petroleum asphalt 70# was used in this study, meeting the requirements of Chinese JTG F40-2004 [16], its main characteristics for asphalt are shown in Table 1.

#### 3.1.2. Aggregates

The fine aggregate and coarse aggregate used in this study are all limestone, and the properties of the aggregates are shown in Table 2 (fine) and Table 3 (coarse). The mineral powder used in this study is also made from limestone, and its apparent relative density is 2.74, hydrophilic coefficient is 0.60, the plasticity index is 2.3.

#### 3.1.3. Composite reinforcing material (CRM)

The additive used in this study is a new composite reinforcing material (CRM) that is produced by an engineering consultancy firm specialized in highway materials. It is a kind of granular material, which is made from polymers, lignin fibers, natural asphalt and other chemical additives through a special blending process. Lignin fibers in CRM can absorb some asphalt and reach a stable state after dispersion and reinforcement of asphalt. And the adhesive cementation of fibers and asphalt plays a role of filling voids in the mixture, increasing the cohesion of the asphalt mixture. Polymer materials in CRM can improve the properties of the base asphalt, and a combination of those modifications has a positive effect on the rutting resistance, moisture damage resistance and low temperature cracking resistance of asphalt mixtures. T The additive used in this study is a new composite reinforcing material (CRM) that is produced by an engineering consultancy firm specialized in highway materials. It is a kind of granular material, which is made from polymers, lignin fibers, natural asphalt and other chemical additives through a special blending process. Lignin fibers in CRM can absorb some asphalt and reach a stable state after dispersion and reinforcement of asphalt. And the adhesive cementation of fibers and asphalt plays a role of filling voids in the mixture, increasing the cohesion of the asphalt mixture. Polymer materials in CRM can improve the properties of the base asphalt,

Table 1
Characteristics of asphalt binder.

| Indicator | | Standard requirements | Value |
|---|---|---|---|
| Penetration (25 °C, 5 s, 100 g)/0.1 mm | | 60–80 | 71 |
| Penetration index PI | | −1.0 ~ +1.0 | −0.87 |
| Softening point (R&B)/°C | | ≥46 | 46.7 |
| Ductility (15 °C)/cm | | ≥100 | 116.3 |
| Density (15 °C)/g cm$^{-3}$ | | – | 0.98 |
| Flash point/°C | | ≥260 | 274 |
| Solubility/% | | ≥99.5 | 99.8 |
| Wax content/% | | ≤2.2 | 1.8 |
| Filmy heating operational test | Mass loss/% | ≤ ± 0.8 | 0.07 |
| | Residual Penetration ratio/% | ≥61 | 69 |
| | Ductility (15 °C)/cm | ≥15 | >100 |

Table 2
Characteristics of fine aggregate.

| Item | Standard requirements | Value |
|---|---|---|
| Apparent relative density/% | ≥2.50 | 2.709 |
| Sand equivalent/% | ≥60 | 75 |
| Soundness (>0.3 mm)/% | ≥12 | 15 |

Table 3
Characteristics of coarse aggregate.

| Item | Standard requirements | Value | |
|---|---|---|---|
| | | 4.75–9.5 | 9.5–16 |
| Crushed stone value/% | ≤28 | 7.4 | 7.8 |
| Los Angeles abrasion value/% | ≤30 | 12.9 | 10.4 |
| Apparent relative density/% | ≥2.50 | 2.763 | 2.786 |
| Water absorption/% | ≤3 | 0.72 | 0.63 |
| Soundness/% | ≤12 | 8 | 8 |
| Soft rock content/% | ≤5 | 2 | 2 |
| >9.5 mm needle and plate particle content/% | ≤15 | – | 4.9 |
| <9.5 mm needle and plate particle content/% | ≤20 | 7.9 | – |
| <0.075 mm grain content, water-washing/% | ≤1 | 0.3 | 0.2 |

Fig. 1. Composite reinforcing material (CRM).

and a combination of those modifications has a positive effect on the rutting resistance, moisture damage resistance and low temperature cracking resistance of asphalt mixtures. The appearance and characteristics of this CRM are shown in Fig. 1 and Table 4. The CRM contains about 38% lignin fibers and 62% reinforced materials of polymers and natural asphalts. During the modification process, the CRM is added into hot aggregate before the spray of asphalt binder. The time of dry mixing is suggested to extend for 5 s to help CRM melting.

Because of the composition and morphology of the CRM, it is capable of modifying not only the asphalt binder but also aggregates in which CRM plays roles of wedging, filling, wrapping and mesh constraint. So the overall strength of the mixture is improved, and the anti-rutting ability is enhanced. In addition, the CRM has the following advantages. (1) It can be used in a wide range of areas, especially where the material, equipment and construction technology is limited. It can improve the performance of asphalt pavement, for construction or maintenance of roads. (2) It can be used as a reinforcing material, partially or fully replacing the asphalt modifier. (3) Its application to asphalt production has no requirements for amendments of the existing production process and equipment.

### 3.2. Experimental plan

In order to reflect the modification effects on pavement performance of the CRM, a typical dense gradation (AC-13C) with a nominal aggregate size of 13.2 mm was selected, and the passing rate of key sieve of 2.36 mm is less than 40% by weight of all aggregates, as shown in Table 5. Firstly, in accordance with the Marshall mixture design method, a series of asphalt mixture with the CRM contents of 0%, 0.4%, 0.6%, 0.8% by weight of total mixture were prepared by dry process to determine the optimum asphalt

Table 4
Properties of composite reinforcing material.

| Name | Density (25 °C)/g cm$^{-3}$ | Melting point/°C | Grain size/mm |
|---|---|---|---|
| CRM | 0.98 | 160–170 | 5–7 |

contents (OAC). As a result, the relation between the OAC and CRM contents is concluded. Secondly, the performance of modified asphalt mixture with different CRM content was evaluated to verify the effectiveness of this additive. Finally, the range of the optimum dosage of CRM was determined by analyzing test data.

### 3.3. Test methods

All tests carried out in this study are in accordance with the Chinese standard JTG E20-2011 [17].

#### 3.3.1. Marshall immersion test and freeze–thaw splitting test

The Marshall immersion test and freeze–thaw splitting test were conducted to evaluate the water stability of the mixture. The specimens in the Marshall immersion test were immersed in water bath at 60 °C for 48 h. The specimens in freeze–thaw splitting test were subjected to continuous freezing at −18 °C for 16 h, and thawing at 60 °C for 24 h, after which the indirect tensile strength was obtained.

The immersion residual Marshall stability (MS) and the freeze–thaw splitting strength ratio were calculated to evaluate the water stability of the mixtures. The immersion residual Marshall stability (MS) was defined as the Marshall Stability ratio of wet and dry specimens. The freeze–thaw strength ratio was defined as the indirect tensile strength ratio (TSR) of freeze–thaw and dry specimens.

#### 3.3.2. The wheel tracking test

The wheel tracking test was conducted at 60 °C under dry conditions to get the dynamic stability (DS) and to evaluate the high-temperature rutting-resistance characteristics of the asphalt mixtures. The equipment used for wheel tracking test is automatic rut instrument HYCZ-5 made by Beijing aerospace aerospace measurement and control technology institute, which has automatic temperature control system. The dimensions of the slab specimens were 300 mm × 300 mm × 50 mm. A solid-rubber wheel traveling at a speed of 42 cycles/min and at a pressure of 0.7 MPa is used to simulate the loading that vehicle driven on pavement layers.

#### 3.3.3. Low-temperature bending test

The low-temperature bending test was to evaluate the tensile performance of asphalt mixtures at low temperatures. The experiment equipment is MTS810, mitutoyo ID-S112 LVDT sensors is set behind the middle of beam specimen. After beginning of experiment, concentrated load is put on the middle of team specimen until the beam specimen is destroyed. The system collects the data of displacement and load automatically, and the data can be drawn into X-Y recorder. The maximum loading and middle displacement obtained at the point that the beam specimen is destroyed are the key to calculate flexural strength and maximum tensile strain. The test is conducted at $-10 \pm 0.5$ °C and at a load speed of 50 mm/min.

#### 3.3.4. Oven aging test

The aging test was to simulate the aging effect caused by heat and oxidation in the construction process of mixing, transport, spreading and rolling of asphalt mixture. Oven aging test was also able to simulate the short-term and long-term aging of asphalt mixtures during the service life. Short-term aging was to put the asphalt mixtures prepared into oven at $135 \pm 1$ °C for 4 h $\pm$ 5 min, the mixture was stirred with a shovel every hour. After the short-term aging, the asphalt mixture was further processed into specimens, which was then conditioned in a ventilated oven at $85 \pm 3$ °C for 5 d, to simulate long-term aging during service life.

## 4. Results and discussions

### 4.1. Determination of OAC

As the composition and morphology of the CRM may affect the OAC, many tests were carried out on the performance of the modified asphalt mixtures under different CRM contents to determine the OAC. The results are presented in Fig. 2, which show that the OAC of mixtures increase linearly from 4.3% to 5.0% as the CRM content changed from 0 to 0.8%.

In order to verify the accuracy of above regression formula in Fig. 2, a mixture of 0.5% CRM dosage was prepared and tested, and the result indicated that the OAC was 4.75% which is very close to the result obtained through equation: $Y = 0.8714 \times 0.5 + 4.2829 = 4.72$. Thus it is affirmed that the regression formula above fits well with the correlation between OAC and the CRM content.

Since the performance of different CRM dosage will be studied, the OAC with 1.2% CRM content needs to be determined. The result can be obtained from equation above, when $X = 1.2$, $Y = 0.8714X + 4.2829 = 0.8714 \times 1.2 + 4.2829 = 5.3$.

Fig. 2 shows that the OAC increases about 0.3–0.4% with every additional 0.4% CRM dosage. That is, When the CRM content increases 0.1% by weight of total mixture, the OAC will increase by 0.1% for ordinary asphalt mixture. It is necessary to explain that such conclusion can only be restricted to the mix used in the paper. It may not be applicable to other mix designs.

CRM contains lignin fiber, which is an inert organic fiber obtained from chemically treated wood, with stable chemical properties and high temperature resistance, and

Table 5
Gradation of AC-13C asphalt mixture.

| Sieve size/mm | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
|---|---|---|---|---|---|---|---|---|---|---|
| AC-13C passing percentage/% | 100 | 95.85 | 74.69 | 47.73 | 27.84 | 20.37 | 16.33 | 12.66 | 10.58 | 7.55 |

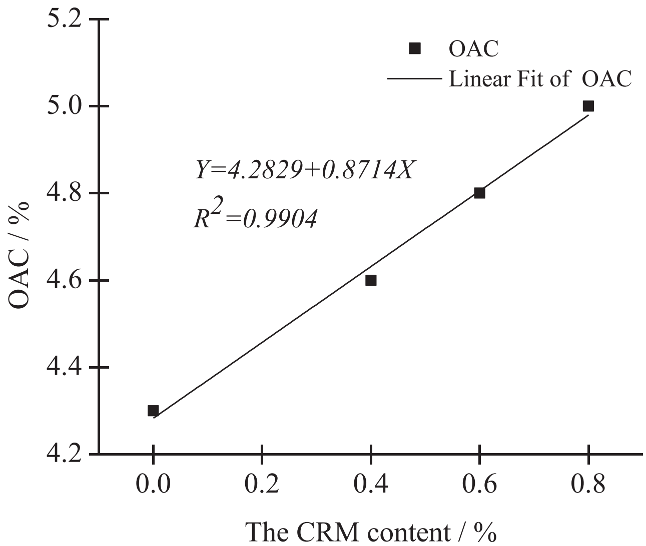



Fig. 2. Relationship between OAC and CRM contents.

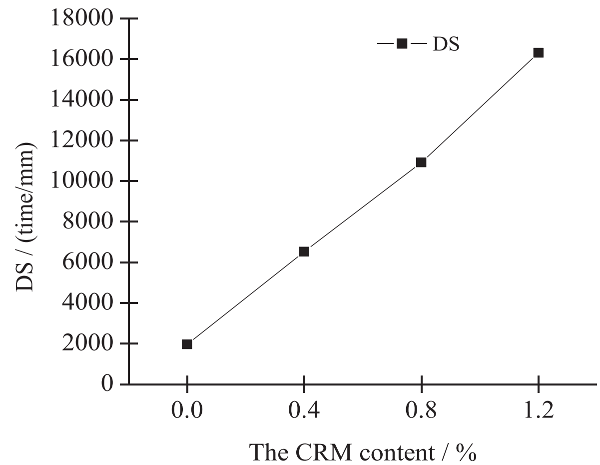



Fig. 3. Relationship between dynamic stability and CRM contents.

generally will not be corroded by acid solution. Fiber has a good absorption of asphalt due to its large specific surface. The more fiber in the mixture, the more asphalt will be absorbed, and the OAC will increase as a result. This confirms the findings by Zhu [18] in previous studies.

### 4.2. Pavement performance

Laboratory tests were conducted to evaluate the pavement performance of modified asphalt mixtures with CRM contents of 0.4%, 0.8%, 1.2% and unmodified asphalt mixture.

#### 4.2.1. Evaluation of high temperature stability

The composite reinforcing material (CRM) can effectively improve the high temperature stability of asphalt mixtures. The dynamic stability is improved with the increase of CRM, as shown in Fig. 3.

It can be seen from Fig. 3 that the dynamic stability of the mixture is 3 times as high as that of unmodified AC-13 when the mixture is added with 0.4% CRM. And it is 5.6 times and 8 times as high as unmodified AC-13 asphalt mixture when CRM increased to 0.8% and 1.2%, respectively. Test results show that the rutting resistance of asphalt mixture in high temperatures is improved significantly when adding an amount of CRM, which can be an effective measure to solve the rutting problem of asphalt pavement.

The reason that the CRM contributes greatly to high temperature stability is that asphalt mixture is produced at a temperature higher than the melting point of CRM (160–170 °C as in Table 4), which turned the CRM into a viscous flow state during the process. When the CRM particles deform and play a major role of binder and cohesion between aggregates, they strengthen the bonding between the binder and aggregates, and promote the overall ability of the mixture to withstand the load. In addition, there is some natural asphalt present in the CRM. The amount of asphaltene in natural asphalt is much greater than that in base asphalt, the content of asphaltene in modified asphalt will thus increase, resulting in an increase of polarized substances in bitumen, which promoted the bond between molecules and enhanced the viscosity. Therefore, it is more difficult to break the bond between them unless the temperature is high enough. And the dynamic stability of asphalt mixture is an important indicator of its high temperature stability.

#### 4.2.2. Evaluation of low temperature cracking resistance

The test results show that the ultimate flexural tensile strength and the maximum tensile strain of asphalt mixture are improved after adding composite reinforcing material, as shown in Fig. 4.

When the CRM content is 0%, flexural tensile strength and maximum tensile strain of the asphalt mixture are 7.8 MPa and 2003με. When the CRM content increases, flexural tensile strength and maximum tensile strain increase at first and then decrease. When the content is 0.4%, the flexural tensile strength reaches the maximum value of 10.5 MPa, an increase by 34.6% compared with unmodified asphalt mixture. When the CRM content is 0.8%, the tensile strain reaches a maximum value of 2766με, i.e. 38.1% higher compared with that of unmodified asphalt mixture. Although the improvement of low temperature performance is not particularly substantial, it is still able to produce a positive effect on the low temperature cracking resistance of mixture showing a good application prospect.

Due to the ability of asphalt binder to withstand low temperature tensile stress, the contribution of asphalt binder to the cracking resistance of asphalt mixture is much higher than that of aggregates. The asphalt binder filled between aggregates will play a role of bonding when temperature drops, so that asphalt mixture doesn't crack prematurely. However, when the temperature is lowered

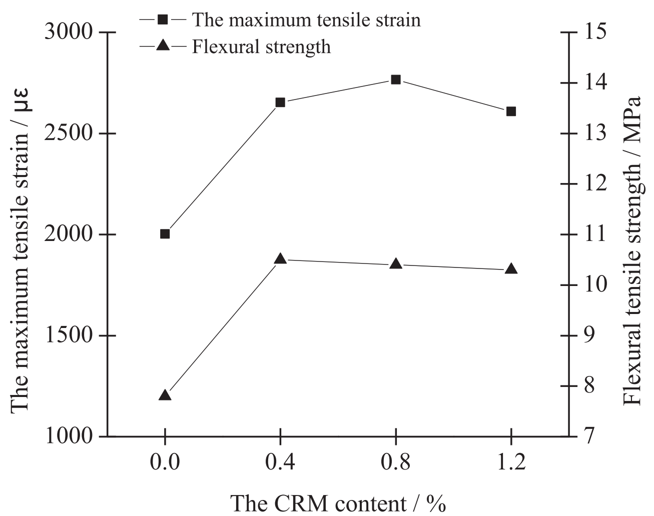



Fig. 4. Relationship between low temperature performance and CRM contents.

to a certain extent, ordinary asphalt binder will not be able to withstand the excessive tensile stress and cracks will appear. The CRM used in this research is a new type of anti-rutting agent which is made from a mix of high polymer material, lignin fiber, natural asphalt and chemical agents. The polymer material for asphalt modification is able to increase its strength and toughness and meanwhile maintain its low temperature flexibility. The friction angle and cohesive force of asphalt binder can be improved by the incorporation of lignin fiber, which can also improve the shear strength of asphalt mixture and contribute to the low temperature performance of the mixture [19].

#### *4.2.3. Evaluation of water stability*

Water stability of asphalt mixture is mainly determined by the nature of mineral aggregate, the interaction between asphalt and mineral aggregate, the air void of asphalt mixture, and the thickness of asphalt film. Generally, water is easier to infiltrate aggregate surface than asphalt binder which then reduces the adhesion between asphalt and aggregates, and leads to moisture damage to the asphalt mixture [20]. So the presence of water is largely a threat to the asphalt mixture in road pavement.

The relationship between immersion residual stability and freeze–thaw splitting strength with CRM contents is shown in Figs. 5and 6(a, b), respectively.

The immersion residual stability ratio of unmodified asphalt mixture is 88.2% and the indirect tensile strength ratio (TSR) is 80.8%. When adding 0.4% CRM modifier, the immersion residual stability ratio and the TSR increase to 93.9% and 91.5%, respectively. If the content of modifier continues to increase, the immersion residual stability ratio and the TSR start to decrease.

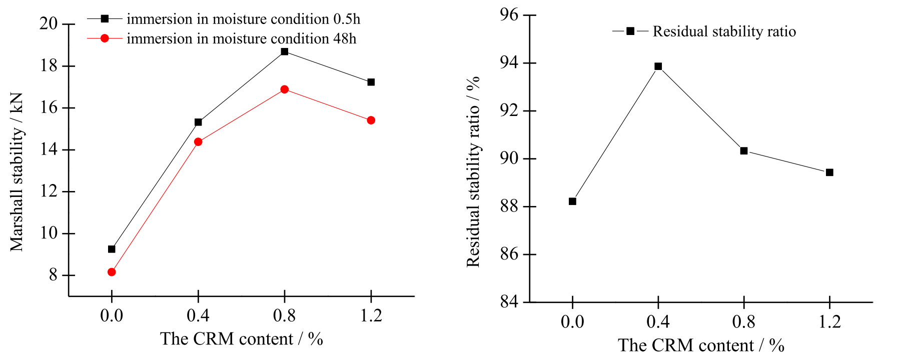
Figs. 5(b) and 6(b) show that the immersion residual stability ratio is higher than the indirect tensile strength ratio (TSR) with the same content of modifier. The reason is that the specimens for Marshall Immersion test were compacted 75 times and porosity of the specimens has been reduced to 3–5%. It is difficult for water to enter the gap between aggregates and asphalt films, and thus water damage is less likely to occur. Porosity of the specimens for freeze–thaw split test is controlled at 7%, where the specimens were compacted 50 times closer to the actual compaction on site [21]. CRM is a viscous fluid with good deformation ability at high temperatures. It is able to fill large pores, change their structure, and reduce the number of connected pores so effectively and prevent the migration of asphalt binder. The lignin fiber in CRM is porous, it has a strong tendency to adsorb asphalt, making the asphalt film on mineral aggregates thicker, and the amount of free asphalt is reduced as a result. This improves the adhesive force between asphalt and aggregates and enhances the water resistance of the asphalt mixture. In addition, the polymer materials in CRM can enhance the adhesion between binder and aggregates, and make it more resistant to water induced damage.

#### *4.2.4. Evaluation of aging performance*

The short-term aging (4 h) and the long-term aging (5 days) tests were carried out with 4 different CRM dosages of 0%, 0.4%, 0.8%, 1.2%. Then the water stability and low temperature cracking resistance were tested (high temperature stability is not appropriate because aging can produce beneficial effects on it). The change of the aging behavior of modified asphalt mixture was evaluated by flexural tensile strength, the maximum tensile strain and indirect tensile strength ratio (TSR). Test results are shown in Figs. 7 and 8.

On the one hand, the aging process makes aggregates absorb more asphalt; on the other hand, asphalt is subject to the effects of heat and oxygen [22]. Both effects increase the stiffness of asphalt, and weaken the low temperature ability (e.g. anti-cracking). With aging continuing, the flexural tensile strength increases, while the maximum tensile strain decreases, which is shown in Fig. 7. The trabecular specimens in the low temperature bending test crack along the interface between aggregates. With the propagation of cracks, an extrusion and shear action to large particles appear, and eventually lead to the compression-shear damage. The stiffness of asphalt binder is increased after aging, so is the interface bond with mineral aggregate. The more the binder is aged, the greater the flexural tensile strength becomes. The asphalt binder becomes hard and brittle after aging, which is unable to resist large deformation in low temperatures. The more the binder is aged, the smaller the deformation when the mixture fails. The failure strain depends on the mid-span deflection when the trabecular specimens fail. The maximum tensile strain of the mixture after aging is inversely proportional to the degree of aging. Fig. 7 shows that although modified asphalt mixture can barely meet the technical requirements after short-term aging, and its performance fell sharply after long term aging, it is still better than the unmodified asphalt mixture.

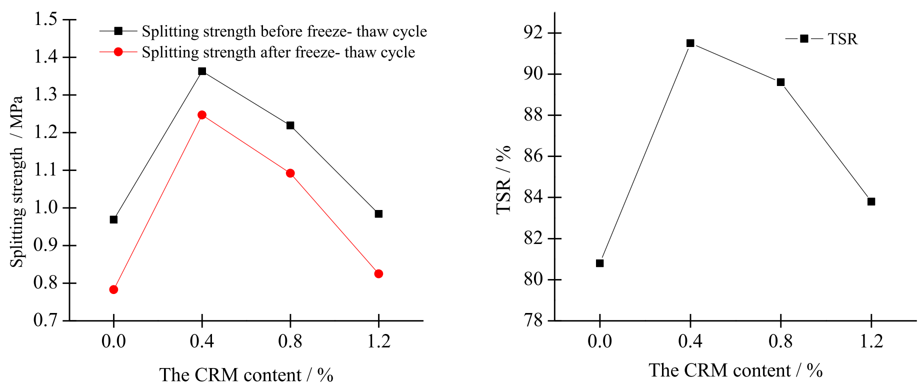
With regard to water stability of the aged asphalt mixtures, when the CRM content increases from 0.4% to




(a). The Marshall immersion stability and CRM contents

(b). The Marshall immersion residual stability ratio and CRM contents

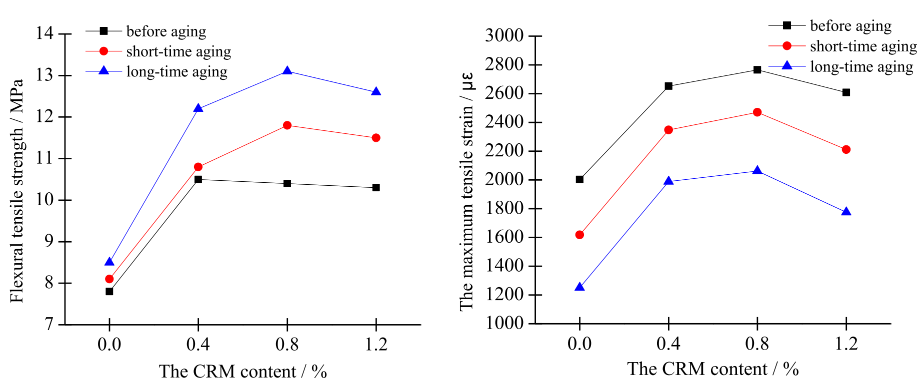
Fig. 5. Marshall immersion tests.




(a). The Splitting strength and and CRM contents

(b). Indirect tensile strength ratio(TSR) and CRM contents

Fig. 6. Freeze–thaw splitting tests.




(a). The flexural tensile strength and the CRM content

(b). The maximum tensile strain and the CRM content

Fig. 7. Low-temperature bending test after aging.

0.8% and 1.2%, the TSR value of asphalt mixture is improved by 6%, 1.1% and 0.2%, respectively, compared with unmodified asphalt mixture after short term aging, and by 8.2%, 5.4% and 5.4% after long term aging, which is shown in Fig. 8. Thus, the incorporation of CRM can effectively reduce the influence of aging effect on the water stability of asphalt mixture.

For short-term and long-term aging situation, low temperature performance and moisture damage resistance of modified asphalt mixture are improved with the use of

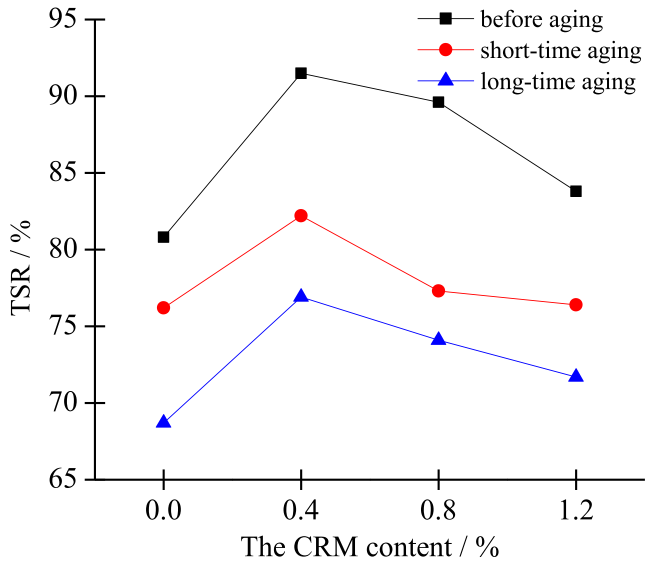



Fig. 8. Freeze–thaw splitting tests after aging.

CRM. The flexible tensile strength and maximum tensile strain see an optimal value at a CRM content of 0.8%, while the TSR value reaches highest with a CRM content of 0.4%. Therefore, CRM has a positive effect on the aging property of asphalt mixture.

### *4.3. Determination of the optimum dosage of composite reinforcing material*

Five CRM contents with 0%, 0.4%, 0.6%, 0.8%, 1.2% was chosen to conduct tests of freeze–thawing split tests, high-temperature rutting tests, low-temperature bending tests. The indirect tensile strength ratio (TSR), maximum tensile strain and dynamic stability (DS) can be obtained. As the CRM content changes, indirect tensile strength ratio (TSR), dynamic stability (DS) and maximum tensile strain present a certain pattern of change, as shown in Fig. 9.

An environment in which water and temperature has a detrimental effect on the asphalt mixture was simulated. In the Technical Specification for Construction of Highway Asphalt Pavements, the stipulation about TSR in the worst environment is at least 85%, while the Failure strain is at least 2800με in the relative worse environment. In paper, the author improves 5% on the basis of TSR stipulation and makes 90% as the threshold value. Failure strain of ≥2800με and TSR of ≥90% are selected as technical standards for low temperature stability and water stability.

Fig. 9(a) shows the change of low temperature stability against CRM content. When the CRM content increases, the maximum tensile strain of asphalt mixture increases firstly and then decreases. When adding 0.59–0.95% CRM, the tensile strain of the modified asphalt mixture can reach a value above 2800με.

Fig. 9(b) shows the change of water stability against CRM content, which shows a similar trend to Fig. 9(a).

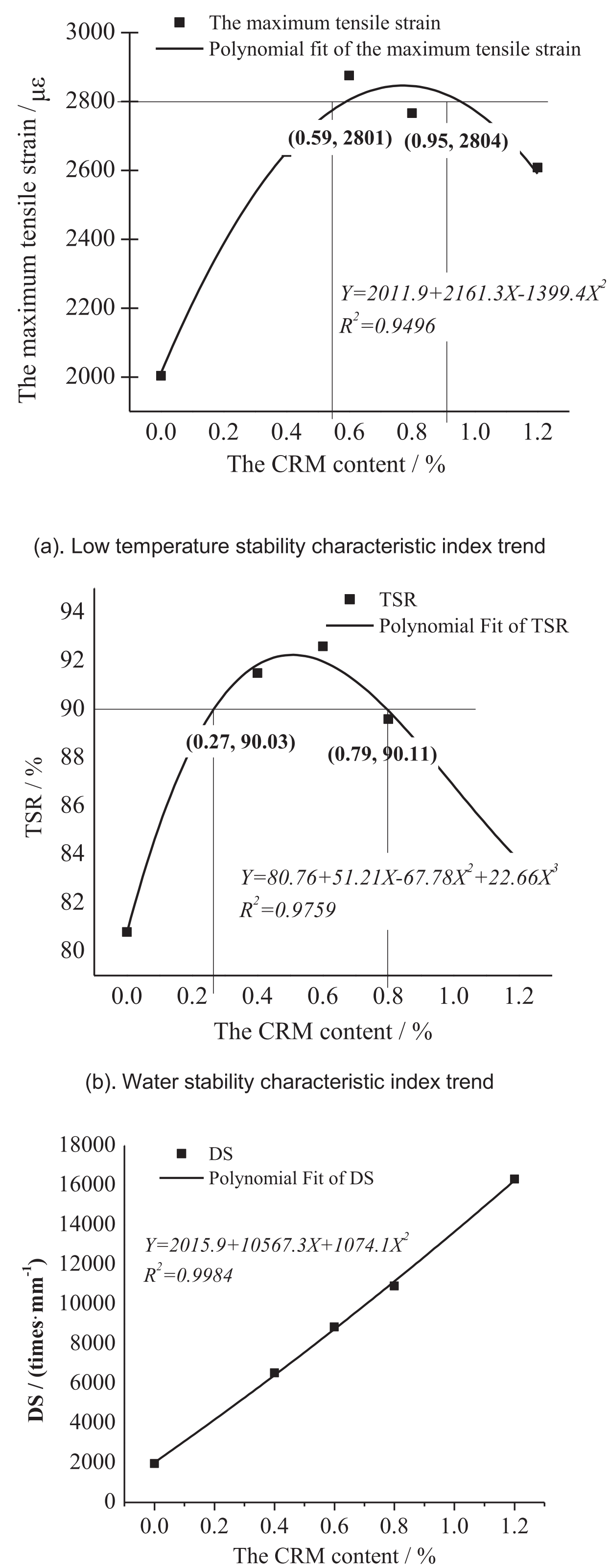



Fig. 9. Change of pavement performance with modified asphalt mixture.

When adding 0.27–0.79% CRM, the indirect tensile strength ratio (TSR) of modified asphalt mixture can reach a value above 90%.

Fig. 9(c) shows the change of high-temperature stability against CRM content. It can be seen that the dynamic stability (DS) presents a linear relationship with the increase of CRM.

Along with the increase of amount of Material CRM, the value of dynamic stability improves constantly, it has a positive effect on high-temperature rutting-resistance. This effect is not same to water stability and low-temperature performance. Author thinks that the cause may lie in: when the amount of CRM is over, the dispersion effects of granular CRM in asphalt is not very homogeneous, because the amount of asphalt is certain, the net structure formed by CRM dispersing in asphalt is not an ideal state to cover aggregate. This kind of heterogeneous state seriously affects the performance including water stability and low-temperature cracking-resistance. That is a possible reason for deteriorated phenomenon when the amount of CRM is beyond the optimum dosage.

An important finding of this study is that the optimum content of modifier ranges from 0.59% to 0.79% considering both the low temperature stability (Fig. 9(a)) and water stability (Fig. 9(b)). The dynamic stability increases in proportion to the CRM content within the investigated range, with a value from 8507 times $mm^{-1}$ to 10,748 times $mm^{-1}$. Thus, when the content of CRM is between 0.59% and 0.79%, the road performance of asphalt mixtures is better in general. However, the choice of specific content should also consider the cost, environment and traffic requirement which may change the weighting of these technical criteria.

## 5. Conclusions

Through laboratory tests of asphalt mixtures modified by CRM, the pavement performance made using the CRM modified asphalt mixture is evaluated. Based on the results, the following conclusions can be drawn.

(1) The high temperature stability of asphalt mixtures modified by CRM is improved compared to unmodified asphalt mixture. The dynamic stability continues to rise with the increase of CRM, and the low temperature cracking resistance and moisture damage resistance increase at first with CRM and then decrease, but all higher than those of unmodified asphalt mixtures. The optimal CRM dosage range of 5.9–7.9% in asphalt mixtures is determined using freeze–thaw splitting ratio and failure strain.

(2) The modified asphalt mixtures can still remain good water stability and low temperature cracking resistance compared to unmodified asphalt mixtures, after short-term aging. The performance deteriorates to some extent after long-term aging, but the overall performance is still significantly better than unmodified asphalt mixtures. Therefore, CRM has a positive effect on improving the aging resistance of asphalt mixtures.

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