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Research Article

Effect of Superplasticizer and Wetting Agent on Volumetric and Mechanical Properties of Cold Recycled Mixture with Asphalt Emulsion

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Cold recycled mixture with asphalt emulsion (CRME) has gained more appreciation due to its environmental and economical advantages. Surfactant greatly affects the interaction between asphalt emulsion and cement, which can greatly affect the volumetric and mechanical properties of CRME. If the surfactant can greatly improve the volumetric and mechanical properties of CRME, that could be of great attraction. In this study, a polycarboxylate-based superplasticizer and wetting agent (DN500, polymers containing high-pigment groups) were employed to improve the volumetric and mechanical properties of CRME. Results indicate that the addition of superplasticizer and DN500 can reduce the void content of CRME and increase the indirect tensile strength (ITS) and stiffness modulus as well as critical strain energy density (CSED) of CRME. Besides, the failure strain of CRME is also increased by adding superplasticizer and DN500. This phenomenon is probably due to that superplasticizer can decrease the viscosity of cement asphalt emulsion paste (CAEP) and help to form a better asphalt film, and DN500 can moderately decrease the viscosity of CAEP and increase the wetting ability of asphalt emulsion as a wetting agent. CRME with superplasticizer has the best mechanical properties among all CRMEs. Compared to reference CRME, the ITS, stiffness modulus, and CSED of CRME with superplasticizer can increase by 33.7%, 8.0%, and 17.5% at the optimum water content, respectively. It is recommended to improve the volumetric and mechanical properties of CRME by adding superplasticizer.

1. Introduction

Asphalt pavement tends to deteriorate gradually during its service life due to traffic load and environment action [1]. As a result, many reclaimed asphalt pavements (RAPs) are produced every year. To minimize nonrenewable fossil fuels and mine resource, recycling of RAP attracts more attention in these years [1, 2]. Nowadays, recycling of RAP has two methods: cold recycling and hot recycling [1]. In cold recycling method, the RAP is first milled and then mixed with asphalt emulsion, water, virgin aggregates, and active additives, such as cement and mineral powder. The mixture is called as the cold recycled mixture with asphalt emulsion (CRME). Generally, virgin aggregates should be added in order to meet to grading criteria [3, 4]. Compared with the hot recycling, the mixing, laydown, and compaction of CRME can be carried out at the ambient temperature because of the low viscosity of asphalt emulsion. This is beneficial to extend the construction season and construction time. Besides, cold recycling technology (CRT) can also greatly reduce the emission of harmful gases due to no heating required during production [5, 6]. Moreover, CRT can maximize the utilization rate of RAP which can be higher than 70%. It has been proven to be a technically reliable, environmentally friendly, cost-effective method of strengthening and maintaining a wide range of aged asphalt pavements in different countries [7].

Although the CRT has been widely used in pavement rehabilitation in the world due to its pronounced advantages, there are still some serious challenges in the future application. CRME is normally used in the base and sub-base layers because of its relatively weaker mechanical properties compared to the hot recycled mixture [8]. For instance, the indirect tensile strength (ITS) of CRME is much lower than that of the conventional hot mixture. Pavement scholars and engineers have been trying to use CRME as traditional asphalt layer material in recent years. Therefore, the volumetric and mechanical properties of CRME should be further improved to achieve this ambitious goal.

Many researchers focused on the ITS of CRME in both laboratory and filed pavement. Previous studies indicated that the cement could accelerate the breaking of asphalt emulsion and the cement hydration products could enhance the hardness of cement asphalt emulsion paste (CAEP), which increased the ITS of CRME [5, 7, 9, 10]. However, the enhancement effect of cement on CRME is still limited. Besides, the high cement content can decrease the ductility of CRME, thus increasing the risk of cracking. Therefore, the upper cement content in CRME is usually limited to 2%. In addition to the low ITS, some studies showed that the use of CRME ordinarily came out with some problems such as the high void content, stripping, and long curing time [7]. Some voids are formed due to water evaporation during curing so that the void content in the hardened state is very high [11]. Because of the high void content, a large amount of water can easily permeate the interior of the CRME specimen, which affects the adhesive ability of the asphalt emulsion binder and leads to aggregate stripping. It is known that the cement hydration degree and breaking of asphalt emulsion affect the strength of CRME to a great extent [2]. However, the cement hydration and emulsion breaking processes take a long time, so the CRME needs long curing time to achieve the desirable strength. In short, there is a growing need to improve the mechanical properties of CRME to promote the use of RAP [12].

According to the strength theory of the asphalt mixture, the strength of the mixture closely depends on the cohesive force of the asphalt binder and the internal friction resistance provided by aggregate skeleton. Cement can promote cement hydration and breaking of asphalt emulsion to enhance its cohesive force, thus improving the mechanical properties of the asphalt emulsion mixture. However, the high void content reduces the internal friction resistance of aggregate skeleton, so the mechanical properties are also decreased. Factors influencing the volumetric and mechanical properties of CRME were intensively investigated in the past, such as the gradation types, asphalt emulsion content, the additional water content, the cement content and cement types, and filler types [3, 7, 8, 10, 13–20]. These studies are all very meaningful to optimally design the mechanical properties of CRME.

To the best of our knowledge, few studies were conducted to control the interaction between asphalt emulsion and cement for improving the physical and mechanical properties of CRME, although controlling such interaction is believed to be very important. In the field of grouting cement asphalt emulsion mortar in high-speed railway, the interaction between asphalt emulsion and cement was intensively studied [21–26]. Results indicated that superplasticizer can greatly improve the demulsifying behavior of asphalt emulsion and the rheological properties of fresh cement asphalt emulsion paste (CAEP) [21, 27]. Therefore, the addition of superplasticizer may improve the mechanical properties of CRME. Besides, the mechanical properties of CRME are closely related to whether the CAEP can be well coated on the aggregate surface. It is well known that the wetting agent can reduce the contact angle of aqueous solution. Therefore, it is possible to improve the mechanical and volumetric properties of CRME by adding the superplasticizer and wetting agent.

Based on the above consideration, superplasticizer and wetting agent were added into CRME to improve its mechanical and volumetric properties. The mechanical and volumetric properties of CRME with superplasticizer and wetting agent at different additional water contents are discussed in this paper. Besides, the action mechanism of the wetting agent and superplasticizer is discussed by rheology test. To the best of our knowledge, it is a very meaningful work to improve the mechanical and volumetric properties of CRME.

2. Experimental Program

2.1. Material and Specimen Preparation. CRME was composed of cationic slow-setting asphalt emulsion, basalt aggregate, RAP, Portland ordinary cement P.O 42.5, and mineral powder. All these materials were obtained from the market. The properties of asphalt emulsion are listed in Table 1 according to the Chinese standard [28]. The cement and mineral powder composition are listed in Tables 2 and 3, respectively. The RAP was obtained from one expressway in Liaoning province in China. Through sieving tests, it was found that the gradation of RAP could not meet the required specification of the Chinese standard [29]. Thus, new aggregates were added to satisfy the gradation requirements. The amounts of new aggregates were 20% by the weight of dry mixture (aggregates and fillers). A uniform dense aggregate gradation for AC-13 was used in this study according to Chinese Technical Specifications [29]. Figure 1 presents the gradation of RAP materials, mix blends, and specification limits. The total amount of fillers (including cement and mineral powder) was 6% by the weight of dry mixture, in which cement accounts for 2% and mineral powder accounts for 4%. The CRMEs are prepared by the following procedure which is shown in Figure 2. Long mixing time can well ensure the uniformity of the mixture. However, the mixing time of asphalt emulsion should be not more than 60 s to avoid the breaking of asphalt emulsion according to the Chinese standard [29]. No significant breaking phenomenon was observed when asphalt emulsion was mixed for 60 s. Thus, the mixing time of every procedure in Figure 2 was chosen as 60 s.

Table 1: Properties of asphalt emulsion.

Test of emulsion	Value	Test on residue from distillation	Value
Mean particle size (μm)	1.52	Residual content (%)	63.4
Residue on sieve 1.18 mm (%)	0	Penetration (25°C, 0.1 mm)	55.1
Storage stability (1 d, 25°C, %)	0.02	Softening point (R & B, °C)	48.8
Storage stability (5 d, 25°C, %)	0.6	Ductility (25°C, mm)	84
Mixing stability with cement, residual (%)	0.75		

Table 2: Chemical components of P.O 42.5 cement.

Chemical composition	CaO	SiO_2	Al_2O_3	MgO	SO_3	Fe_2O_3	K_2O_3	TiO_2	Na_2O
Percentage (%, by weight)	62.13	23.45	5.24	2.08	2.05	3.39	0.63	0.07	0.77

Table 3: Mineral components of mineral powder.

Mineral composition	C_3S	C_2S	C_3A	C_4AF
Percentage (%, by weight)	46.52	29.57	9.02	8.78

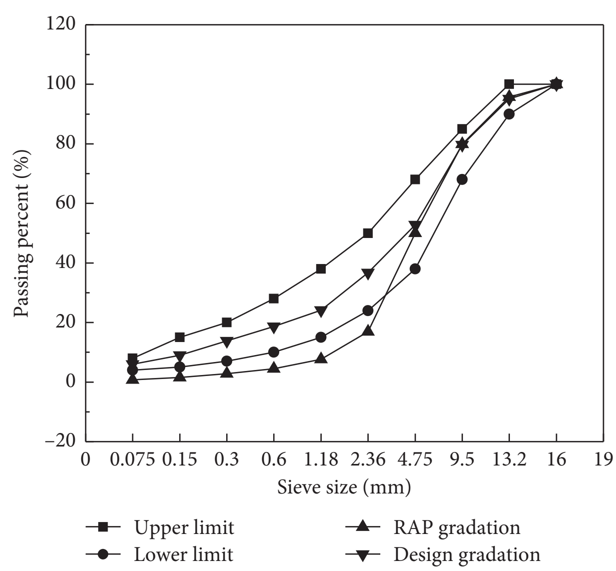

Figure 1: Gradation of CRME.

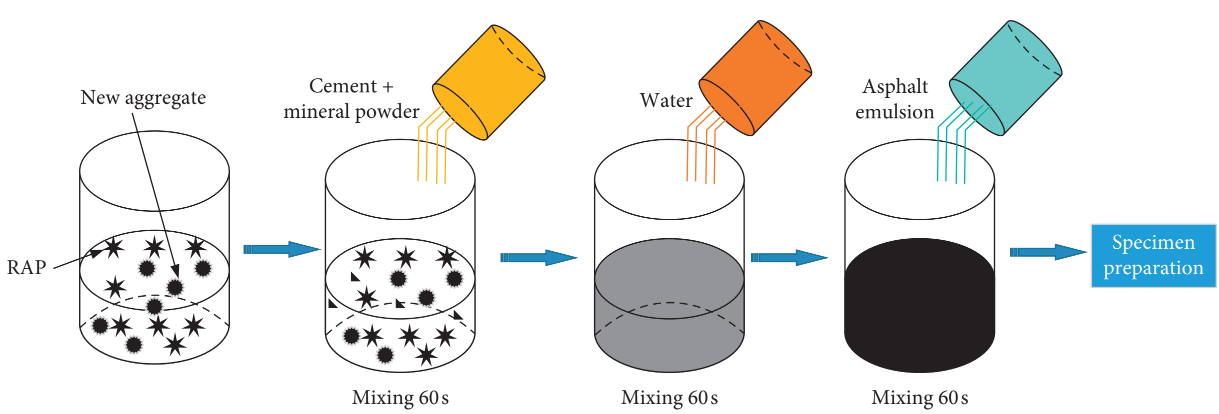

Figure 2: Preparation process of the CRME.

There are several methods to determine the optimum asphalt emulsion and the optimum additional water content. However, there is no universally accepted mix design for CRME. In this study, the specimens were firstly prepared with 3% of the asphalt emulsion content (asphalt emulsion to all aggregate ratio by weight). The additional water content was added to the mixture at percentages ranging from 2% to 6% by weight of the total dry mixture at 1% increments. Four specimens were prepared for one mixture. RAP and virgin aggregates were dried in the oven before the experiment. The asphalt emulsion mixture was mixed by the automatic mixing machine for the asphalt mixture and then compacted by applying 75 blows per side with the Marshall hammer. After compaction, the specimens were firstly kept for 24 h at ambient temperature in the molds to finish an initial curing, and then they are extruded and cured in the oven for 3 days at a temperature of 50°C [18]. The initial curing could ensure enough strength to extrude from the molds and the following 3 days curing was to accelerate asphalt emulsion breaking process and cement hydration process to quickly achieve the desirable strength. The optimum additional water content was determined at 3.5% by the weight of dry mixture by using the ITS, void content, and the maximum specific gravity. After obtaining the optimum additional water content, a variable asphalt emulsion content from 2.5% to 5% was used to prepare specimens. The optimum asphalt emulsion content was determined at 3.7% by the same method as the optimum additional water content.

In this study, there are two surfactants used in the CRME. One is polycarboxylic acid-based superplasticizer and the other is wetting agent (DN500, polymers containing high-pigment groups) whose function is to increase the contact angle of liquid (the additional water and asphalt emulsion). In order to determine the optimal dosage of surfactants, different superplasticizers and DN500 dosages were studied, with results listed in Table 4. According to Table 4, the optimum superplasticizer and DN500 dosages are 2% of the weight of cement and 0.5% of total water, respectively. Therefore, reference CRME, CRME with 2% of superplasticizer, and CRME with 0.5% of DN500 were investigated in this study. Meanwhile, the paper studied the experiment about CRME with superplasticizer and DN500, but results showed that the ITS of CRME with superplasticizer (0.95 MPa) was slightly higher than that of CRME with superplasticizer and DN500 (0.86 MPa). Thus, superplasticizer and DN500 were investigated alone in this study. Actually, 0.5% of DN500 in water was recommended by the manufacturer because water can have the best wetting ability at this content. Besides, the optimum superplasticizer content in CRME is higher than that in pure cement paste (normally 1%) perhaps because cement particles only account for 2% of the dry materials in CRME and other solids can also adsorb some superplasticizers. The wetting agent was divided into two parts to be added into the mixture. The first part which accounts for 3/4 was added into asphalt emulsion, and the rest part was added into additional water. In order to study the effect of adding superplasticizer and wetting agent in different additional water contents, the effect of additional water content ranging from 1% to 5% was investigated in CRME with superplasticizer and wetting agent. It is difficult to fabricate the Marshall specimens with 1% of additional water content for CRME without superplasticizer and wetting agent due to too dry of mixture to be compacted. Therefore, the additional water content ranging from 2% to 6% was tested for reference CRME.

Table 4: Effect of individual addition of different dosages of superplasticizer and DN500 on the ITS of CRME.

Dosages of SP (%)	ITS (MPa)	Dosages of DN500 (%)	ITS (MPa)
0	0.68	0	0.68
1	0.82	0.1	0.70
2	0.95	0.3	0.71
3	0.84	0.5	0.83
4	0.80	0.8	0.82

2.2. Testing Program

2.2.1. Void Content Test. The void content of CRME is calculated according to the following equation [28]:

$$VV = \left(1 - \frac{\rho_s}{\rho_t}\right) \times 100\%, \tag{1}$$

where ρ_s is the apparent specific gravity of the mixture and ρ_t is the maximum specific gravity of the mixture. Since the maximum specific gravity of CRME changes with curing time due to water evaporation, the final void content of CRME was studied in this paper. The apparent specific gravity of CRME can be measured by the surface-dry condition method after curing. According to the Chinese standard [28], the maximum specific gravity of CRME can be calculated by

$$\rho_t = \frac{100 + P_a}{P_1/\gamma_1 + P_2/\gamma_2 + \cdots + P_n/\gamma_n + P_a/\gamma_a} \times \rho_w, \tag{2}$$

where P_a is the asphalt aggregate ratio; $P_1, P_2, \ldots, P_n$ are the blending percentage of aggregate of each grade (the aggregate proportion of each grade is 1); $\gamma_1, \gamma_2, \ldots, \gamma_n$ are the specific gravity of aggregate of each grade; γ_a is the specific gravity of bitumen; and ρ_w is the specific gravity of water.

2.2.2. Indirect Tensile Strength (ITS) Test. The ITS test usually determines tensile properties of the asphalt mixture, which can reflect the cracking properties of asphalt pavement [30]. The ITS of CRME is calculated by using the following equation [28]:

$$\text{ITS} = \frac{2F_{\max}}{\pi d h}, \tag{3}$$

where ITS is the indirect tensile strength of the specimen; $F_{\max}$ is the applied load at failure; h is the thickness of the specimen; and d is the diameter of the specimen. The specimens were loaded at a deformation rate of 50 mm/min and at a temperature of 15°C.

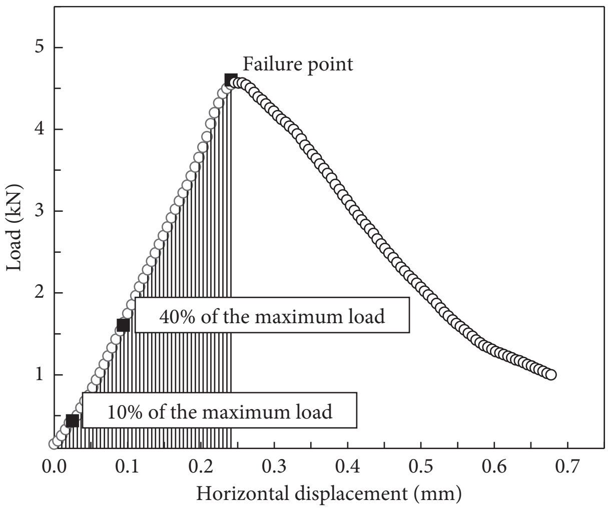

Figure 3: Typical curve of force-horizontal displacement.

2.2.3. Stiffness Modulus Test. The stiffness modulus is the most important parameter in the mechanical design of asphalt pavement [20]. The stiffness modulus of CRME was calculated by the loading range between 10% and 40% of the maximum load according to the Chinese standard [28] because the load has a good linear relation with displacement in the range. A typical force-displacement curve of CRME is shown in Figure 3, and the stiffness modulus was calculated by the following equation [8, 31]:

$$E = \frac{0.3F_{\max}(4 + \pi\mu - \pi)}{\pi h(u_{40\%} - u_{10\%})}, \quad (4)$$

where E is the stiffness modulus of the specimen; $F_{\max}$ is the maximum force achieved during the test; h is the thickness of the specimen; μ is Poisson's ratio of the specimen, and its value is 0.3 according to the Chinese standard [28]; $\mu_{10\%}$ is the horizontal displacement corresponding to 10% of the failure load; and $\mu_{40\%}$ is the horizontal displacement corresponding to 40% of the failure load.

2.2.4. Failure Strain and Critical Strain Energy Density (CSED) Test. Failure strain is an index of deformability. A larger failure strain indicates a better deformability. The critical strain energy density (CSED) is based on the stress and strain in the center of the specimen. It can be an indicator of cracking and fatigue resistance [8]. A large CSED indicates a better cracking resistance and a long fatigue life for the mixture. The failure strain of CRME is evaluated by equation (5), and the CSED of CRME is calculated by using the following [8, 31]:

$$\varepsilon = \frac{2u}{d} \cdot \frac{1 + 3\mu}{4 + \pi\mu - \pi}, \quad (5)$$

$$U = \frac{4}{\pi d^2 h} \cdot \frac{1 + 3\mu}{4 + \pi\mu - \pi} \int_u F(u)\mathrm{d}u, \quad (6)$$

where h is the thickness of the specimen; d is the diameter of the specimen; u is the horizontal displacement; and μ is Poisson's ratio of the specimen, and its value is 0.3 according to the Chinese standard [28].

2.2.5. Rheology Test. In this experiment, rheometer shown in Figure 4 was adopted to measure the apparent viscosity under different shear rates at a constant temperature of 20°C. The diameter of the rotor and the inner diameter of the cylinder are 26.659 mm and 28.920 mm. Thus, the thickness of the shear layer is 1.1305 mm. The shear process as shown in Figure 5 was performed in the rheology test. First, a 60 s preshear at 100 s^{-1} was intended to create a uniform condition for specimens before testing. Then, specimens were rested for 180 s. Finally, specimens were then sheared with a gradually increasing shear rate from 0 to 100 s^{-1} for 100 s. The apparent viscosity of the cement asphalt emulsion paste (CAEP) decreased at first and then increased between 0 and 100 s^{-1}, showing that the paste has a minimum apparent viscosity between 0 and 100 s^{-1} [32]. The minimum apparent viscosity of the specimen was analyzed in the following section. And the mix proportion list is shown in Table 4. This test was performed thrice for each specimen at least. CAEP was composed of cationic slow-setting asphalt emulsion, Portland ordinary cement P.O 42.5, surfactant (superplasticizer and DN500), and mineral powder. In this study, the mix proportions in Table 5 are to study the effect of water-to-cement (W/C) on CAEP. CAEP had a constant asphalt emulsion-to-cement (AE/C) at 1.75% and a constant mineral powder-to-cement (M/C) at 2%. The dosage of superplasticizer and DN500 was the same as above.

3. Results and Discussion

3.1. The Void Content of CRME with Different Surfactants. Figure 6 shows the void content of CRME with different surfactants. It can be observed from Figure 6 that the addition of superplasticizer and wetting agent can moderately affect the void content of CRME. The minimum void content is 12.42%, 11.11%, and 11.72% for reference CRME, CRME with DN500, and CRME with superplasticizer, respectively. The void content of CRME can reduce by 5.59% and 10.55% by DN500 and superplasticizer, respectively. Therefore, both addition of DN500 and superplasticizer can be beneficial to the compactibility of CRME. Besides, the corresponding additional water content of CRME at the minimum void content is 3%, 4%, and 4% for reference CRME, CRME with DN500, and CRME with superplasticizer, respectively. The addition of superplasticizer can reduce the water requirement for obtaining the optimum compactibility of CRME. Superplasticizer can sharply reduce the flocculation structure and adsorption ability of cement particles, and also, it can greatly improve the mixing stability of asphalt emulsion with the cement [24, 25]. Thus, more free water can be released during compaction when superplasticizer is added, which is beneficial to the compactibility of CRME. However, it should be noted that the addition of superplasticizer can be harmful to the compactibility of CRME when the additional water content is high. This phenomenon is probably due to that the excess free water released by superplasticizer can

Figure 4: Rheometer.

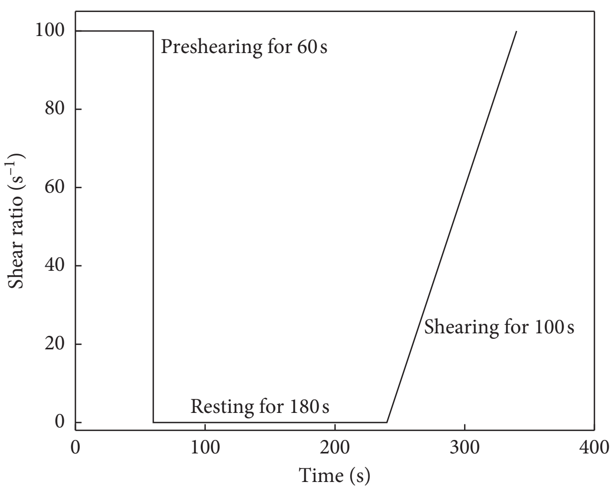

Figure 5: Shear rheology method of CAEP.

Table 5: Mix proportions of cement bitumen emulsion pastes for rheology test.

Mix	W/C	A/C	M/C
CAEP1	0.4	1.75	2
CAEP2	0.6	1.75	2
CAEP3	0.8	1.75	2

Note: every CAEP includes reference paste, paste with superplasticizer (SP) and paste with DN500.

lead to the high hydrodynamic pressure during compaction. The addition of DN500 does not change the water requirement for obtaining the optimum compactibility of CRME. Thus, its function differs from superplasticizer in improving the compactibility. As a wetting agent, DN500 can increase the wetting ability of fresh cement asphalt emulsion paste (CAEP), thus improving the coating ability of CAEP on aggregate. With more uniform coating state, the compactibility of CRME can be improved. In summary, the superplasticizer and DN500 can reduce the void content of CRME with different action mechanisms.

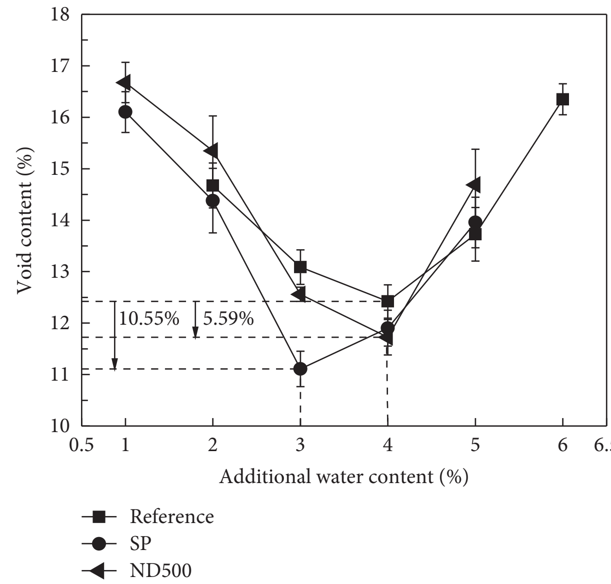

Figure 6: The void content of CRME with different surfactants.

3.2. The ITS of CRME with Different Surfactants. Figure 7 shows the ITS of CRME with different surfactants. It can be seen from Figure 7 that both addition of superplasticizer and DN500 can increase the maximum ITS of CRME. Certainly, as previously shown in Figure 6, the enhancement effect of superplasticizer and DN500 on CRME is related to the decreased void content of CRME when the two surfactants are added. Besides, this enhancement effect is also related to the improving effect of the two surfactants on the interaction between asphalt emulsion and cement particles. Meanwhile, the fresh mixing state of CRME with 3% of additional water content is shown in Figure 8. It can be seen from Figure 8 that the wetting degree of the mixture is ranked as follows: CAEP with superplasticizer > CAEP with DN500 > reference CAEP. The surfaces of course aggregates are well coated by enough CAEP by adding superplasticizer and DN500. Superplasticizer and DN500 can improve the mixing state of CRME and thus can increase the ITS of CRME. In comparison of Figures 6 and 7, CRME with superplasticizer has an equal void content with reference CRME at 2% of additional water content; however, the ITS of CRME with superplasticizer is much higher than that of reference CRME. Similarly, the ITS of CRME with DN500 is higher than that of reference CRME at 2% of additional water content although the void content of CRME with DN500 is higher than that of reference CRME. Superplasticizer can greatly improve the mixing stability of asphalt emulsion with cement [24, 25] and decrease the viscosity of CAEP [33], which can be beneficial to the coating ability of CAEP on the aggregate surface. As a result, the ITS of CRME can be increased by superplasticizer. Similarly, as a wetting agent, DN500 can greatly increase the wetting ability of asphalt emulsion, which can also increase the strength of CRME. Compared to the maximum ITS of reference CRME, superplasticizer and DN500 can increase the maximum ITS of CRME by 33.7% and 16.7%, respectively. Besides, the price of superplasticizer and DN500 is 1.4 $/kg and 2.8 $/kg,

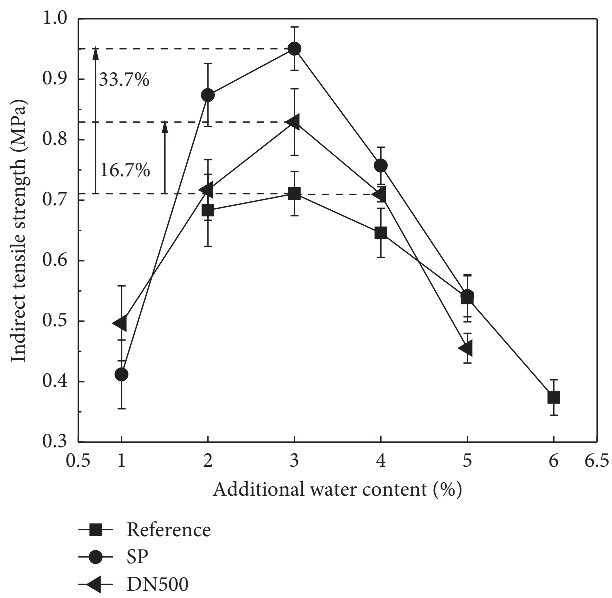

Figure 7: The ITS of CRME with different surfactants.

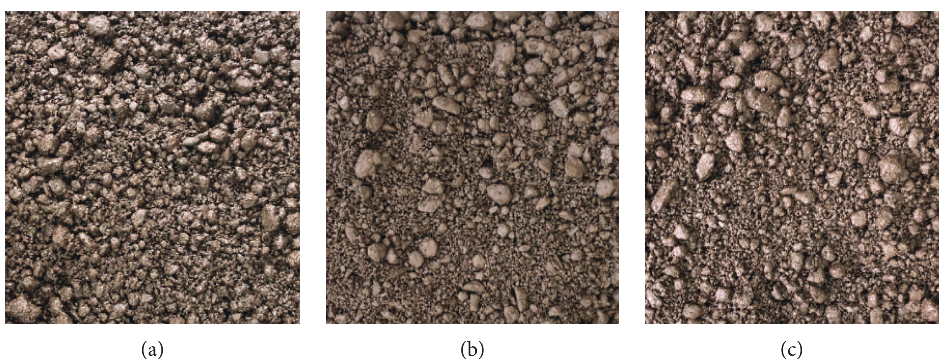

Figure 8: Mixing state of CRME with 3% of additional water content. (a) CRME with SP. (b) Reference CRME. (c) CRME with DN500.

respectively. Because superplasticizer and DN500 content is only 2% of cement and 0.5% of total water by weight, the material cost of CRME is only 0.57 $ and 0.86 $ per ton with the individual addition of superplasticizer and DN500, respectively. Therefore, the addition of superplasticizer and DN500 nearly does not increase the material cost of CRME. Adding superplasticizer or DN500 into CRME is an efficient and economical way to increase the ITS of CRME.

In comparison of Figures 6 and 7, it is clearly found that the maximum ITS of CRME did not occurr at the additional water content of the minimum void content. The corresponding additional water content of the maximum ITS for all CRMEs is 3%. However, the additional water content of CRME at maximum ITS is lower than that at the minimum void content for reference CRME and CRME with DN500. Previous study indicated that the cement asphalt emulsion mixture with maximum ITS had better mechanical properties than that with minimum void content [8]. Thus, the optimum water content of all CRMEs is 3% in this study. The volumetric properties and strength theory of CRME can explain this phenomenon. According to the strength theory of the asphalt mixture, the strength of the mixture closely depends on the cohesive force of the asphalt binder and the internal friction resistance provided by aggregate skeleton. The internal friction of aggregates decreases with the increasing void content. However, the cohesive force of cement asphalt emulsion paste is highly related to water-to-cement ratio. The harden cement asphalt emulsion paste becomes looser with the increasing water-to-ratio due to water evaporation [8]. Thus, low water content is beneficial to the hardness and cohesive force of cement asphalt emulsion paste. Because of both effects, the corresponding water content of the maximum ITS is lower than the water content of the minimum air void content.

3.3. *The Failure Strain of CRME with Different Surfactants.*

The failure strain is an indicator of the deformability ability of the asphalt mixture which is related to the cracking resistance of CRME. Figure 9 illustrates the failure strain of CRME with different additional water contents and surfactants. It can be seen from Figure 9 that the failure strain of

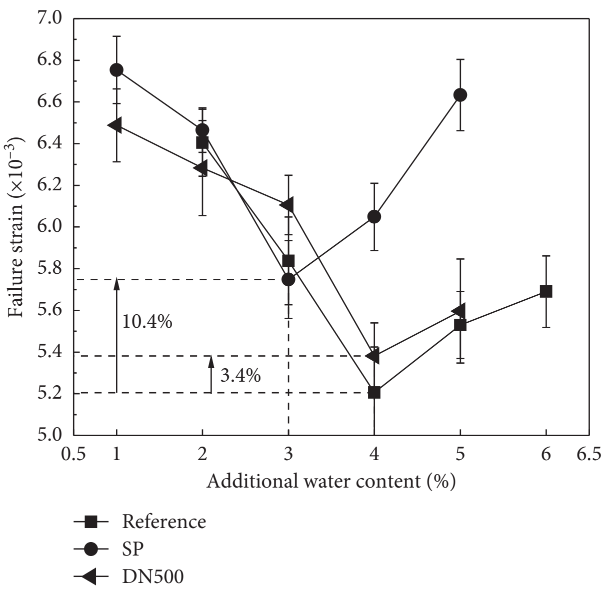

Figure 9: The failure strain of CRME with different additional water contents and surfactants.

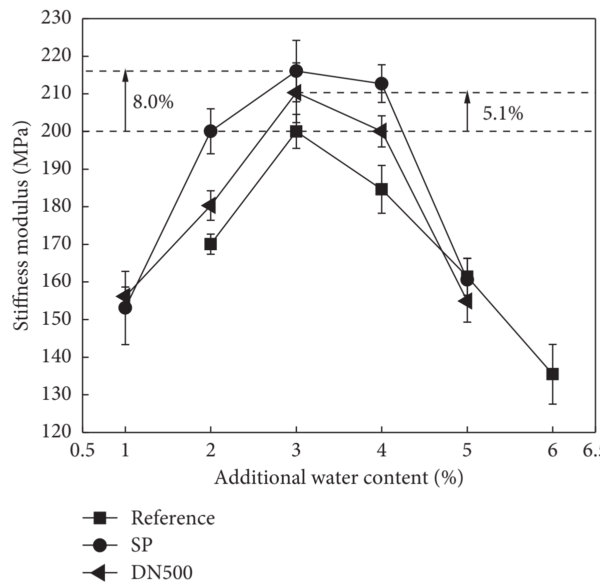

Figure 10: The stiffness modulus of CRME with different additional water contents and surfactants.

CRME firstly decreases and then increases with the increasing additional water content. Besides, the failure strain of CRME with superplasticizer and CRME with DN500 is higher than that of reference CRME except for special points. Especially, the minimum failure strain of CRME with superplasticizer can increase by 10.4% compared to the minimum failure strain of reference CRME. A higher failure strain of CRME indicates a better cracking resistance. Therefore, the addition of superplasticizer is greatly beneficial to the cracking resistance of CRME. It should be noted from Figures 6 and 9 that the changing law of failure strain with additional water content is similar to that of void content with additional water content. All CRMEs with lower void content have lower failure strain. This phenomenon was also observed in a previous study with the following probable reason [8]. Voids are beneficial to hinder the propagation path under loading; thus, the increasing void content may increase the failure strain. Besides, a good asphalt film can also increase the deformability of CRME [8]. CRME with superplasticizer and CRME with DN500 have lower void content but higher failure strain than reference CRME, which indicates that the addition of superplasticizer and DN500 are both beneficial to the film formation of asphalt emulsion. As mentioned previously, superplasticizer can greatly improve the mixing stability of asphalt emulsion with cement and DN500 can increase the wetting ability of asphalt emulsion. Both the two surfactants can improve the asphalt film formation. As a result, the deformability of CRME is improved by the two surfactants. Because of the improvement in the asphalt film formation, the failure strain of CRME with superplasticizer at the optimum water content of 3% can be still equal to that of reference CRME.

3.4. The Stiffness Modulus of CRME with Different Surfactants. The stiffness modulus of CRME with different additional water contents and surfactants is shown in Figure 10. It is observed from Figure 10 that the stiffness modulus of CRME firstly increases and then decreases with the increasing additional water content. Besides, the stiffness modulus of CRME with superplasticizer and CRME with DN500 is slightly higher than that of reference CRME. The maximum stiffness modulus of CRME with superplasticizer and CRME with DN500 increased by 8% and 5%, respectively. The stiffness modulus of CRME is mainly related to its strength. In combination of Figures 7 and 10, the relationship between the stiffness modulus and ITS of CRME is obtained, which is shown in Figure 11. It can be observed that a strong correlation exists between ITS and stiffness modulus for all CRMEs, perhaps because all CRMEs have the similar components except the surfactant. The stiffness modulus increases with the increasing ITS. Because the two surfactants can increase the strength of CRME, they can also increase the stiffness modulus of CRME. Compared to the reference CRME, the stiffness modulus of CRME with superplasticizer has a significant increase. A higher stiffness modulus indicates a better deformation resistance. Therefore, the addition of superplasticizer is beneficial to the deformation resistance of CRME.

3.5. The Critical Strain Energy Density (CSED) of CRME with Different Surfactants. Although ITS and failure strain are very suitable to characterize the mixture performance in general, they are still not sufficient to reflect the cracking resistance of CBEM because the stiffness modulus of CBEM differs greatly with mix proportion. A more suitable indicator is CSED which has been proved to be a good fatigue cracking indicator of the bitumen mixture [34, 35]. It is also suitable to characterize the fracture behavior of CBEM [36]. The CSED of CRME with different additional water contents and surfactants is shown in Figure 12. It can be seen from Figure 12 that the CSED of CRME firstly increases and then

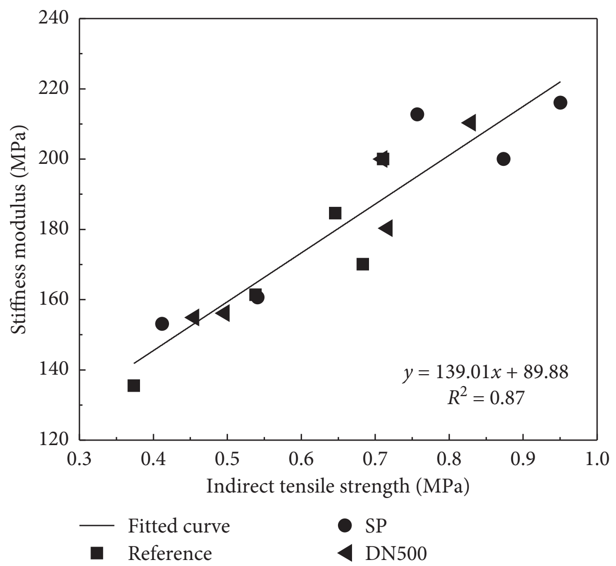

Figure 11: Relationship between stiffness modulus and ITS with different surfactants.

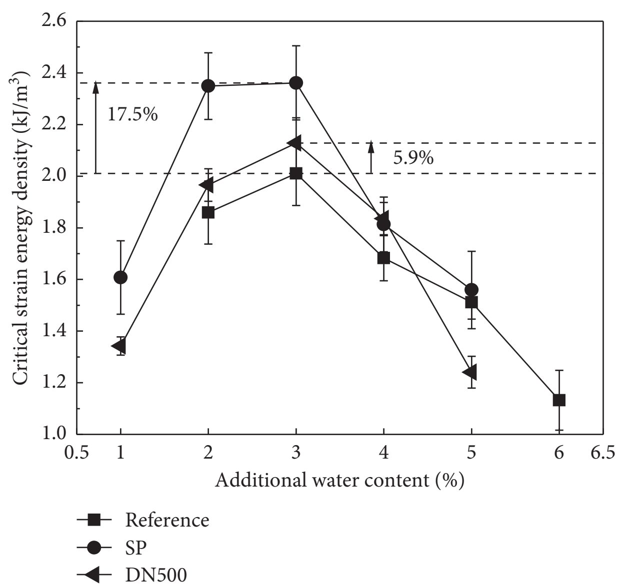

Figure 12: The CSED of CRME with different additional water contents and surfactants.

decreases with the increasing additional water content. Besides, the peak CSED of CRME with superplasticizer and DN500 increases by 17.5% and 5.9% compared to that of reference CRME, respectively. The addition of superplasticizer can significantly increase the CSED of CRME with superplasticizer. In comparison combination of Figures 6 and 12, the relationship between the CSED and ITS of CRME is obtained, which is shown in Figure 13. It can be observed from Figure 13 that a strong correlation exists between ITS and CSED for all CRMEs. The CSED increases with the increasing ITS. Because superplasticizer can greatly increase the strength of CRME, it can also increase the CSED of CRME. Since

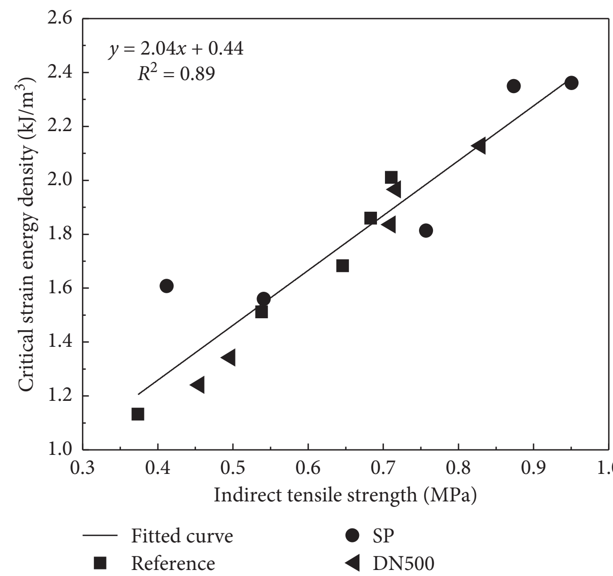

Figure 13: Relationship between CSED and ITS with different surfactants.

CSED is an aggregative indicator of the fracture and fatigue cracking resistance, it can be inferred that the fracture and fatigue cracking resistance of CRME can be greatly improved by superplasticizer.

3.6. The Apparent Viscosity of CAEP with Different Surfactants. The apparent viscosity of CAEP can reflect the interaction between asphalt droplets and cement particles. It can also affect the compactibility of CRME and the coating ability of paste on the aggregate surface. Figure 14 shows the apparent viscosity of CAEP with different surfactants. It can be seen from Figure 14 that the apparent viscosity of paste is ranked as follows: CAEP with superplasticizer < CAEP with DN500 < reference CAEP. Superplasticizer can greatly decrease the viscosity of CAEP, which is beneficial to the coating ability of CAEP and the compactibility of CRME. It is reasonable that the addition of superplasticizer can reduce the void content of CRME and improve the mechanical properties of CRME. As a surfactant, DN500 can also moderately decrease the viscosity of CAEP, which is helpful to the compactibility of CRME. Besides, DN500 can improve the coating ability of CAEP as a wetting agent. Therefore, the addition of DN500 can also improve the mechanical properties of CRME.

4. Conclusions

This experimental study focused on using the low content level of suitable surfactants to improve the volumetric and mechanical properties of CRME. Based on the results and discussion, the following conclusions can be drawn:

(1) The addition of superplasticizer can reduce the void content of CRME and greatly increase the ITS of CRME. Meanwhile, the deformability of CRME can also be slightly improved by superplasticizer. This

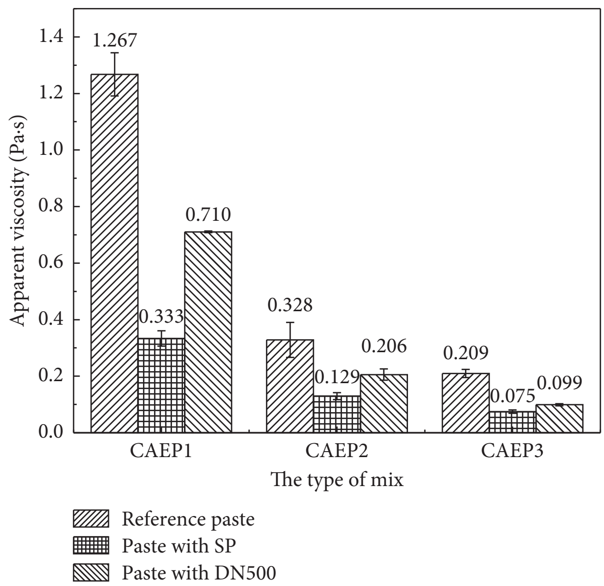

Figure 14: The apparent viscosity of CAEP with different surfactants.

phenomenon is probably due to that superplasticizer can decrease the viscosity of CAEP and help to form a better asphalt film.

(2) The addition of wetting agent (DN500) can also reduce the void content of CRME and increase the ITS of CRME. Meanwhile, the deformability of CRME is not degraded with the increase of strength by adding DN500. This is because DN500 can moderately decrease the viscosity of cement asphalt emulsion paste and increase the wetting ability of asphalt emulsion as a wetting agent.

(3) The stiffness modulus and CSED of CRME have a linear relationship between the ITS of CRME. Since the addition of superplasticizer can increase the strength of CRME, it can also increase the stiffness modulus and CSED of CRME.

(4) Since the ITS, failure strain, and CSED are all the indicators of cracking resistance of CRME and the stiffness modulus is the indicator of deformation resistance, the addition of superplasticizer and DN500 is beneficial to the cracking and deformation resistance of CRME. CRME with superplasticizer has the best mechanical properties among all CRMEs. Compared to reference CRME, the ITS, stiffness modulus, and CSED critical strain energy density of CRME with superplasticizer can increase by 33.7%, 8.0%, and 17.5% at the optimum water content, respectively. It is recommended to improve the volumetric and mechanical properties of CRME by adding superplasticizer.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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