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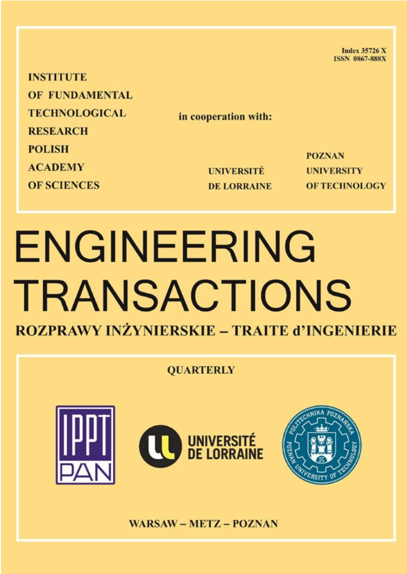

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Characteristics Evaluation and Application of SBS Composite Modified bitumen Materials in Low Temperature Environment

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To improve the resistance of bitumen pavement to low temperature cracking, the study proposes a composite modified bitumen based on styrene butadiene styrene copolymer and crumb rubber. It is also tested for its performance in low temperature environment. The test results indicated that although after aging and freeze-thaw cycles, the creep rate of both modified bitumen and styrene butadiene styrene copolymer/crumb rubber were reduced. However, the creep rate of styrene butadiene styrene copolymer/crumb rubber composite modified bitumen was always better than that of styrene butadiene styrene copolymer modified bitumen. As an example, the creep rate of aged bitumen was 0.37 and 0.44 at -12°C, respectively. When bitumen mixes underwent freeze-thaw cycles and age, their fracture energy densities all drastically decreased. The fracture energy density of styrene butadiene styrene copolymer/crumb rubber composite modified bitumen mixtures, on the other hand, was larger than that of styrene butadiene styrene copolymer modified bitumen mixtures. The above results indicate that the composite modified bitumen with styrene butadiene styrene copolymer/crumb rubber has good rheological ability and freeze-thaw resistance, which can effectively ensure the low temperature performance of bitumen pavement.

Keywords: SBS; Modified bitumen; Rheological propertiess; Low temperature properties; Cyclic freezing and thawing; Crumb rubber.

1 Introduction

As the most common pavement surfacing material, compared with other pavements, bitumen pavement (AP) has the advantages of smooth surface, comfortable driving, and easy maintenance and repair. However, in the low temperature (LT) environment, the bitumen binding material is prone to cracking problems, which seriously affects the performance and life of AP [1-2]. The LT cracking problem of AP can be improved by improving the rheological properties of bitumen. One typical bitumen modification that can successfully increase the ductility and viscoelasticity of bitumen while lowering its temperature sensitivity is styrene butadiene styrene copolymer (SBS) [3-4]. In the 1840s, researchers first attempted to mix natural rubber into matrix bitumen to prepare modified bitumen. Afterwards, synthetic rubber and natural rubber began to be used to modify matrix bitumen. But it was not until 1930 that the preparation process of rubber modified bitumen was more effectively improved. In the 1960s, rubber powder obtained by processing waste tires began to be added to matrix bitumen by some countries to prepare rubberized bitumen and apply it to road construction. However, due to the poor compatibility between rubber powder and bitumen, there are a large number of rubber particles, resulting in disadvantages such as high viscosity, poor flowability, and poor dispersibility of bitumen. Liu B et al. proposed a method of using carbon nanotubes mixed with SBS modified bitumen to address the issue of early damage to bitumen pavement. This study analyzed the effects of different CNT concentrations on the high and low temperature performance as well as aging performance of SBS-A through a series of experiments. The results showed that the optimal concentration of carbon nanotubes was 1.0%, and the changes of modified bitumen during aging were analyzed by infrared spectroscopy [5]. Ting et al. proposed a composite MA based on SBS and methylene diphenyl diisocyanate for the problem of poor stability of SBS-MA. Methylene diphenyl diisocyanate, according to the experimental findings, functioned as a phase compatibilizer between bitumenene and SBS, improving the composite modified phase stability of bitumen while decreasing its chemical softness and polarizability [6]. Mendona et al. addressed the problem of how to improve the elasticity of bitumen by proposing a lignin based MA. According to the testing results, the addition of 3% pine lignin and 9% eucalyptus lignin, respectively, produced bitumen with the best mechanical qualities. It can be concluded that lignin was an excellent alternative to synthetic elastomeric polymers [7]. To address the issue of how to enhance the high temperature (HT) and LT qualities as well as the water stability of bitumen, Li et al. presented an MA based on bamboo fiber. According to the experimental findings, bamboo fiber MA blends performed better in terms of HT, LT, and water stability when compared to SBS MA. When the fiber length was 7.25 mm and the content was 0.22%, the optimum performance of the bitumen was obtained [8]. Amini et al. proposed a composite MA based on titanium dioxide, aluminum trioxide and multiwall carbon nanotubes in response to the problem of how to improve the rutting and fatigue resistance of bitumen. The experimental results indicated that the above MA had higher viscosity and aging resistance, and its fatigue life was 1.7 times longer than that of ordinary bitumen [9]. Chen S et al. proposed to improve the performance of SBS modified bitumen by grinding molybdenum disulfide (MoS2) and polyphosphate (PPA) in cyclic oil and mechanically activating them to produce PPA modified MoS2 (OMS-PPA), which was then mixed with SBS modified bitumen. The results showed that compared with SA, the permeation temperature coefficient of SA-OMS decreased by 3.7%, and the permeation temperature of 1-SA-OMS-PPA decreased even more, by 7.1%. After short-term aging, the increase in carboxyl group generation was significantly reduced, and the rate of hardness change was also significantly reduced[10].

In summary, the current research on MA has been quite effective, and many different kinds of MA have been developed. However, most of the MAs are more focused on mechanical properties, and their freeze-thaw cycles (FTC) resistance is relatively neglected. In view of this, in order to improve the cyclic freeze-thaw resistance of bitumen and minimize the manufacturing cost of modified bitumen, the cyclic freeze-thaw performance of composite modified bitumen based on SBS and rubber powder was analyzed. Moreover, to study the performance of composite MA, the study also innovatively analyzes the rheological and LT properties of the MA from both macro- and fine-scale perspectives.

2 Methods and materials

2.1 Material and specimen preparation

Gram-refined bitumen was selected as the matrix bitumen (MaA) for the experiment. SBS modifier was 4303 star type. The rubber powder modifier is 40 mesh (380 um) rubber powder particles The optimal dosage of SBS modifier and rubber powder modifier was determined through experiments on the three major indicators of bitumen, dynamic shear and bending rheology in the early stage. The dosage of SBS modifier and rubber powder modifier is 3% and 20% of the mass of matrix bitumen respectively. SBS MA was prepared by blending SBS modifier in MaA. SBS composite crumb rubber (CCR) MA was prepared by blending SBS modifier and crumb rubber modifier in MaA. The coarse and fine aggregates used in the preparation of bitumen mixtures (AMs) were basalt with a ratio of 97%. The mineral powder was limestone with a ratio of 3% and fineness less than 0.075. The optimum oil/gravel ratios for the preparation of AMs with SBS bitumen and CCR bitumen were 5% and 6%, respectively. The so-called Oil Stone Ratio refers to the mass ratio of asphalt (oil content) to aggregate (stone content) in asphalt mixtures. It is an important parameter in the design of asphalt mixtures, which has a significant impact on the performance of asphalt mixtures.

In preparing the AM specimens, the AM was first pressed into 300mm*300mm*50mm rutted specimens using the wheel milling method. Then the rutted specimen was cut into 250mm*30mm*35mm beams. Moreover, a 4mm*2mm notch was cut in the middle position of the beamlet for subsequent tests.

2.2 Experimental design

2.2.1 Experimental design

Long-term aging (LTA) test of bitumen: 50g of SBS bitumen and CCR bitumen were each put into the sample tray, and then short-term aging was carried out using a rotating film oven, with the heating time and temperature of 5h and 163°C, respectively, and the rotating speed of 5.5 rad/min. Then the aged bitumen was put into the sample tray and made to have a thickness of 3.2mm. Then it was put into pressure aging vessel (PAV) for 20h for LTA simulation. The temperature of PAV was set at 100°C and the pressure was 2.1 MPa [11]. When the aging was completed, the bitumen samples were removed and placed in a stainless steel cylinder with heating and stirring to remove air bubbles inside the bitumen.

LTA test of the mixture: First, the AM was baked in an oven for four hours at 135°C after being equally spread out at a thickness of 21 kg/m2 in an enameled tray. Then the mixture was pressed into rutting specimens using the wheel milling method and cut into small beams. Then the heated mixture was pressed into a rutted specimen using the wheel milling method and cut into small beams. Then the obtained trabecular specimens were placed in a HT and LT alternating box heated under forced ventilation for 120h at a heating temperature of 85°C [12]. After heating, the door of the box was opened and the specimens were removed after cooling to room temperature.

Bitumen FTC test: Firstly, 50g of SBS bitumen and CCR bitumen were weighed and evenly spread in a stainless steel cylinder (the diameter of stainless steel cylinder is 122mm), and the thickness of the pavement was 3.2mm. Then, the stainless steel cylinder was injected with water and 8% salt solution until it was submerged in the bitumen. Then the stainless steel cylinder was sealed using cling film and placed in a HT and LT alternating chamber for freezing-thawing cycle. The freezing temperature was -20°C for 2h. The thawing temperature was 60°C for 4h. The number of FTC was 5, 10, 15, and 20.

FTC test: The specimens were first placed in water or salt solution (8%). Then the specimen was evacuated with a vacuum extractor until the vacuum level was 97.3 kPa, and immersed in the vacuum condition for 15 min. Then the atmospheric pressure was resumed and the immersion was continued for 1 h. Then the specimen was taken out and placed in a specimen box, and water or salt solution (8%) was injected into the box until the specimen was submerged. Then they were placed in a HT and LT alternating chamber for FTC [13]. The freezing temperature and time were -20°C and 8h, respectively. The melting temperature and time were 60°C and 16h, respectively. The number of cycles was 5, 10, 15 and 20.

2.2.2 Experimental design of rheological and physical-chemical properties

Bending creep strength test: The test equipment was a bending beam rheometer, and the test indexes were strength modulus and creep rate (CR). The test temperatures were -24℃, -18℃ and -12℃.

Infrared spectroscopic tests: Infrared tests were performed on different specimens using Fourier transform infrared spectrometer (FTIR). The number of scans and spectral acquisition intervals were 32 and 650 cm-1-4000 cm^{-1} with a resolution of 4 cm^{-1}, respectively.

Contact angle measurement test: First, the bitumen was heated until it was molten, and then it was put on a slide. After that, the slide was heated on a hot plate and left to flow naturally. The heating temperature was 120°C. After cooling, it was placed in a sealed container and set aside. Next, the basalt aggregate was cut into cubes with a side length of 1 cm and polished smooth. The polished basalt specimens were then placed in an oven for drying at 45°C for 6h [14]. After the basalt specimens cooled to room temperature, they were removed and placed in a sealed container for backup. Then the contact angle of the specimens was measured by dropping the liquid onto the specimens to be tested using the probe of the contact angle measuring instrument.

Atomic force microscopy test: For the test, the scanning mode of the AFM was

PeakForce QNM, the scanning frequency was 0.977Hz, the scanning range was 20mm*20um, and the probe was Bruker Rtespa-150.

2.2.3 Low temperature cracking property test

Constrained specimen temperature stress test: Firstly, epoxy resin adhesive was utilized to bond the ends of the AM beamlet specimen with the ends of the test system. After the epoxy resin adhesive solidified, the specimen was kept at 5°C for 6h. Then the specimen was cooled down and the thermometer stress change curve was measured until the specimen was fractured, with a cooling rate of 10°C/h.

Three-point bending test (TPBT): the specimen was placed flat in the bending test fixture to form a simply-supported beam, and the dynamic hydraulic servo universal testing machine was utilized to apply the load. The loading speed was 1mm/min, the test temperature was -12℃, and the acquisition frequency was 10Hz. It should be mentioned that the specimen must first be dyed with matte white paint throughout the collecting procedure in order to prevent specimen reflection. Moreover, a roller is used to make black spots on the surface of the specimen to ensure the accuracy of the acquisition.

2.2.4 Anti rutting test

Prepare rutting plate specimens using bitumen mixture and conduct rutting tests using the SYD-0719C-2 fully automatic rutting tester. Maintain constant wheel pressure and uniform walking speed during the experimental loading process. Place the rutting plate specimen together with the test mold onto the testing device, with the test wheel placed at the center of the specimen. The direction of travel of the test wheel should be consistent with the rolling direction, and the test time should be 1 hour. The test can be stopped when the rutting deformation reaches 25mm.

3 Results

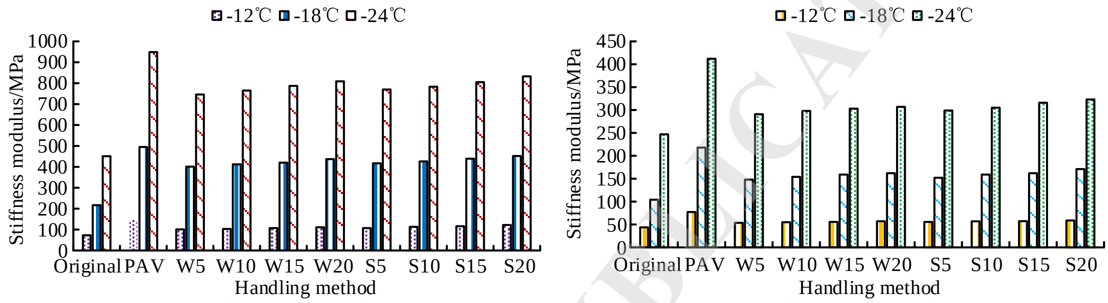
3.1 Low temperature rheological characterization of composite MA

To test the rheological properties of CCR bitumen, the study conducts flexural creep strength tests on aged, FTC and virgin MA and analyzed them using infrared spectroscopy. The basic properties of CCR bitumen are shown in Table 1.

Table 1 Basic properties of CCR bitumen

Item	Unit	Value
Needle penetration	dmm	52.5
Softening point	℃	228
Ductility	cm	85.7

As can be seen from Table 1, the penetration, softening point and elongation of CCR bitumen are 52.5dmm, 228℃ and 85.7cm respectively. Figure 1 displays the modulus of strength of MA at various temperatures.

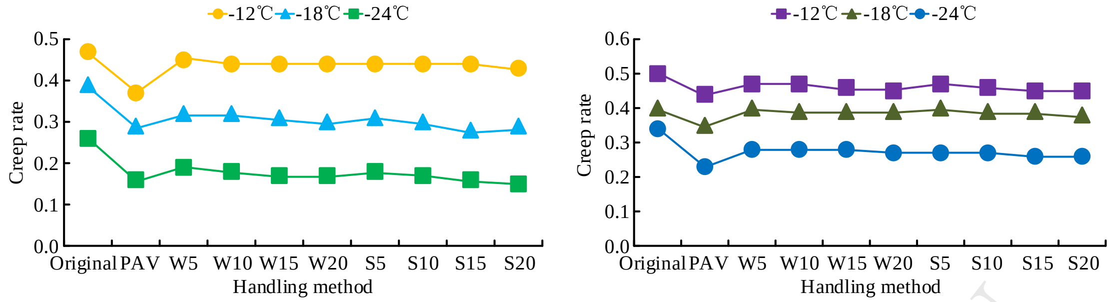


(a) The stiffness modulus of SBS asphalt (b) The stiffness modulus of CCR asphalt

Note: Wx and Sx represent x water FTC and x salt FTC, respectively.

Figure 1. Strength modulus of MA at different temperatures

In Figure 1(a), compared to the virgin SBS bitumen, the modulus of strength of SBS bitumen after LTA and water/salt FTC increased significantly and is inversely proportional to the temperature. Among them, the aged SBS bitumen had the largest modulus of strength. The modulus of strength is 145 MPa, 495 MPa, and 949 MPa at -12°C, -18°C, and -24°C, respectively. In Figure 1(b), the modulus of strength of the bitumen after both aging and FTC increased compared to the original CCR bitumen. Furthermore, as the temperature drops, the modulus of strength rises. Among them, the aged CRC bitumen at -24°C has the largest modulus of strength, which is 412 MPa. Under identical conditions, the modulus of strength of CCR bitumen is less than that of SBS bitumen. The aforementioned findings suggest that CCR bitumen has superior LT rheological characteristics in contrast to SBS bitumen. Figure 2 depicts the MA CR at various temperatures.



(a) The creep rate of SBS asphalt (b) The creep rate of CCR asphalt

Figure 2 CR of modified bitumen at different temperatures

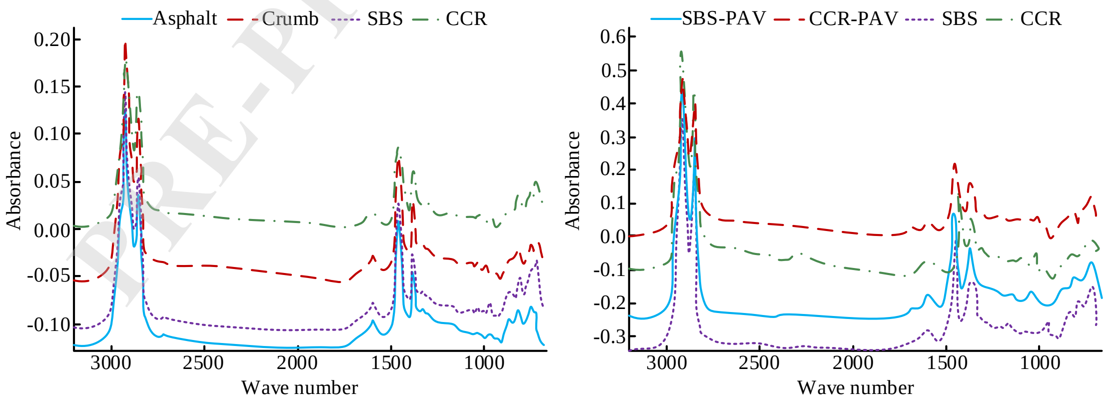
In Figure 2, the CR of the MA after aging and FTC are reduced compared to the original MA. The most significant reduction in the CR of aged bitumen is at least 10.9%. In addition, the CR of MA decreased with the decrease of temperature. However, comparing Figures 2(a) and 2(b), it can be observed that the change in the CR of CCR bitumen is relatively small compared to that of SBS bitumen. Taking the bitumen after aging treatment as an example, the CR of SBS bitumen and CCR bitumen is 0.37 and 0.44 respectively under the condition of -12 ℃. The above results show that CCR bitumen has better strain relaxation ability compared with SBS bitumen. The CR/strength modulus ratios of MA at different temperatures are displayed in Table 2.

Table 2 CR/stiffness modulus ratio (10^5/MPa)

bitumen type	Processing method	-12℃	-18℃	-24℃
SBS MA	Original	647.3	179.7	57.6
	PAV	257.4	58.6	16.9
	W5	441.5	79.8	25.5
	W10	429.2	77.7	23.5
	W15	411.4	73.8	21.6
	W20	393.1	68.6	21.0
	S5	414.2	74.3	23.4
	S10	389.6	70.4	21.7
	S15	379.5	63.8	19.9
	S20	355.1	64.2	18.0
CCR MA	Original	1134.9	384.6	133.6

PAV	571.6	160.6	55.8
W5	884.3	270.3	96.2
W10	849.2	253.2	94.0
W15	818.5	245.3	92.4
W20	786.2	240.7	87.9
S5	846.9	263.2	90.3
S10	810.4	245.3	88.5
S15	792.3	240.7	82.3
S20	761.7	222.2	80.5

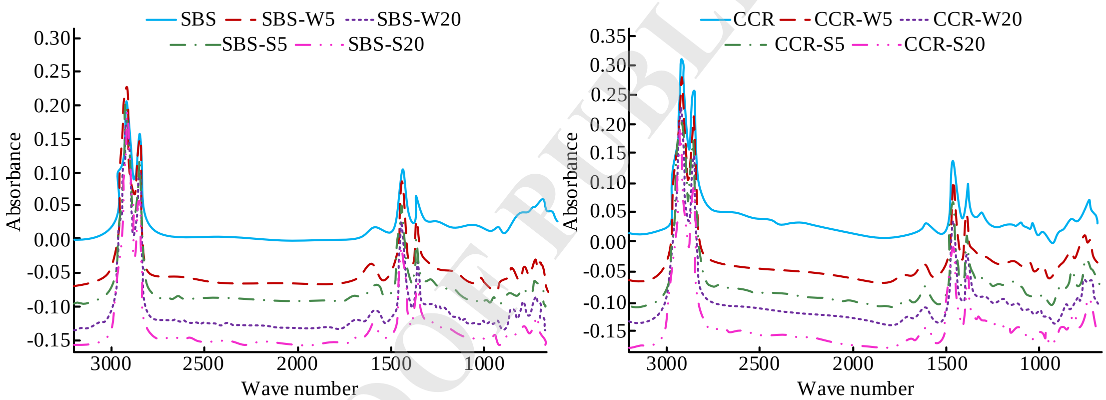
In Table 1, the CR/strength modulus ratios of both SBS bitumen and CCR bitumen are significantly reduced after aging and FTC. Taking the aging bitumen at -12℃ as an example, the CR/strength modulus ratios of the two are 257.4 and 571.6, which are reduced by 60.2% and 49.5%, respectively. Meanwhile, with the decrease in temperature and the increase in the FTC, the CR/strength modulus ratios of both SBS bitumen and CCR bitumen decreased. In addition, under the same conditions, the CR/strength modulus ratio of CCR bitumen is always higher than that of SBS bitumen. For example, at -18℃, the CR/strength modulus ratios of SBS bitumen and CCR bitumen after aging are 58.6 and 160.6, respectively. The above results demonstrate that CCR bitumen has excellent LT deformation capability compared with SBS bitumen. Figure 3 displays the infrared spectra of various MAs both before and after aging.



(a) Infrared spectra of asphalt samples (b) Infrared spectra of asphalt before and after aging

Figure 3 Infrared spectrum before and after aging of different modified bitumen

In Figure 3(a), the absorption peaks of MaA, crumb rubber MA, SBS bitumen and CCR bitumen are basically at the same position, i.e., at wave numbers 2918.2 cm^{-1} and 2849.5 cm^{-1}, in the functional group region. All the above absorption peaks are generated by the stretching vibration of methylene and its derivatives. Comprehensive analysis suggests that bitumen mainly contains alkanes, cycloalkanes and aromatic compounds. In Figure 3(b), after aging, the absorbance of both SBS bitumen and CCR bitumen is reduced compared with the original samples, in which the reduction of SBS bitumen absorbance is more significant. Among them, the aging SBS bitumen disappears at wave number 966.5, while the aging CCR bitumen wave peaks did not change significantly. It can be concluded that the polybutadiene and polystyrene of SBS bitumen are decomposed after aging, while there is no significant change in CCR bitumen. These results indicates that CCR bitumen has better anti-aging properties than SBS bitumen. Figure 4 displays the infrared spectra of SBS and CCR bitumen prior to and following FTC.



(a) SBS asphalt before and after freeze-thaw cycles

(b) CCR asphalt before and after freeze-thaw cycles

Figure 4 Infrared spectra of bitumen before and after cyclic FTC

In Figure 4(a), the absorption peaks at wave numbers 1599.7 and 1694.6 of SBS bitumen changed significantly after FTC. It displayed that the aromatic hydrocarbon components of SBS bitumen changed after FTC. Moreover, both the cycloalkanes and unsaturated chains are oxidized, resulting in water aging of the bitumen. In Figure 4(b), the infrared spectral changes of CCR bitumen after FTC are basically the same as those of SBS bitumen, but the degree of change is smaller. This indicates that compared with SBS bitumen, CCR bitumen has better freeze-thaw (FT) resistance. The functional group indices before and after FTC are shown in Figure 5.

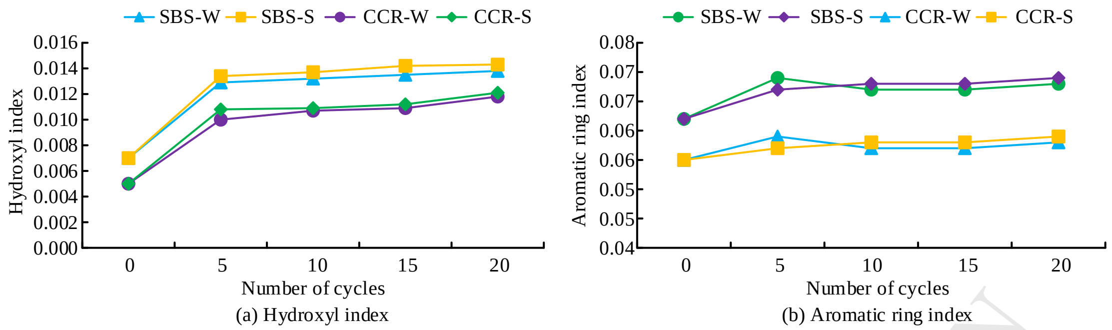


Figure 5 Functional group index before and after cyclic FTC

In Figure 5(a), the hydroxyl index of both SBS bitumen and CCR bitumen increased significantly after FTC. Among them, the hydroxyl index of SBS bitumen is basically above 0.013, while that of CCR bitumen is in the range of 0.010-0.012. It can be concluded that the hydroxyl functional group changes of CCR bitumen after FTC are small. In Figure 5(b), the cycloaromatic index of both SBS bitumen and CCR bitumen increases significantly after FTC. Among them, the cycloaromatic indices of both SBS bitumen are above 0.065, while the cycloaromatic indices of CCR bitumen are around 0.060. This reveals that FTC have less effect on the cycloaromatic functional groups of CCR bitumen. In order to investigate the mechanism of changes in the rheological properties of composite modified bitumen, the microstructure was analyzed using fluorescence microscopy, and the results are shown in Figure 6.

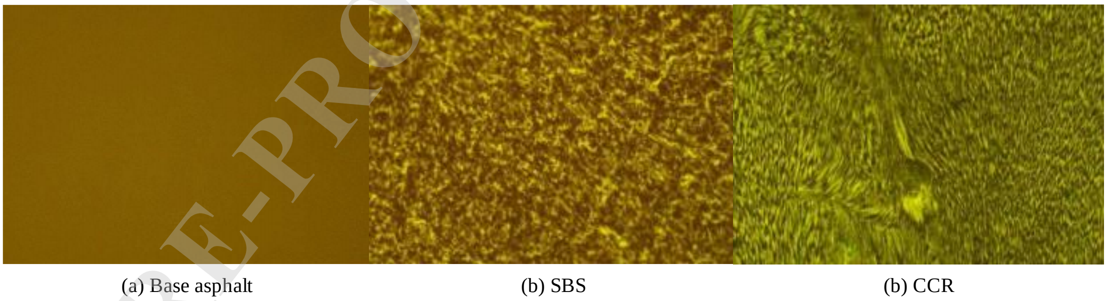


Figure 6 Fluorescence microscope test results

As shown in Figure 6, the matrix bitumen is a homogeneous phase. SBS has a dense network structure, and SBS particles absorb light oil and expand, rapidly expanding in volume and gradually expanding and splitting, forming a visible network structure that wraps bitumen in the grid. However, due to the poor stability of the above structure, the modification effect of SBS bitumen is relatively average. In CCR bitumen, rubber powder and SBS are dispersed in the bitumen, and SBS particles serve as anchor points interwoven with the flocculated rubber powder. The two form a relatively stable spatial structure dispersed in bitumen through coupling, thereby improving the rheological properties of bitumen.

3.2 Adhesion characterization of composite MA

To investigate the adhesion properties of MA, the study is conducted to test the contact angle and atomic force to understand the adhesion and Derjaguin-Muller-Toporov (DMT) modulus of bitumen. Figure 7 displays the bitumen contact angle test results.

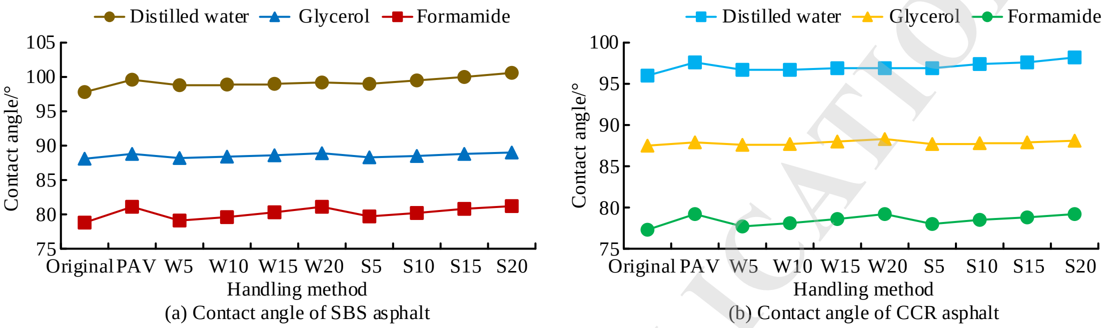


Figure 7 Test results of bitumen contact angle

In Figure 7(a), the contact angle of SBS bitumen after both aging and FTC is higher than that of the original sample. In the case of distilled water, for example, its contact angles with the original and aged samples are 97.8° and 99.6°, respectively. In Figure 7 (b), the contact angles of CCR bitumen are all higher than the original samples. Similarly in the case of distilled water, its contact angles with the original and aged samples are 96.0° and 97.6°, respectively. By comparing SBS MA and CCR MA, it is possible to determine that, under identical circumstances, SBS bitumen has a wider contact angle than CCR bitumen. With distilled water, the contact angles of SBS and CCR bitumen at this time are 98.9° and 96.7°, respectively, using water FTC ten times as an example. According to the contact angle can be calculated on the viscosity aggregation work of bitumen. Figure 8 presents the findings.

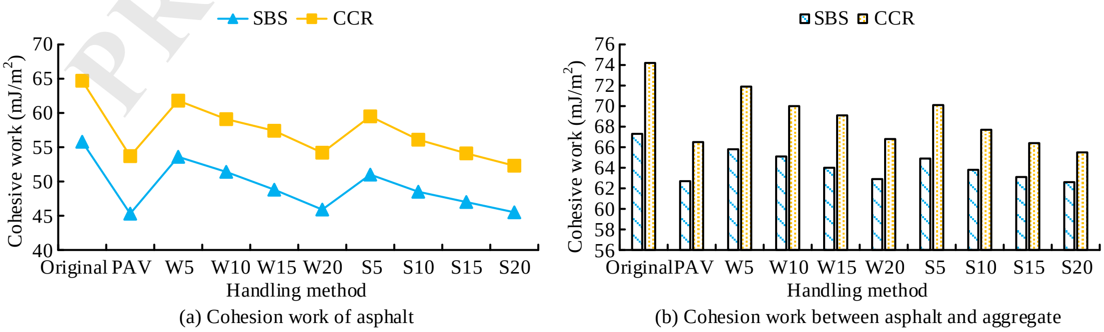


Figure 8 Cohesion work of bitumen

In Figure 8 (a), the work of cohesion is higher for CCR bitumen under the same conditions compared to SSB bitumen. For example, the cohesive polymerization function of SSB bitumen and CCR bitumen after FTC for 5 times is 53.6 mJ/m^2 and 61.8 mJ/m^2, respectively. In Figure 8 (b), the cohesive polymerization function between CCR bitumen and aggregate is higher than that of SSB bitumen under the same conditions. Taking the aged bitumen as an example, the work of adhesion between SSB bitumen and CCR bitumen and aggregate is 62.7mJ/m^2 and 66.5mJ/m^2 , respectively. The microscopic adhesion and DMT modulus of the bitumen are shown in Figure 9.

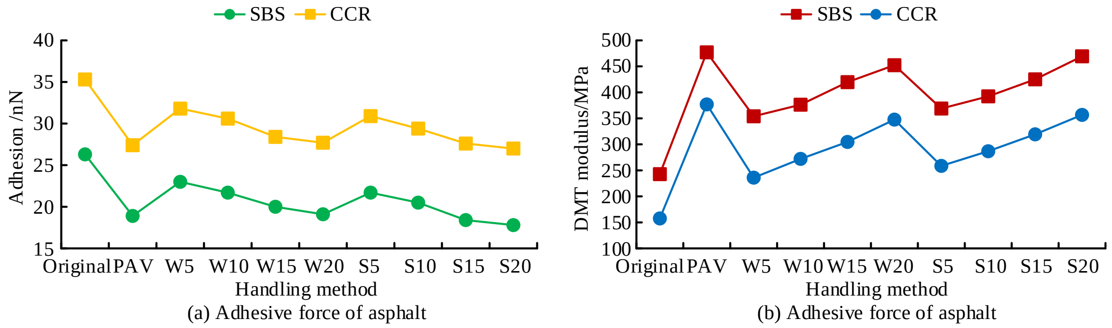
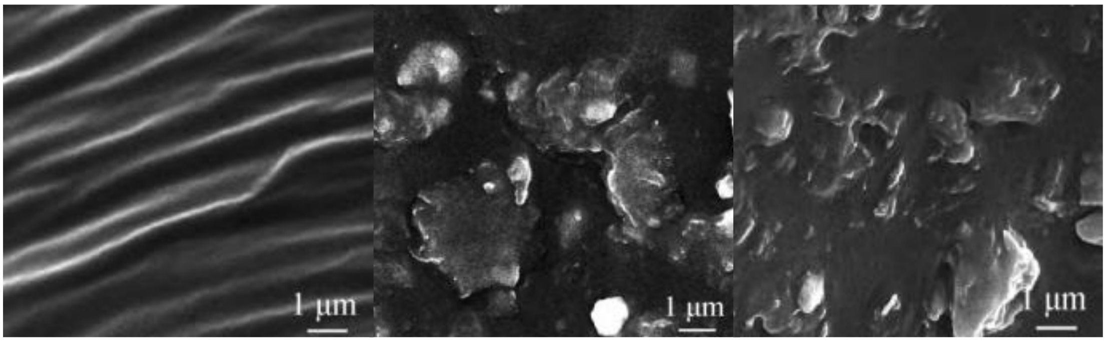


Figure 9 Microscopic adhesion force and DMT modulus of bitumen

In Figure 9 (a), the adhesion force of bitumen is significantly reduced after treatment with either aging or FTC. In addition, the adhesion force of CCR bitumen is greater under the same conditions. As an example, the adhesion force of SBS bitumen and CCR bitumen after aging is 18.9 nN and 27.4 nN, respectively. Figure 9 (b), the DMT modulus of bitumen is significantly reduced after treatment by aging or FTC. Moreover, the DMT modulus of CCR bitumen is smaller under the same conditions. For example, the DMT modulus of SBS bitumen and CCR bitumen is 354.0 MPa and 236.0 MPa for five times of water FT, respectively. The above results indicate that CCR bitumen has better cracking, aging and FT resistance. In order to investigate the mechanism of changes in CCR bitumen performance, the phase structure of modified bitumen was analyzed using scanning electron microscopy, and the results are shown in Figure 10.



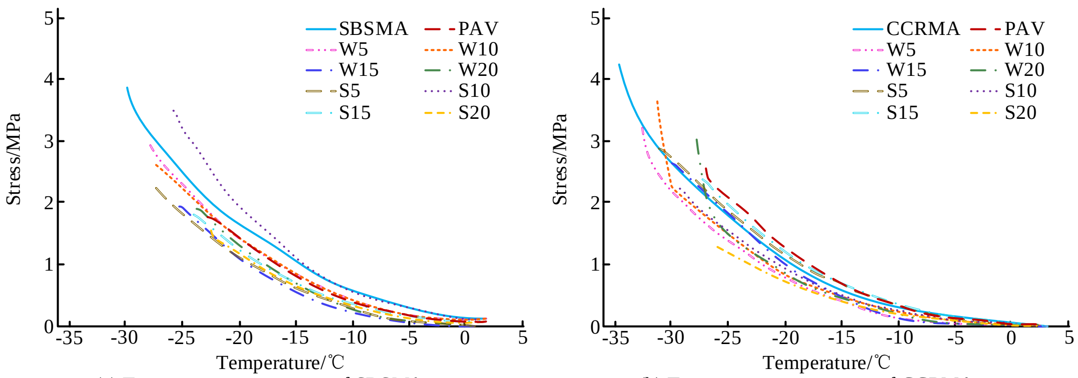
(a) Base asphalt (b) SBS (c) CCR

Figure 10 Scanning Electron Microscope Photo

As shown in Figure 10, the surface of the matrix bitumen is smooth and free of impurities, with a linear morphology that is close to a homogeneous structure. In SBS modified bitumen, the SBS modifier is in a dispersed phase, but due to the difficulty in forming a stable structural system between SBS particles and bitumen, the modification effect is relatively average. In CCR modified bitumen, the particle distribution of modifier is more dense, and a thicker gel like substance is formed at the interface, which indicates that the rubber powder and SBS have sufficient vulcanization reaction and swelling reaction in bitumen, enhancing the tensile deformation resistance and elastic recovery ability of bitumen under external force.

3.3 Low temperature cracking characterization of composite MA mixes

The study used both TPBTs and constrained specimen temperature stress tests to evaluate the LT cracking properties of MA mixes. The results of the restrained specimen temperature stress test are shown in Figure 11.



(a) Temperature stress curve of SBSMA (b) Temperature stress curve of CCRMA

Figure 11 Results of temperature stress test on restrained specimens

In Figure 11 (a), the freeze-off temperatures of AMs after aging and FTC are significantly higher compared to the original SBS AMs. The FT temperatures of SBS MA mixture (SBSMA), SBSMA-PAV and SBSMA-W5 are -30.0°C, -22.5°C and -27.7°C, respectively. In Figure 11 (b), the freeze-off temperatures of CCR AMs are also significantly increased after aging and FTC. The FT temperatures of CCR MA mixture (CCRMA), CCRMA-PAV and CCRMA-W5 are -34.3°C, -27.1°C and -32.5°C, respectively, which are lower than those of SBS AM. The aforementioned findings suggest that CCR bitumen resists LT cracking well. Figure 12 displays the findings of the beams' TPBT.

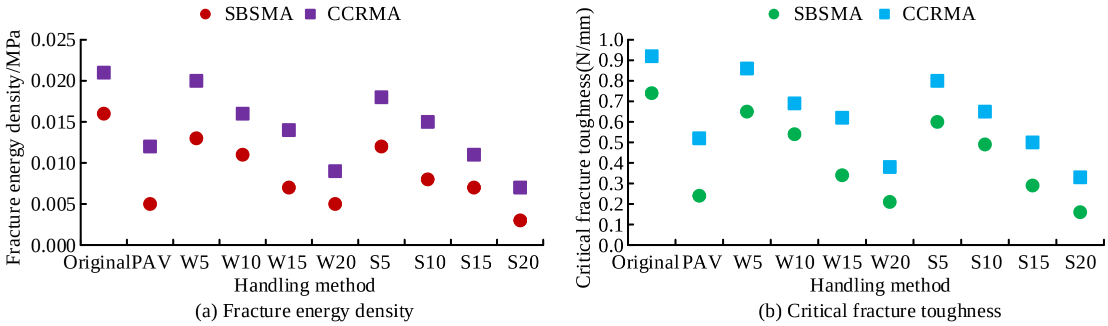


Figure 12 Three point bending test results of small beam

In Figure 12 (a), the fracture energy densities (FEDs) of AMs are significantly reduced after both aging and FTC. However, the FED of CCR AMs is higher than that of SBS AMs. For example, the FEDs of SBSMA-PAV and CCR-PAV are 00.005 MPa and 0.012 MPa, respectively. In Figure 12 (b), the critical fracture toughness (CFT) of AMs are significantly reduced after both aging and FTC. However, the CFT of CCR AMs is higher under the same conditions. For example, the CFT of SBSMA-PAV and CCR-PAV are 0.24N/mm and 0.52N/mm, respectively. The above results indicate that CCR bitumen has better toughness and cracking resistance. The study statistically analyzes the FED and CFT in order to understand the sensitivity of the FED and CFT to each of the influencing factors. The sensitivities of the influencing factors are shown in Table 3.

Table 3 Sensitivity of influencing factors

Influence factor	Index	Coefficient of variation/%
Preburning	Fracture energy density	0.42
	Critical fracture toughness	0.39
FTC	Fracture energy density	0.37
	Critical fracture toughness	0.36

Freeze thaw type	Fracture energy density	0.09
	Critical fracture toughness	0.07
Types of bitumen	Fracture energy density	0.27
	Critical fracture toughness	0.22

In Table 2, both FED and CFT are the most sensitive to aging, with coefficients of variation (COV) of 0.42 and 0.39, respectively. The second is more sensitive to the FT times, with COV of 0.37 and 0.36, respectively. In addition, both FED and CFT are the least sensitive to freeze thaw type, with COV of 0.09 and 0.07, respectively. The results of the rutting test are shown in Figure 13.

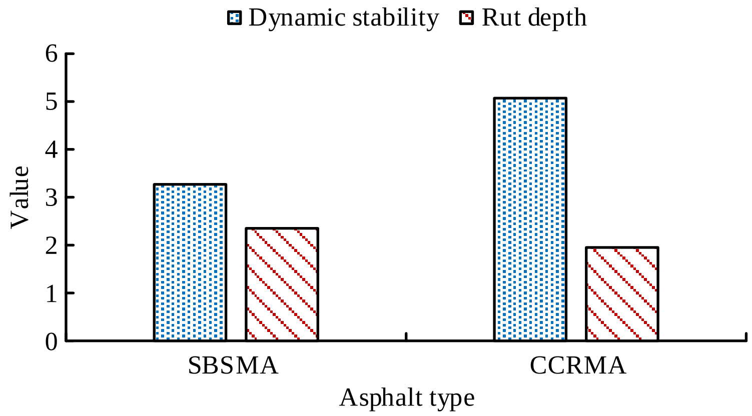


Figure 13 Track test results

As shown in Figure 13, compared to SBSMA, CCRMA has greater dynamic stability and smaller rut depth. The dynamic stability of SBSMA and CCRMA is 3.27 times/mm and 5.07 times/mm, respectively, and the rut depth is 2.35mm and 1.94mm, respectively. The above results indicate that the rubber powder composite SBS can effectively improve the deformation resistance of bitumen materials. In terms of economic benefits, although SBS modified bitumen has good road performance, its high cost limits its large-scale application. CCR composite modified bitumen can reduce the amount of SBS modifier while ensuring the performance of bitumen by adding rubber powder, thus saving the production cost of bitumen.

4 Discussion

A composite MA-CCR bitumen based on crumb rubber and SBS modifier was created, and its rheological characteristics and LT cracking capabilities were examined in order to extend the life of AP and lower the likelihood of its cracking in an LT environment. The experimental results indicated that both SBS bitumen and CCR bitumen exhibited a significant growth in the modulus of strength after aging and FTC. Furthermore, as the temperature dropped, the bitumen's modulus of strength rose. However, compared to SBS bitumen, the modulus of strength of CCR bitumen under the same conditions was smaller. Taking the aged bitumen as an example, the modulus of strength of SBS bitumen and CCR bitumen were 949 MPa and 412 MPa, respectively, at -24°C. Furthermore, the change in the CR of CCR bitumen was negligible in comparison to SBS bitumen. Using aged bitumen as an example, the CR values at -12°C were 0.37 and 0.44 for SBS and CCR bitumen, respectively. In comparison to SBS bitumen, it may be said that CCR bitumen has a higher capability for strain relaxation. Compared to the MA based on nano ZnO and SBS proposed by Li X et al [15], the MA with CCR exhibited better FTC resistance and creep performance, and the creep performance of the MA based on nano ZnO and SBS was improved by about 5% compared to that of the SBS MA. The creep performance of CCR-MA was improved by about 19% compared with SBS bitumen. This was due to the mixing and solubilization between SBS modifier, crumb rubber modifier and bitumen, which resulted in physical cross-linking structure [16-17]. An investigation of the infrared spectra of various bitumens was carried out in order to better understand the mechanism underlying the changes in the properties of MA. The outcomes indicated that SBS bitumen and CCR bitumen mainly contained alkanes, cycloalkanes and aromatic compounds. After aging, the absorbance of both SBS bitumen and CCR bitumen decreased compared with the original samples, among which, the decrease of SBS bitumen absorbance was more significant. Among them, the wave peak of aged SBS bitumen disappeared at wave number 966.5, while the wave peak of aged CCR bitumen did not change significantly. It can be concluded that the polybutadiene and polystyrene of aged SBS bitumen were decomposed. This led to an increase in the content of hydroxyl, aromatic ring and sulfinyl group, which weakened its LT performance, while there was no significant change in CCR bitumen. After FTC, the aromatic hydrocarbon fractions of both SBS and CCR bitumen changed. Moreover, both the cycloalkanes and unsaturated chains were oxidized, which caused water aging of the bitumen, but the degree of water aging of CCR bitumen was smaller [18]. In addition, fluorescence microscopy detection results showed that compared to SBS modified bitumen, in CCR modified bitumen, SBS particles serve as anchor points interwoven with flocculated rubber powder, and the two can form a relatively stable spatial structure dispersed in bitumen through coupling, thereby improving the rheological properties of bitumen. At the same time, the scanning electron microscope showed that in CCR modified bitumen, the particle distribution of modifier was denser, and a thicker gel like material was formed at the interface. It can be seen that rubber powder and SBS have sufficient vulcanization and swelling reactions in bitumen, enhancing the tensile deformation resistance and elastic recovery ability of bitumen under external forces.

To investigate the adhesion properties of the MA and the LT characteristics of its mixtures, the study conducted contact angle and atomic force tests, as well as constrained specimen temperature stress tests and TPBTs. The findings displayed that the cohesion function of the MA was reduced after both aging and FTC, but the cohesion function of CCR bitumen under the same conditions was higher compared to SSB bitumen. For example, the cohesive polymerization function of SSB bitumen and CCR bitumen was 53.6 mJ/m^2 and 61.8 mJ/m^2 after 5 water FTC, respectively. Meanwhile, the DMT modulus of bitumen was significantly reduced after aging or FTC treatment. Moreover, the DMT modulus of CCR bitumen was smaller under the same conditions. Taking water freezing and thawing 5 times as an example, the DMT modulus of SBS bitumen and CCR bitumen were 354.0 MPa and 236.0 MPa, respectively. This was because aging and FTC would make the viscous component of bitumen change into the elastic component, which would lead to the decrease of deformation ability of bitumen. While SBS and crumb rubber in CCR bitumen would weaken the effect of temperature, water salt and other factors on the viscous component, so CCR bitumen had better deformation capacity [19-20]. Through comparison with Yang Y et al. [21], it is possible to observe that following FTC, there was a noticeable surface cracking phenomenon and a notable increase in the width and number of main cracks in the bitumen cold recycled mixtures. In addition, the study's findings were supported by the progressive decrease in the fatigue number of the full-field maximum horizontal strain and the notable increase in the average volume of air voids and intermediate voids. Meanwhile, the results of Wang N et al [22] also demonstrated that after FTC, the mechanical properties of AMs were greatly reduced and the key particles in the AM structure were significantly displaced. The FED and CFT of the AMs decreased significantly after aging and FTC, while the freeze-fracture temperature increased significantly. This was due to the fact that aging increased the polar components in the bitumen, making it more prone to fracture. Meanwhile, the freezing pressure generated by freezing and thawing increased the porosity of AMs, leading to the entry of liquids into the interior of the pores. Additionally, while thawing, positive pressure occurred, which consequently caused the AM's strength to decrease. When it came to LT cracking, CCR AMs outperformed SBS AMs. Its superior deformation ability to release stresses in the form of deformation and the higher energy required for cracking were the causes of this.

5 Conclusion

The study suggested a composite MA based on SBS and crumb rubber to improve the frost resistance of APs, and it assessed the MA's performance. The outcomes showed that after LTA and water/salt FTC were decreased, the CR of MA was decreased. Among them, the CR of aged bitumen was reduced most significantly, by at least 10.9%. In addition, the CR of MA decreased with decreasing temperature. However, compared with SBS bitumen, the change in the CR of CCR bitumen was relatively small. Taking the bitumen after aging treatment as an example, the CR of SBS bitumen and CCR bitumen was 0.37 and 0.44, respectively, at -12°C. In addition, the freeze-off temperatures of AMs after aging and FTC increased significantly, but the freeze-off temperature of CCR AMs was always higher than that of SBS AMs. For example, the freeze-off temperatures of SBSMA-W5 and CCRMA-W5 were -27.7°C and -32.5°C, respectively. These results indicate that CCR bitumen has good rheological properties and LT cracking resistance. CCR composite modified bitumen can be used for highway pavement laying to improve the durability and service life of the pavement due to its excellent high temperature stability and low temperature crack resistance. At the same time, the composite modified bitumen can also be used for waterproof and anti-corrosion coating of breakwaters and piers to resist the erosion of seawater. The current study only analyzed the performance of CCR bitumen with a single SBS and rubber powder content, which limits the comprehensiveness of the research results. Future research will expand to CCR bitumen with different doping levels, systematically analyzing the effects of different proportions of rubber powder and SBS on bitumen performance to determine the optimal mixing ratio. This will help optimize the mechanical properties and durability of bitumen, while reducing costs and providing scientific basis for the widespread application of bitumen pavement.

Declaration of Conflicting Interest

The Author(s) declare(s) that there are no known competing financial interests or personal relationships that could influence the work reported in this paper

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