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Effect of cement and emulsified asphalt contents on the performance of cement-emulsified asphalt mixture

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HIGHLIGHTS

- The influences of cement and emulsified asphalt on mixture properties were studied.
- The mesoscopic void structures of cement-emulsified asphalt mixture were investigated.
- Performance of mixture was analyzed from perspective of mesoscopic void structures.

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ABSTRACT

The effects of cement and emulsified asphalt contents on the performance of cement-emulsified asphalt mixture were systematically evaluated, including the indirect tensile strength, compressive strength, modulus of resilience, tensile strength ratio, dynamic stability, maximum bending strain, and Cantabro loss. In addition, the mesoscopic images and void characteristics of cement-emulsified asphalt mixtures with different material compositions were obtained, using scanning electron microscopy (SEM) and computed tomography (CT). The results indicated that at a constant cement content of 3%, when the emulsified asphalt content increased from 6% to 9%, the indirect tensile strength, compressive strength, and modulus of resilience first increased and then decreased. At a constant emulsified asphalt content of 8%, when the cement content increased from 0% to 4%, the indirect tensile strength first increased and then decreased, and the compressive strength and modulus of resilience each reached its maximum at a cement content of 3%. The addition of cement significantly improved the high-temperature stability and moisture stability of the asphalt mixture but was not conducive to its low-temperature performance. In addition, a minimum Cantabro loss was observed at a cement content between 2% and 3%. The mesoscopic void structures formed in different cement and emulsified asphalt contents also significantly affected the mechanical properties and mixture performances.

1. Introduction and literature review

A cement-emulsified asphalt mixture contains cement, emulsified asphalt, and aggregates, and is mixed at a normal temperature. In the mixture, the emulsified asphalt aggregates and demulsifies, and the cement hydrates, crystallizes and solidifies, forming a new engineering material [1,2]. Emulsified asphalt is liquid at normal temperature, and the process of mixing, paving and compacting with aggregate and cement would cause emulsion asphalt to demulsification [3,4]. Part of the moisture produced by the demulsification was consumed by the hydration reaction of the cement, and the other part was lost by evaporation. The asphalt and aggregate heating process were avoided throughout the construction process, thus avoiding the emission of asphalt smoke from heating, thereby greatly reduced energy consumption and carbon emissions during construction [5,6]. Therefore, it has been applied more and more in civil engineering, especially in pavement engineering.

Because a cement-emulsified asphalt mixture contains both cement and emulsified asphalt, which have different engineering properties, the properties of the mixture are thus between those of cement and emulsified asphalt [7–9]. The mechanical properties, such as indirect tensile strength and compressive strength, are

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closely related to the cement content, emulsified asphalt content, and curing time [10,11]. Oruc et al. examined the modulus of resilience of cement-emulsified asphalt mixture and concluded that the modulus of resilience of a cement-emulsified asphalt mixture with a low cement content (1%) has the same correlation with temperature as that of hot mix asphalt [12]. Kavussi et al. studied the fatigue properties of cement-emulsified asphalt mixture and determined the fatigue life of the mixture at different cement contents and temperatures [13].

Optimization of the mixture gradation and the addition of lime and silica fume, can improve the mechanical properties and frost resistance of cement-emulsified asphalt mixture, according to previous studies [14–16]. Nejad et al. analyzed the mechanical and fatigue properties of a cement-emulsified asphalt mortar mixed with ground granulated blast furnace slag (GGBS) and silica fume, the results indicated that silica fume can enhance the compressive strength and indirect tensile strength of the mixture [17]. Niazi et al. examined the performance of cold in-place recycled mixtures modified with emulsified asphalt following the addition of cement and lime. According to the results, the addition of lime improved the mixture's Marshall stability, modulus of resilience, tensile strength, and resistance to moisture damage and permanent deformation [18].

Scanning electron microscopy (SEM) and other testing methods were employed to classify the mesostructure characteristics of cement-emulsified asphalt mixture, after which the formation mechanism of the strength was analyzed [19,20]. Previous studies have found that cement-emulsified asphalt mortar is made up of granulated particles and fibrous ettringite (AFt) of cement, in which the granulated particles are composed of asphalt-coated mineral powder and unhydrated cement, and the AFt include hydrated calcium silicate (C-S-H) gels and calcium hydroxide (CH) crystals, etc. [21,22]. The grid- and cluster-shaped AFt, which is composed of small amounts of unhydrated cement and asphalt mortar that are interlaced with each other [6], forms the cement asphalt mortar by physical mixing [23]. Compared to ordinary asphalt mortar, cement asphalt mortar has higher viscosity, adhesive and cohesive force, which improve the interface between the mortar and aggregates, and improve the adhesive force and mechanical properties of concrete [24,25].

Despite of previous researches on the performance of cement-emulsified asphalt mixtures, they have mainly concentrated on the conventional performance and mesostructure characteristics of the cement-emulsified asphalt mixture. Studies have indicated that cement and emulsified asphalt have a significant influence on the performance of the mixture [26]. However, the influences are not sufficiently quantified and systematic research on other mixture performance is lacking. In addition, analyses on the performance of cement-emulsified asphalt mixture have been mainly based on the mesoscopic images obtained by SEM. Studies have not been performed yet on its mesoscopic void structure. In this study, by fixing the content of cement or emulsified asphalt while changing the content of the other in indoor tests, the effects of cement and emulsified asphalt contents on the performance of cement-emulsified asphalt mixture were systematically appraised. The assessed performance include indirect tensile strength, compressive strength, modulus of resilience, moisture susceptibility, low-temperature bending, rutting, Cantabro abrasion and fatigue tests. The mesoscopic features and void structure of each cement-emulsified asphalt mixture were obtained by scanning electron microscopy (SEM) and computed tomography (CT). Changes in the mixture performance were further analyzed and explained. This paper provides a reference for the selection of proper cement and emulsified asphalt content in the cement-emulsified asphalt mixture.

2. Materials and test methods

2.1. Materials

Emulsified asphalt was prepared in the laboratory, the main technical parameters are shown in Table 1. Ordinary Portland cement (32.5R) was used in the test.

Basalt was used as the aggregate under the following conditions: a sand equivalent of 81.2%; a sturdiness of 7%; a polishing value of 46 (British pendulum tester; BPN); a Los Angeles wear loss of 22.2%; and a crushing value of 11.9%. The gradation of the cement-emulsified asphalt mixture used in the experiment is presented in Table 2.

2.2. Test scheme

According to available research results and common experience [11,26], cement-emulsified asphalt mixtures have been tested with emulsified asphalt contents of 6%, 7%, 8%, and 9%, and cement contents of 0% 2%, 3%, and 4%. To analyze the effects of cement and emulsified asphalt contents on the performance of the mixture, the experiments were designed as follow: (a) analyze the effects of different emulsified asphalt contents (6%, 7%, 8%, and 9%) on the performances of the mixture at a median cement content of 3% and, (b) analyze the effects of different cement contents (0%, 2%, 3%, and 4%) on the performances of the mixture at a median emulsified asphalt content of 8%. Specimens were cured for 7 days indoor with 20 °C temperature according to the ASTM C31 [27]. Each performance test evaluated four samples, and the average was taken as the test result.

2.3. Test methods

2.3.1. Mechanical property tests

The mechanical properties of the cement-emulsified asphalt mixtures were evaluated by the indirect tensile, compressive, and modulus of resilience tests.

Marshall specimens were used in the indirect tensile strength tests. Each specimen had a height of 63.5 ± 1.3 mm and a diameter of 101.6 mm. The test temperature was set at 20 °C and the test followed the standard test method for the indirect tensile (IDT) strength of bituminous mixtures in accordance with *ASTM D6931-17* [28].

Table 1
Main technical parameters of the emulsified asphalt.

Test items	Test results	Specifications	Test methods
Residue on sieving, %	0.01	≤0.1	*ASTM D6933*
Residue content by evaporation, %	64.1	≥55	*ASTM D6997*
Ductility of residue (15 °C), cm	72.5	≥40	*ASTM D6997*
Storage stability (5d), %	2.9	≤5	*ASTM D6930*

Table 2
Mineral aggregate gradation for the test.

Sieve size, mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.75
Pass percent, %	100.0	95.1	80.4	55.5	34.4	21.8	17.4	12.5	10.1	6.7

Cylindrical specimens with a diameter of 100 mm and a height of 100 mm were used for the compressive strength tests. The test temperature was set at 15 °C and the test was carried out in accordance with the standard test method for the compressive strength of asphalt mixtures (*ASTM D1074-17*) [29].

Based on the test results, the compressive strength *P* was divided into 10 load stages, of which the first five stages of loads (0.1*P*, 0.2*P*, 0.3*P*, 0.4*P*, and 0.5*P*) were used as the test loads. Initially, each specimen was loaded from 0 to 0.1*P* at a rate of 2 mm/min and the deformation, L_1, of the specimen was recorded. Then each specimen was unloaded from 0.1P to 0 at the same rate and the deformation, L_1', was recorded 30 s following the conclusion of unloading. The rebound deformation, ΔL_1, defines the difference in deformation of the specimen with and without the loading. The rest of the loads, namely 0.2*P*, 0.3*P*, 0.4*P* and 0.5*P*, were respectively loaded on the specimens. The loading and unloading specimen deformations, L_i (i = 2–5), were then recorded and the rebound deformation, ΔL_i, of each load was calculated. The compression modulus of resilience was calculated according to Eq. (1) using the fifth-stage load as an example [30].

$$E' = \frac{\frac{4P_5}{\pi d^2} \times h}{\Delta L_5}, \tag{1}$$

where E' is the compression modulus of resilience (MPa); P_5 is the fifth-stage load value, 0.5*P*, applied to the specimen (N); d is the diameter of the specimen (mm); h is the axis height of the specimen (mm); and ΔL_5 is the rebound deformation of the fifth-stage load.

2.3.2. Moisture susceptibility test

The tensile strength ratio (TSR) index, calculated by Eq. (3), obtained from the freeze-thaw splitting test was used to evaluate the moisture susceptibility of the mixture in accordance with *AASHTO T 283* [31].

$$\mathrm{TSR} = \frac{R_{T2}}{R_{T1}} \times 100 \tag{6}$$

where R_{T1} was the average value of indirect tensile strength of the first group of specimens that did not undergo a freeze-thaw cycle (MPa), R_{T2} was the average value of indirect tensile strength of the second group of specimens that after freeze-thaw cycles (MPa).

2.3.3. Low-temperature bending test

The low-temperature bending test was used to evaluate the low-temperature characteristics of the mixture [32]. The test specimen was a 250 mm (length) × 30 mm (width) × 35 mm (height) prism cut from a rut board. The specimen was loaded at three points in the universal testing machine (UTM), where the two pivot points had a distance of 200 mm, the test temperature was set at −10 °C, and the loading rate was 50 mm/min. The flexural tensile strength R_B, the maximum bending strain ε_B at the bottom of the beam, and the flexural creep stiffness S_B at the time of failure were calculated by Eqs. (2)–(4), respectively.

$$R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2}, \tag{2}$$

$$\varepsilon_B = \frac{6 \times h \times d}{L^2}, \tag{3}$$

$$S_B = \frac{R_B}{\varepsilon_B}, \tag{4}$$

where R_B is the flexural tensile strength of the specimen (MPa); ε_B is the bending strain of the specimen at the time of failure ($\mu\varepsilon$); S_B is the flexural creep stiffness of the specimen (MPa); *b* is the width of the section (30 mm); *h* is the height of the section (35 mm); *L* is the pivot spacing (200 mm); and *d* is the mid-span deflection of the specimen at failure (mm).

2.3.4. Cantabro abrasion test

The Cantabro abrasion test was used to evaluate the anti-abrasion performance of the mixture under impact load [30]. A standard Marshall specimen, which had 50 times compaction on each side, was placed in water tank at a controlled temperature of 15 °C ± 0.5 °C. The specimen was then removed, wiped with a towel to remove water from the surface, and weighed to obtain the mass m_0, after which the specimen was immediately subject to the Los Angeles abrasion test. The Los Angeles abrasion test equipment rotated 300 times at a speed of about 30–33 r/min. Following the completion of the test, the largest residual specimen was weighed to obtain m_1. The Cantabro loss can then be calculated by Eq. (5).

$$\Delta S = \frac{m_0 - m_1}{m_0} \times 100, \tag{5}$$

where ΔS is the Cantabro loss of the asphalt mixture; m_0 is the mass of the specimen before the test; and m_1 is the weight of the residual specimen after the test.

3. Test results of mechanical properties

3.1. Indirect tensile strength

The effect of emulsified asphalt content on the indirect tensile strength of the mixture at a constant cement content of 3% is shown in Fig. 1a. The effect of cement content on the indirect tensile strength of the mixture at a constant emulsified asphalt content of 8% is presented in Fig. 1b.

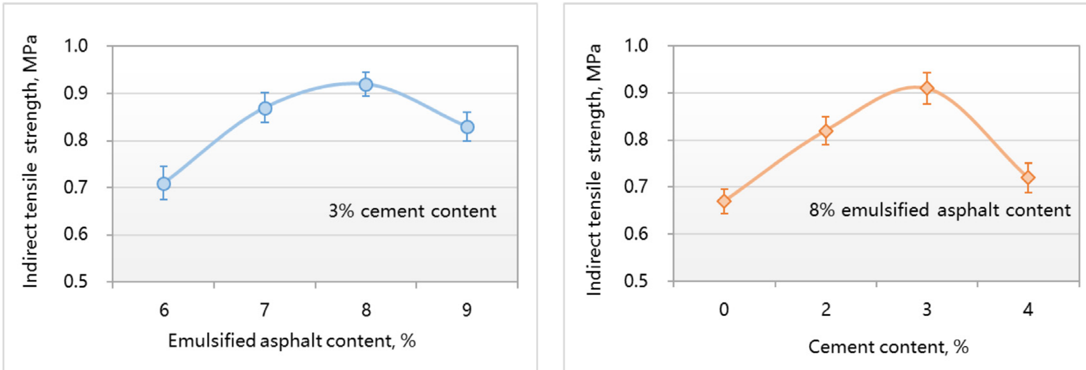
It can be seen that indirect tensile strength of the mixture first increased and then decreased following an increase in the content of cement and emulsified asphalt. At a cement content of 3% and an emulsified asphalt content of 8%, indirect tensile strength of the cement-emulsified asphalt mixture reached a peak value of about 0.9 MPa.

3.2. Compressive strength

The effect of cement and emulsified asphalt content on the compressive strength of the mixture is shown in Fig. 2. At a constant cement content of 3% (Fig. 2a), the compressive strength of the mixture first increased and then decreased following an increase in the emulsified asphalt content. A maximum compressive strength of about 4.3 MPa was observed at an emulsified asphalt content of 8%. At a constant emulsified asphalt content of 8% (Fig. 2b), an increase in the cement content from 0% up to 3% did lead to an obvious increase in the compressive strength of the mixture. The compressive strength of the mixture was about 3.1 MPa when the cement content was 0% and increased rapidly to about 3.9 MPa and 4.3 MPa when the cement content was 2% and 3%, respectively. However, the compressive strength of the mixture decreased slightly when the cement content reached 4%.

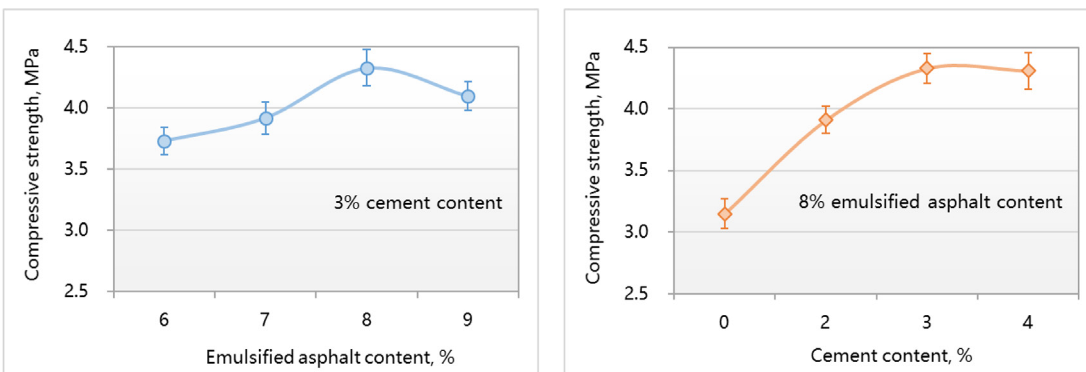
3.3. Modulus of resilience

The influences of cement and emulsified asphalt content on the modulus of resilience of the mixture at 20 °C are presented in Fig. 3. At a constant cement content of 3%, the modulus of resilience first increased and then decreased following an increase in the emulsified asphalt content (Fig. 3a). The modulus of resilience reached a peak value of about 1120 MPa at an emulsified asphalt content of 8%. At a constant emulsified asphalt content of 8%, the



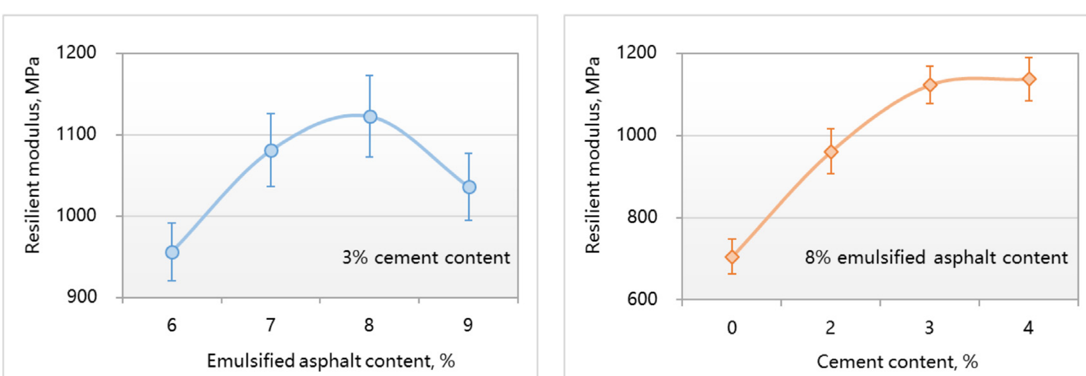
(a) Emulsified asphalt content (b) Cement content

Fig. 1. Influence of cement and emulsified asphalt content on indirect tensile strength.



(a) Emulsified asphalt content (b) Cement content

Fig. 2. Influence of cement and emulsified asphalt content on compressive strength.



(a) Emulsified asphalt content (b) Cement content

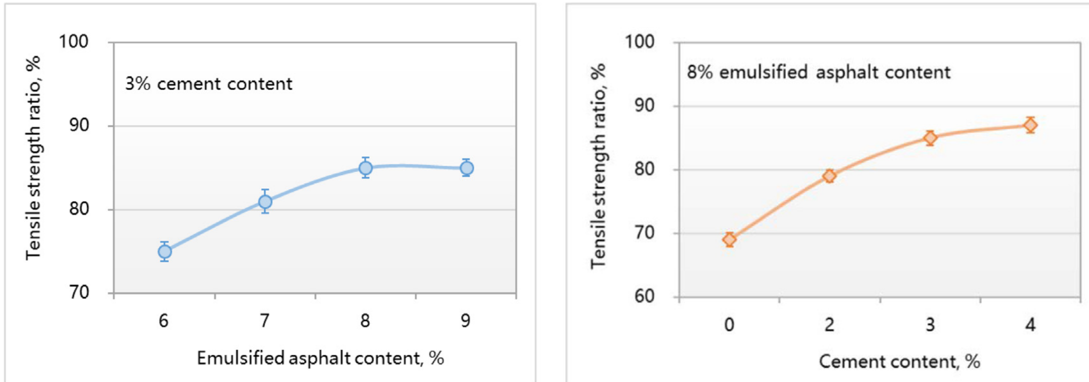
Fig. 3. Effect of cement and emulsified asphalt content on static modulus of resilience.

static modulus of resilience of the cement-emulsified asphalt mixture increased following an increase in the cement content (Fig. 3b). The modulus of resilience was about 700 MPa when the cement content was 0%, increased to about 960 MPa at a cement content of 2%, and was close to the maximum value of about 1150 MPa when the cement content reached 3%.

4. Test results of road performances

4.1. Moisture susceptibility

The freeze-thaw splitting test was undertaken to evaluate the moisture susceptibility of the cement-emulsified asphalt mixture.



(a) Emulsified asphalt content (b) Cement content

Fig. 4. Influence of cement and emulsified asphalt content on tensile strength ratio.

Fig. 4 presents the tensile strength ratio (a measure of moisture susceptibility) of the mixture at different emulsified asphalt and cement contents. An increase in the emulsified asphalt content generated an increase in the tensile strength ratio (Fig. 4a), partly due to the full encapsulation of the aggregates by emulsified asphalt and the void-filling effect. The tensile strength ratio of the mixture was then measured at different cement contents at a constant emulsified asphalt content of 8% (Fig. 4b). The moisture susceptibility of the mixture was greatly improved by the addition of cement. The tensile strength ratio was less than 70% at a cement content of 0% but increased to about 85% at a cement content of 3%.

4.2. High-temperature stability

The rutting test was undertaken to evaluate the influence of cement and emulsified asphalt contents on the high-temperature stability of cement-emulsified asphalt mixture. At a constant cement content of 3%, the high-temperature rut resistance of the mixture decreased following an increase in emulsified asphalt content, as shown in Fig. 5a. Specifically, at an emulsified asphalt content of 9%, the dynamic stability was significantly lower than that at an emulsified asphalt content of 8%. This occurred because an increased amount of emulsified asphalt resulted in a greater probability of aggregates slippage and flow, as well as a reduced high-temperature rut resistance under the combined effect of repeated loading and high temperature, which is similar to that of hot-mix asphalt.

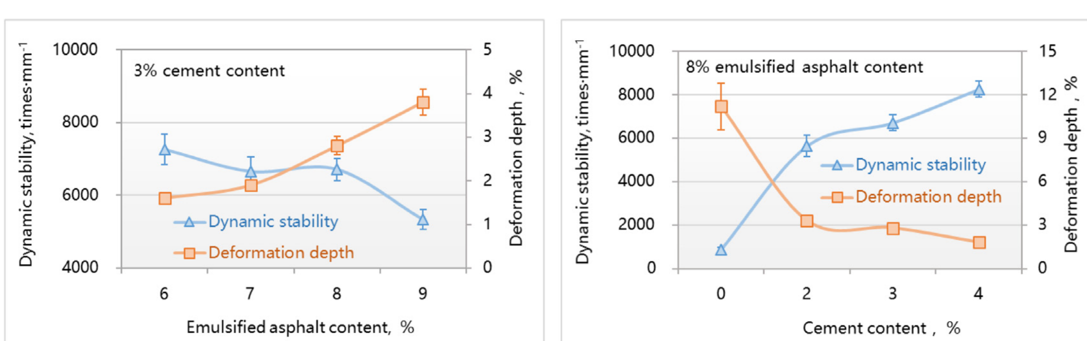
At a constant emulsified asphalt content of 8%, the high-temperature rut resistance of the mixture exhibited a better performance following an increase in cement content, thereby resulting in an increase in dynamic stability and a decrease in deformation depth, as presented in Fig. 5b. The addition of cement greatly improved the high-temperature performance of the mixture. The dynamic stability reached 6715 times/mm at a cement content of 3% because the cement reduced the temperature sensitivity of the mixture and increased the high-temperature viscosity of the asphalt mortar, thereby enhancing the high-temperature deformation resistance of the mixture.

4.3. Low-temperature characteristics

The maximum bending strain and the flexural creep stiffness (measure of low-temperature performance) test was undertaken to characterize the crack resistance of the mixture at low temperature. Normally, larger maximum bending strains are associated with smaller flexural creep stiffness values and better low-temperature crack resistance. The flexural tensile strength, maximum bending strain, and flexural creep stiffness of the mixture at temperature of −10 °C are presented in Figs. 6–8 at a constant cement content of 3% and at a constant emulsified asphalt content of 8%.

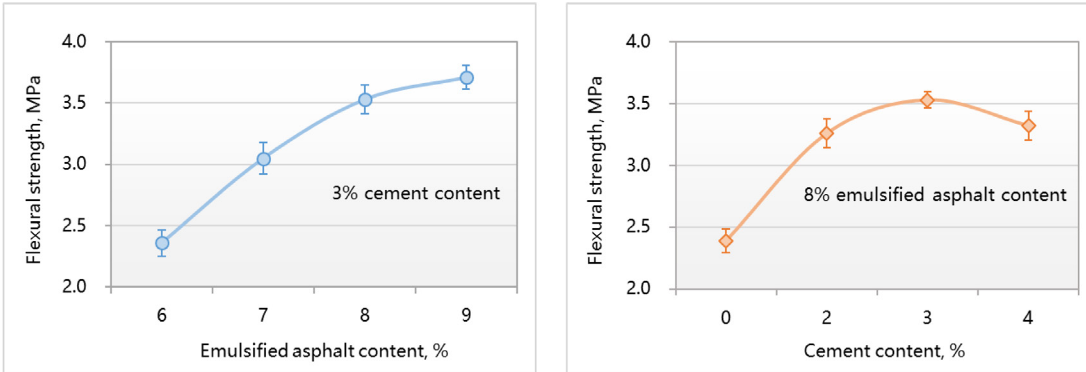
At a constant cement content of 3%, an increase in emulsified asphalt content resulted in an increase of the flexural tensile strength and the maximum bending strain of the cement-emulsified asphalt mixture. Meanwhile, the flexural creep stiffness exhibited a decrease, indicating that an increase in emulsified asphalt content can significantly improve the low-temperature crack resistance of the mixture.

At a constant emulsified asphalt content of 8%, when the cement content increased from 0% to 4%, the flexural tensile



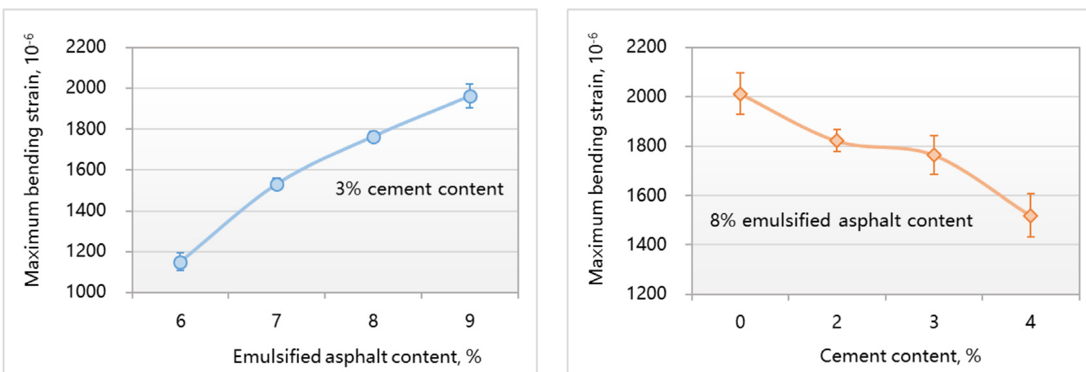
(a) Emulsified asphalt content (b) Cement content

Fig. 5. Influence of cement and emulsified asphalt content on high temperature rut resistance.



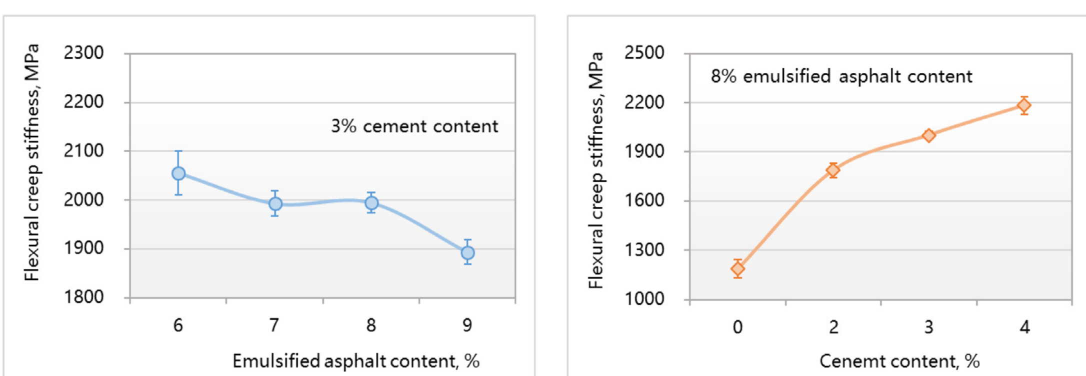
(a) Emulsified asphalt content (b) Cement content

Fig. 6. Effect of cement and emulsified asphalt content on flexural strength.



(a) Emulsified asphalt content (b) Cement content

Fig. 7. Effect of content on maximum bending strain.



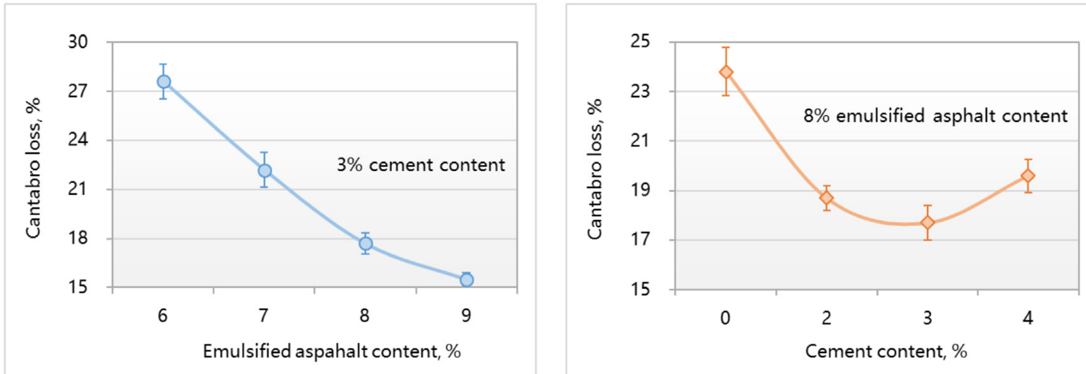
(a) Emulsified asphalt content (b) Cement content

Fig. 8. Effect of cement and emulsified asphalt content on flexural creep stiffness.

strength of the mixture first increased and then decreased. The maximum bending strain decreased, and the flexural creep stiffness increased, indicating that the low-temperature crack resistance of the mixture decreased following an increase in cement content, especially at a cement content of above 3%. The flexural tensile strength of the mixture was high when the cement content was between 2% and 3%. However, rigidity of the mixture increased and the maximum bending strain significantly decreased when the cement content increased to 4%.

4.4. Abrasion resistance performance

The results of Cantabro abrasion test on the cement-emulsified asphalt mixture are shown in Fig. 9. At a constant cement content of 3%, an increase in emulsified asphalt content resulted in an increase in the abrasion resistance of the mixture (Fig. 9a). As the emulsified asphalt content increased to 8%, the asphalt film wrapped around the aggregates thickened, thereby improving the integrity and cohesiveness of the specimen and allowing the



(a) Emulsified asphalt content (b) Cement content

Fig. 9. Effect of cement and emulsified asphalt content on abrasion resistance.

Cantabro loss of the mixture to be kept below 20%. The Cantabro loss of the mixture under different cement contents at a constant emulsified asphalt content of 8% is presented in Fig. 9b. The Cantabro loss of the mixture decreased first and then increased slightly as the cement content increased from 0% to 4%.

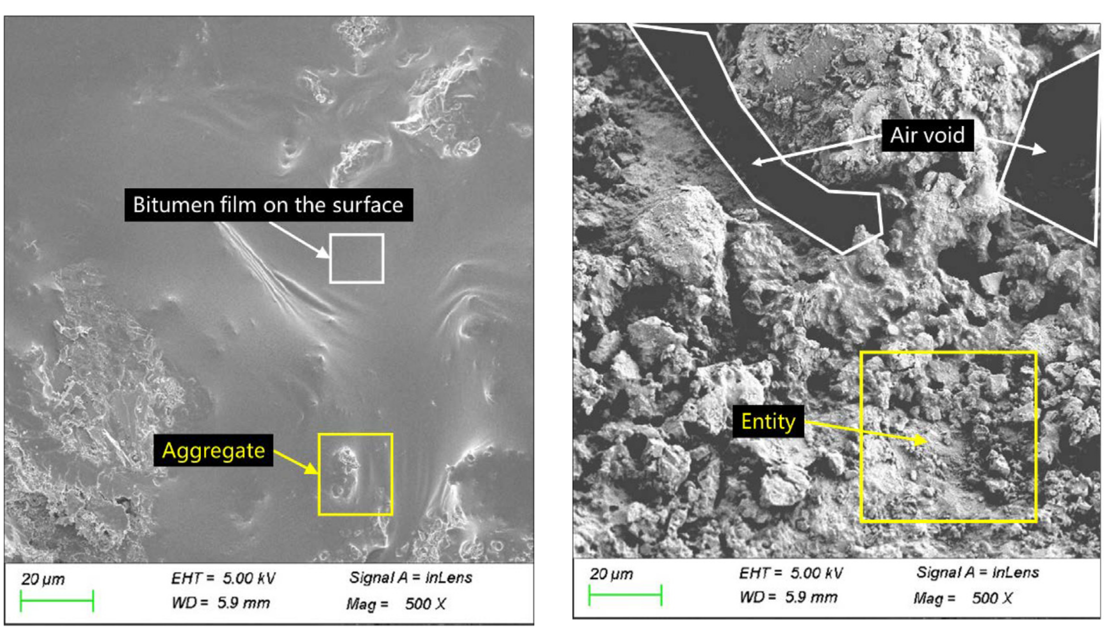
5. Scanning electron microscopy (SEM) and computed tomography (CT) results

Based on the SEM and CT scanning images of each specimen, the influence of cement and emulsified asphalt contents on the mechanical properties and road performances of cement-emulsified asphalt mixtures were further analyzed from the perspective of the material's mesostructure.

Following the addition of cement in emulsified asphalt, the viscosity of the asphalt mortar increased and the workability decreased. Fig. 10a is a SEM image of the ordinary asphalt mixture, and Fig. 10b is a cement-emulsified asphalt mixture (3% cement, 8% emulsified asphalt). Though the moisture from the demulsification of the asphalt provided the necessary moisture for cement hydration, a loose slurry structure with an increased amount of voids was formed. Compared to the ordinary asphalt mixture, the surface of the cement-emulsified asphalt slurry was not smooth after hardening, and it exhibited many protrusions that appeared uneven. In addition, many pores were also formed inside the slurry, thereby resulting in a loose overall structure.

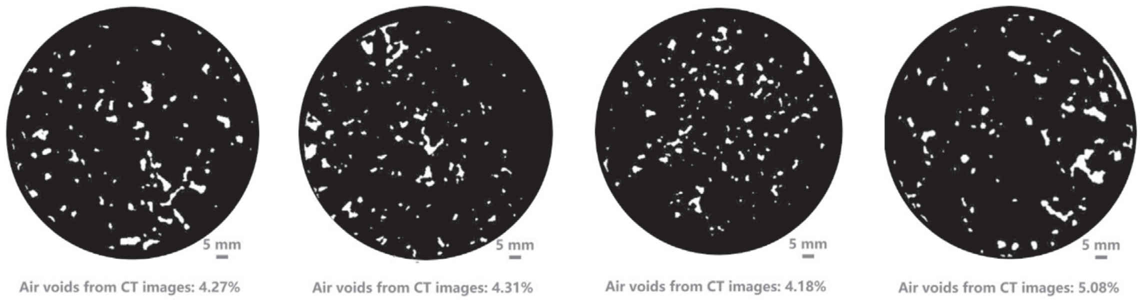
The specimen was CT-scanned at 2-mm intervals, images of the specimen are presented in Figs. 11 and 12. The void of the section was analyzed and the void ratio of the CT image calculated.

At a constant emulsified asphalt content of 8% and cement contents of 0% (Fig. 11a), 2% (Fig. 11b), and 3% (Fig. 11c), the difference in the void ratio of the mixture was small and exhibited an average value of about 4.2%. As the cement content increased to 4%, the void ratio of the mixture increased significantly to 5.1%. As presented in Fig. 11d. The number of big pores clearly increased because an increase in the cement content significantly increased the viscosity of the asphalt mortar, thereby resulting in poor



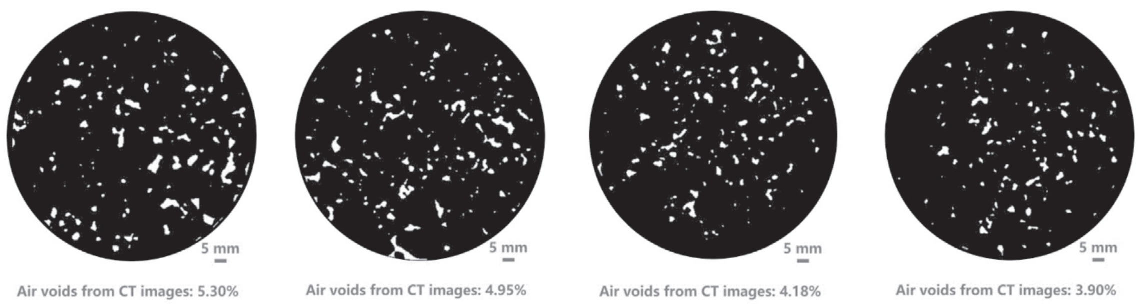
(a) Ordinary asphalt mixture (b) Cement-emulsified asphalt mixture

Fig. 10. SEM images (500×).



(a) 0% cement (b) 2% cement (c) 3% cement (d) 4% cement

Fig. 11. CT images of cement emulsified asphalt mixtures with different cement contents (all at 8% emulsified asphalt content), where the air voids were shown in white and the mixture was shown in black.



(a) 6% emulsified asphalt (b) 7% emulsified asphalt (c) 8% emulsified asphalt (d) 9% emulsified asphalt

Fig. 12. CT images of cement-emulsified asphalt mixture with different emulsified asphalt contents (all at 3% cement content), where the air voids were shown in white and the mixture was shown in black.

fluidity after the mixture was shaped. The mixture exhibited poor workability and was difficult to mix and compact, leaving more voids in the finished mixture. Therefore, the amount of cement in the cement-emulsified asphalt mixture should not exceed 3%.

The difference in the mesoscopic void structure can also explain why the indirect tensile strength, compressive strength and modulus of resilience of the mixture did not increase with an increase in cement content, when the cement content exceeded 3%. Generally speaking, the mechanical strength of the mixture is closely related to the void ratio [32]. A larger void ratio results in a lower mechanical strength. In addition, the indirect tensile strength is more sensitive to the void structure, thereby resulting in a more significant decrease. An increase in cement content resulted in an increase in the AFt which partially compensated for the decrease in compressive strength and modulus of resilience, thereby resulting in no obvious decline of them. At a cement content of 4%, the increase in void structure of the mixture also resulted in an increase in the Cantabro loss and a decrease in the fatigue performance of the mixture.

In addition, when the cement content in the mixture was relatively high, the AFt grew and pierced through the asphalt film, separating the continuous asphalt film, so that it was difficult to form an overall spatial network, as shown in Fig. 13. At the same time, the cement was not sufficiently hydrated in the mixture due to asphalt packing and the acidic environment adverse to hydration. The AFt could not sufficiently form a structure that used the hardened cement mortar as its spatial framework, resulting in a cement-emulsified asphalt mixture without having a complete grid structure to take the compressive load and also resulting in a decreased compressive strength.

The emulsified asphalt played a role in the bonding aggregates and filling voids in the mixture. As the amount of emulsified

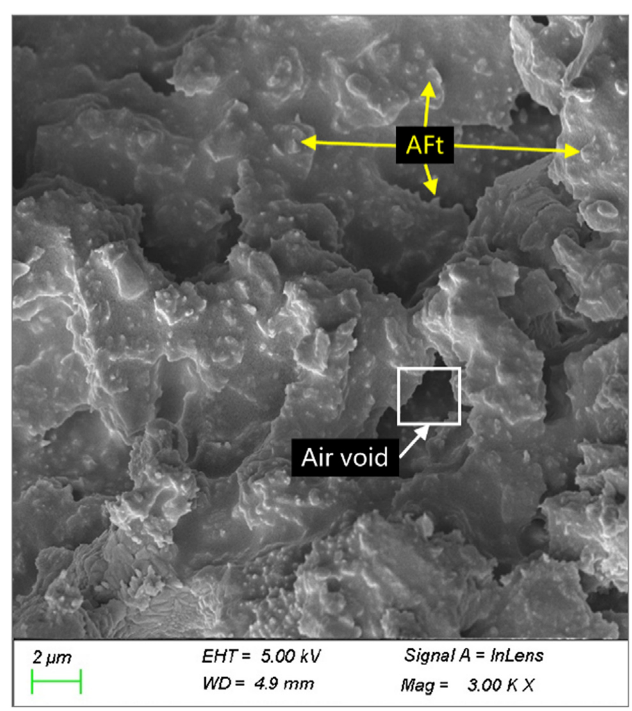


Fig. 13. Cement hydration of cement-emulsified asphalt mixture (3000×).

asphalt increased, the void ratio of the mixture, according to the CT images, decreased (Fig. 12). Like hot-mix asphalt, emulsified asphalt also has an optimum content. When the content was too low, the amount of emulsified asphalt was insufficient for bonding, filling, and hydrating the cement and thus prevented the growth of sufficient mixture strength. When the content exceeded the optimal percentage, the excessive emulsified asphalt fully encapsulated the cement particles and restricted the hydration of the cement, which degraded the mechanical properties of the mixture.

The mesostructure of the void in the mixture also affected the mixture's road performance [33–35]. Some studies have indicated a strong relationship between the void ratio of asphalt mixture and moisture susceptibility [36]. The swelling pressure of the moisture residing in the voids during the freeze-thaw process destroyed the structure and decreased the strength around the void due to an increase in the void ratio. As a result, tensile strength of the specimen greatly decreased after freeze-thaw cycles. As the emulsified asphalt content increased, the lubrication provided by the emulsion improved the compactibility of the specimen. At the same time, when there was enough emulsified asphalt to fill the voids between the aggregates, the void ratio of the mixture and the influence of the freeze-thaw action decreased and the tensile strength ratio of the mixture increased. Therefore, the tensile strength ratio increased following an increase in the emulsified asphalt content. As the content of emulsified asphalt increased, the lubrication of the emulsion promoted the compaction of the specimen and the emulsion filled the gaps between the aggregates, which reduced the void ratio of the mixture, reduced the freezing-thaw effect of the mixture, and finally, the freeze-thaw splitting strength ratio of the mixture was increased. Therefore, the freeze-thaw splitting strength ratio increased as the emulsified asphalt content increase. When the emulsified asphalt content was constant and the cement content was increased, the hydration product of the cement improved the water stability of the mixture, so that the stability of the water increased with the increase of the cement content.

6. Conclusions

(1) Changes in the cement and emulsified asphalt contents significantly influenced the strength characteristics of cement-emulsified asphalt mixture. At a constant cement content of 3%, when the emulsified asphalt content increased from 6% to 9%, the indirect tensile strength, compressive strength, and modulus of resilience first increased and then decreased. At a constant emulsified asphalt content of 8%, when the cement content increased from 0% to 4%, the indirect tensile strength first increased and then decreased. The compressive strength and modulus of resilience reached the maximum when the cement content was about 3%.

(2) The addition of cement significantly improved the high-temperature stability and moisture susceptibility of cement-emulsified asphalt mixture but was not conducive to the low-temperature performance of the mixture. The optimal mixture abrasion resistance was observed at a cement content between 2% and 3%.

(3) In the cement-emulsified asphalt mixture, the cement reacted with the external moisture and moisture from the demulsification of the asphalt. The AFt interlaced with the asphalt film to form a grid structure, which improved the moisture susceptibility and high-temperature stability of the mixture [18].

(4) Due to the properties of the cement and emulsified asphalt, the internal structure of cement-emulsified asphalt mixture was looser than traditional hot-mix asphalt mixture. Bubbles formed during the molding process of the mixture, 'voids' were left after the bubbles ruptured, voids were also left by the evaporation of moisture following demulsification, pores of various sizes were observed, and the voids between aggregates after compaction generated a complex voided structure in the cement-emulsified asphalt mixture. The mesoscopic void structure formed by the different cement and emulsified asphalt contents also significantly affected the mechanical properties and road performances of the cement-emulsified asphalt mixtures.

Declaration of Competing Interest

None.

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