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Early-age Strength and Long-term Performance of Asphalt Emulsion Cold Recycled Mixes with Various Cement Contents

Jinhai Yan[1], Zhen Leng[2]*, Feng Li[3], Haoran Zhu[4], Shihui Bao[5]

ABSTRACT

Cold recycling with asphalt emulsion is an economical and environment-friendly technology for asphalt pavement maintenance and rehabilitation. This study aims to investigate the early-age strength and long-term performance of the asphalt emulsion cold recycled mixes with various cement contents, as well as the correlation between the early-strength and long-term performance. To achieve this objective, three research tasks were conducted, including: 1) quantifying the early-age strength of four types of asphalt emulsion cold recycled mixes by measuring their cohesive forces and raveling loss rates through the Hveem cohesion test and raveling test, respectively; 2) characterizing their

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[1] PhD, National Engineering Laboratory for Advanced Road Materials, Jiangsu Transportation Institute Group, 2200 Chenxin Street, Nanjing, China, 211112, jason.yan1@gmail.com

[2] Assistant Professor, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, zhen.leng@polyu.edu.hk
(*Corresponding Author)

[3] Engineer, National Engineering Laboratory for Advanced Road Materials, Jiangsu Transportation Institute Group, 2200 Chenxin Street, Nanjing, China, 211112, lf78@jsti.com

[4] PhD, National Engineering Laboratory for Advanced Road Materials, Jiangsu Transportation Institute Group, 2200 Chenxin Street, Nanjing, China, 211112, zhr75@jsti.com

[5] Assistant Engineer, National Engineering Laboratory for Advanced Road Materials, Jiangsu Transportation Institute Group, 2200 Chenxin Street, Nanjing, China, 211112, bsh359@jsti.com

long-term performance properties, including moisture stability, high-temperature stability, and low-temperature cracking resistance; and 3) developing the correlation models between the early-age strength and long-term performance of asphalt emulsion cold recycled mixes through regression analysis. It was concluded that adding cement in cold recycled mixes played positive effects on both its early-age strength and long-term performance. In addition, strong linear correlation was found between the early-age strength and long-term performance of asphalt emulsion cold recycled mixes.

KEY WORDS: Reclaimed asphalt pavement; cold recycling; asphalt emulsion; cohesive force; raveling loss rate; failure strain

1 INTRODUCTION

Cold recycling of reclaimed asphalt pavement (RAP) is a cost-effective and environment-friendly technology, which has been widely applied for asphalt pavement maintenance, rehabilitation and reinforcement [1]. Asphalt emulsion, foamed asphalt and cement have been commonly added to RAP to produce cold recycled mixes. Due to the curing effects of asphalt emulsion, cold recycled mixes with asphalt emulsion show different performance characteristics, especially at the early stage, compared with hot-mix asphalt (HMA). Correspondingly, various research studies have been conducted on the mix design, long-term performance, performance evaluation and prediction, and economic and environmental analysis of cold recycling [2-11]. In general, asphalt emulsion cold recycled mixes have been reported to provide satisfactory performance in terms of moisture damage resistance, rutting resistance, and low-temperature cracking resistance compared with HMA [12-15]. However, very few studies have systematically looked into the early-age strength, long-term performance, and their correlation of asphalt emulsion cold recycled mixes with and without cement. As a result, this study aims to investigate the early-age strength and long-term performance of asphalt emulsion cold recycled mixes with different cement contents, as well as their correlation. The early-age strength of the cold mixes was evaluated through the Hveem cohesion test and raveling test, while the long-term performance was characterized through tests on their moisture stability, high-temperature stability, and low-temperature cracking resistance

2 EXPERIMENTAL PROGRAM

2.1 Materials

The RAP samples used to produce the cold recycled mixes in this study were collected from the surface and binder courses of the Ning-Xuan highway in Nanjing, China. The binder extraction and recovery tests indicated that the asphalt content of RAP was 4.3%. The 25 ºC penetration, softening point, and 15 ºC ductility of the extracted RAP binder were 24 (0.1mm), 65 ºC, and 14 cm, respectively. Virgin coarse limestone aggregates (16mm-31.5mm) were added to the cold recycled mixes to improve interface friction between aggregate. The asphalt emulsion used in this study is a cationic slow-setting asphalt emulsion (CSS-1h), and its properties are shown in Table 1. Ordinary Portland cement with a 28-day compressive strength of 42.5 MPa (labelled as PO 42.5 according to the Chinese specification standards, JTJ 034-2000) was used, and its properties are presented in Table 2. Pre-mix water was added to cold recycled mixes to improve the coating of the RAP and virgin aggregates, lubricate the mix during compaction, and accelerate the cement hydration reaction.

TABLE 1 Test Results and Technical Requirements of Asphalt Emulsion

Test Item	Results	Technical Requirement	Test Method
Velocity of setting	Slow	Slow or medium	T0658
Charge	Cationic	Cationic	T0653
Residual content on sieve (1.18 mm), %	0.10	≤0.1	T0652
Standard viscosity, C25.3, s	22	10-60	T0621
Coating characteristic with coarse aggregate, coating squares, %	＞80	≥66.7	T0654
Residue content by evaporation, %	65.7	≥62	T0651
Penetration, 25ºC, 1/10 mm	63	50-150	T0604
Soften point, ºC	47	-	T0606
Ductility,15 ºC, cm	50	≥40	T0605
Solubility in TCE, %	99.5	≥97.5	T0607
Storage stability, 1 day, %	0.3	≤1	T0655
Storage stability, 5 day, %	0.5	≤5	T0655

TABLE 2 Test Results of Ordinary Portland Cement PO 425

Test Item	Results	Technical Requirement	Test Method
Initial setting time, min	405	≥180	T0505
Final setting time, min	455	≥360	T0505
Soundness, mm	1.0	≤5.0	T0505
Compressive strength, 3d, MPa	24.7	≥18.0	T0506
Flexural strength, 3d, MPa	5.0	≥3.5	T0506

In total, four cold recycled mixes as shown in Table 3 were prepared and evaluated. Among the four mixes, Mix III was the design mix for cold recycling adopted in Ning-Xuan highway, and the other three mixes, which have various percentages of cement, were selected to evaluate the effect of cement content. The gradation of the combined RAP and virgin aggregate was designed to meet the requirement of the Chinese specification for cold recycling (JTG F41-2008), as shown in Figure 1.

TABLE 3 Material Compositions of Cold Recycled Mixes

Mix	RAP (%)	Virgin Coarse Aggregate (%)	Asphalt Emulsion (%)	Portland Cement (%)	Pre-mix Water (%)
I	85	15	4.3	0	2.6
II	85	15	4.3	1.0	2.6
III	85	15	4.3	1.5	2.6
IV	85	15	4.3	2.0	2.6

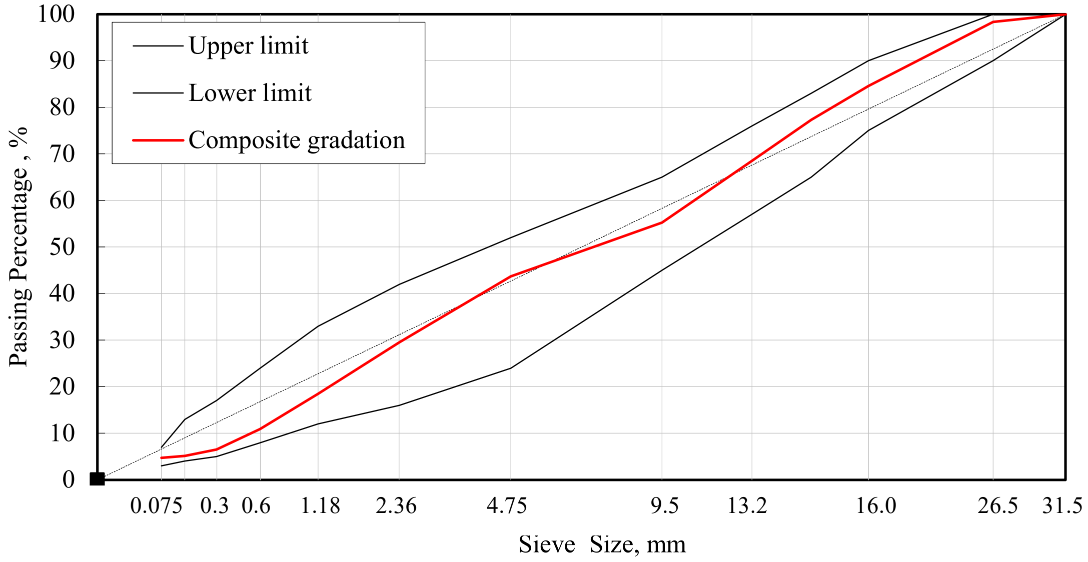

FIGURE 1 Cold Recycled Mix Gradation

2.2 Early-age Strength Characterization

The early-age strength of the cold recycled mixes was quantified by the Hveem cohesive test and raveling test. The test specimens for these two tests were 150 mm in dimeter and 80 ± 3.0 mm in height, and 150 mm in diameter and 70 ± 5.0 mm in height, respectively. 20 gyrations of compaction were applied to each specimen using a Superpave gyratory compactor. Three replicates were prepared for each mix, and all specimens were cured at a temperature of 25 °C and a humidity of 70% for 4 h.

2.2.1 Cohesion Test

The cohesion test was performed in accordance with ASTM D1560-81. Figure 2 shows the Hveem cohesiometer used in this study and a failed specimen after testing. During this test, steel balls keep falling into the bucket at the end of the cantilever beam at a constant speed. The test will stop when the specimen cracks or the vertical deformation is more than 13 mm. The cohesion force value, C (g/cm^2), is calculated based on the weight of steel balls in the bucket using the following equation

$$C = \frac{L}{W \times (0.031H + 0.00269H^2)} \tag{1}$$

where L, W, and H represent the ball weight (g), the specimen diameter (cm), and the specimen height (cm), respectively.

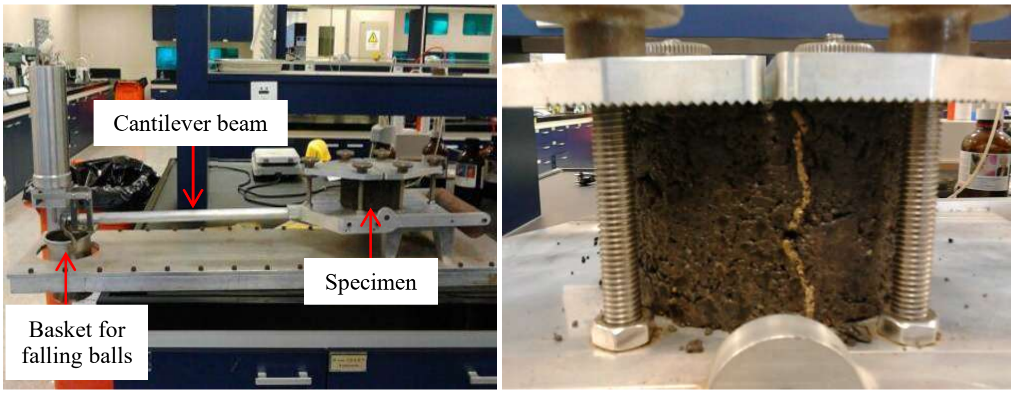

FIGURE 2 Hveem cohesiometer (left) and specimen after failure (right)

2.2.2 Raveling Test

The raveling test was performed in accordance with ASTM D7196-06. Figure 3 shows the raveling tester used in this study and the specimen before and after testing. This test measures the raveling resistance of asphalt emulsion cold recycled mixes by simulating the abrasion caused by early-age traffic. The test is continued for 15 minutes or until a major part of the specimen is broken. When the test is completed, the specimen will be carefully removed from the base and its surface will be gently brushed with a paint brush to remove any loose material. Then, its weight will be measured and the raveling loss rate, L (%), can be calculated using the following equation:

$$L = \frac{W_a - W_b}{W_a} \times 100 \tag{2}$$

where W_a, and W_b represent the weight of the specimen before raveling test (g), and the weight of the specimen after raveling test (g), respectively.

FIGURE 3 Raveling tester and raveling specimen

2.3 Long-term Performance Characterization

The long-term performance characteristics of the cold recycled mixtures evaluated in this study include moisture susceptibility, high-temperature stability, and low-temperature cracking resistance.

Three tests, including the immersion Marshall test, immersion indirect tensile strength (IDT) tests, and freeze-thaw IDT test, were conducted to assess the moisture susceptibility of the fully cured asphalt emulsion mixes. The high-temperature stability and the low-temperature cracking resistance of the fully cured asphalt emulsion mixes were evaluated through wheel track rutting test, and three-point bending test, respectively.

2.3.1 Moisture Susceptibility

2.3.1.1 Immersion Marshall test

Two groups of specimens with each group three replicates were prepared for the immersion Marshall test. The specimens in group 1 were soaked in a water bath at 40 ± 1 °C for 1 h before the Marshall test, while the specimens in group 2 were soaked in a water bath at 25 °C for 23 h, and then placed in a water bath at 40 ± 1 °C for 1 h before the Marshall test. The percentage of residual stability, RS (%), was calculated according to the following equation:

$$RS = MS_2 / MS_1 \times 100\% \tag{3}$$

where MS_2 and MS_1 represent the Marshall stability of specimen in group 2 (kN) and Marshall stability of specimen in group 1 (kN), respectively.

2.3.1.2 Immersion IDT test

Two groups of specimens with each group three replicates were prepared for the immersion IDT test. The specimens in group 1 and group 2 were conditioned with the same methods before testing as those for the immersion Marshall test. The IDT samples were subjected to a load at a vertical displacement rate of 50 mm/min at 15 ºC until the specimen failed. The percentage of the IDT strength ratio, $TSR_{d\text{-}w}$ (%), was calculated according to the following equation:

$$TSR_{d-w} = IDT_2 / IDT_1 \times 100\% \tag{4}$$

Where IDT_2, and IDT_1 represent the IDT strength of the specimen in group 2 (MPa), and the IDT strength of the specimen in group 1 (MPa), respectively.

2.3.1.3 Freeze-thaw IDT test

Two groups of specimens with each group three replicates were prepared for the freeze-thaw IDT tests. The specimens in both groups were soaked in a 25 ºC water bath for at least 2 h before testing at 25 ºC. But in addition, the specimens in group 2 were first vacuum saturated to 55 %-75 %, sealed in plastic bags at -18 ºC for 16 h, and placed in a water bath at 60 ºC for 24 h after removal from the plastic bags. The percentage of the IDT strength ratio, TSR (%), was calculated according to the following equation:

$$TSR = RT_2 / RT_1 \times 100\% \tag{5}$$

where RT_1, and RT_2 represent the IDT strength of the specimen in group 2 (MPa), and the IDT strength of the specimen in group 1 (MPa), respectively.

2.3.2 High-temperature Stability Test

To determine the rutting resistance of the cold recycled mixes, the wheel track test was conducted at 60 ± 1 °C in accordance with JTG E20-2011. Three replicates were prepared for each mix, and the dimensions of each specimen were 300 mm x 300 mm x 50 mm. The dynamic stability (DS), which is defined as the number of wheel passes that causes 1 mm rut from 45 minutes to 60 minutes, was calculated by the following equation:

$$DS = (t_2 - t_1) \times N / (d_2 - d_1) \qquad (6)$$

where t_1 and t_2 are 45 min and 60 min, respectively; d_1 and d_2 represent the vertical deformations at 45 min and 60 min, respectively; and N represents the rolling speed of rubber wheel, which was 42 cycles/min.

2.3.3 Low-temperature Cracking Resistance Test

To evaluate the low temperature cracking resistance of cold recycled mixes, the three-point bending test was conducted at -10 °C with a loading rate of 50 mm/min in accordance with JTG E20-2011. The dimensions of the specimens were 250 mm x 30 mm x 35 mm. The tensile strength and tensile strain at failure were calculated by Equations 7 and 8, respectively. The ratio of the tensile strength and strain at failure was denoted as stiffness, as shown in Equation 9. The failure strain was calculated to evaluate the low-temperature cracking resistance of the asphalt mix.

$$R = 3Pl / 2bh^2 \tag{7}$$

$$\varepsilon = 6hd / l^2 \tag{8}$$

$$S = R / \varepsilon \tag{9}$$

where R, P, b, h, l, d, ε, and S represent tensile strength (MPa), peak load (kN), width of specimen (cm), thickness of specimen (cm), length of specimen (cm), deformation at failure (cm), strain at failure, and stiffness (MPa), respectively.

3 RESULTS AND DISCUSSION

3.1 Early-age Strength

Figure 4 shows the results of the Hveem cohesion test and raveling test. It can be seen that among the four mixes, Mix I, which did not contain cement, had the lowest cohesion force and highest raveling loss rate. In general, a higher cement content leads to a higher cohesion force and a lower raveling loss rate, indicating that adding cement provides positive effect on the early-age strength of asphalt emulsion cold recycled mixes.

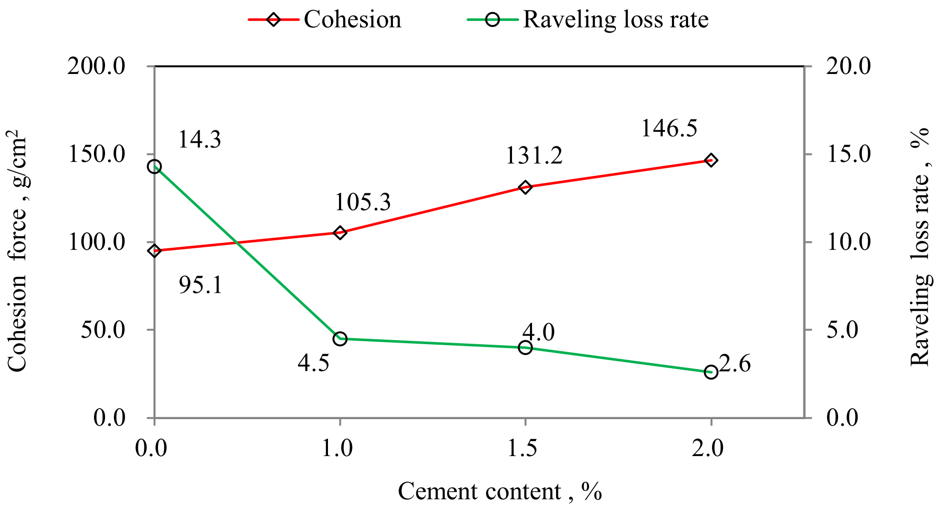

FIGURE 4 Results of cohesion and raveling tests

3.2 Long-term Performance

3.2.1 Moisture Susceptibility

Table 4, Figure 5, and Figure 6 show the results of the moisture susceptibility tests. From Figure 5, it can be seen that Mix I, which contained no cement, had the lowest Marshall stability and IDT strength. A higher cement contents leads to higher MS, IDT and RT values. From Figure 6, it can be observed that RS, TSR_{d-w} and TSR values increase with the increase of cement content, while the results of Mixes II and III are close to each other. The results indicated that adding cement improved the long-term strength and moisture stability of asphalt emulsion cold recycled mixes.

TABLE 4 The Results of Moisture Susceptibility Test

Mix	MS_1 (kN)	MS_2 (kN)	RS (kN)	IDT_1 (MPa)	IDT_2 (MPa)	TSR_{d-w} (%)	RT_1 (MPa)	RT_2 (MPa)	TSR (kN)

I	7.64	5.76	75.4	0.7842	0.6521	83.2	0.4977	0.3528	70.9
II	7.88	6.14	77.9	0.7953	0.6704	84.3	0.5787	0.4105	79.2
III	8.23	6.47	78.6	0.8117	0.6916	85.2	0.5921	0.4592	79.4
IV	8.55	7.03	82.2	0.9354	0.8214	87.8	0.6182	0.4818	81.4

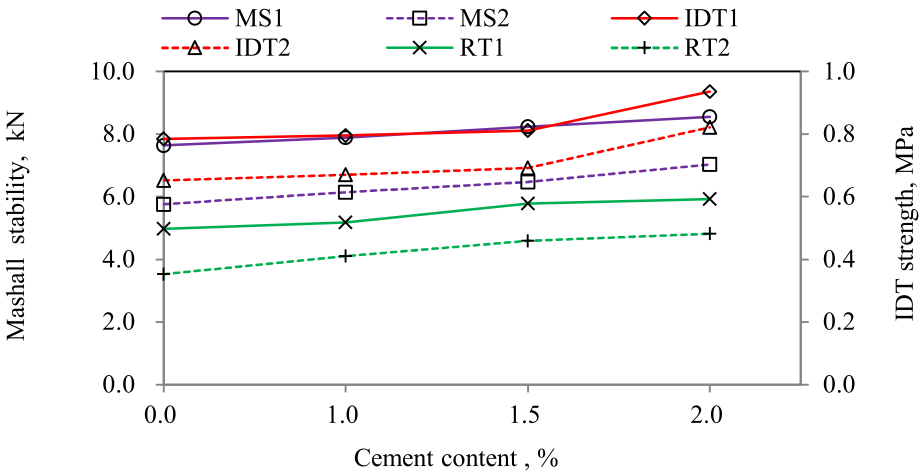

FIGURE 5 The strength results of Marshall test and IDT test

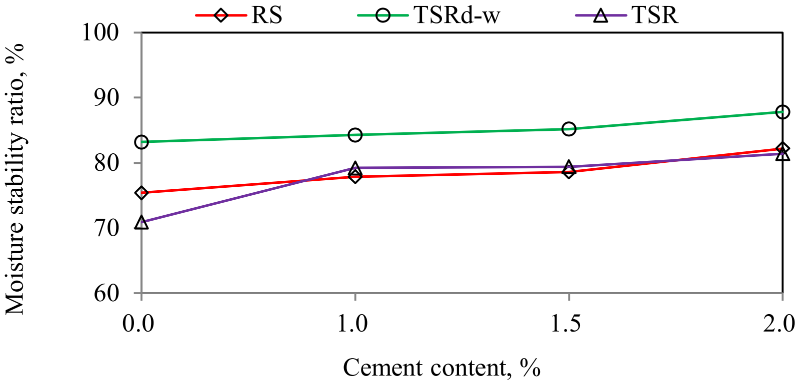

FIGURE 6 Results of the moisture susceptibility test

3.2.2 Wheel Track Rutting Resistance

Figure 7 shows the results for the wheel track rutting tests. It can be seen that Mix I containing no cement had the lowest DS value. With the increase of cement content, DS values increase. In other words, adding cement improved the high-temperature stability of asphalt emulsion cold recycled mixes.

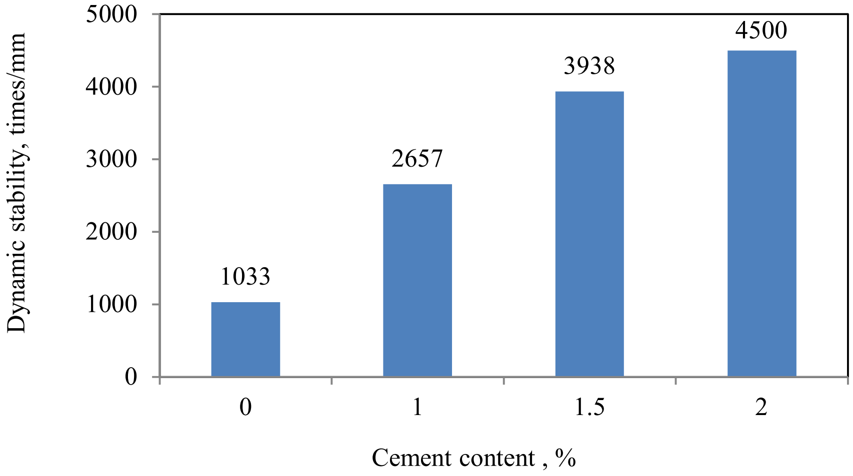

FIGURE 7 Results of wheel track rutting test

3.2.3 Low-temperature Cracking Resistance

Figure 8 shows the results of the low-temperature cracking resistance tests. It was found that Mix I containing no cement showed the lowest failure strain value. With the increase of cement content, the failure strain values first increases, and then decreases. Among the four mixes, Mix III, which contained 15% of cement, showed the best low-temperature cracking resistance. The results indicated that adding cement could increase the low temperature cracking resistance of cold recycled mix without cement, but there might exist an optimum cement content.

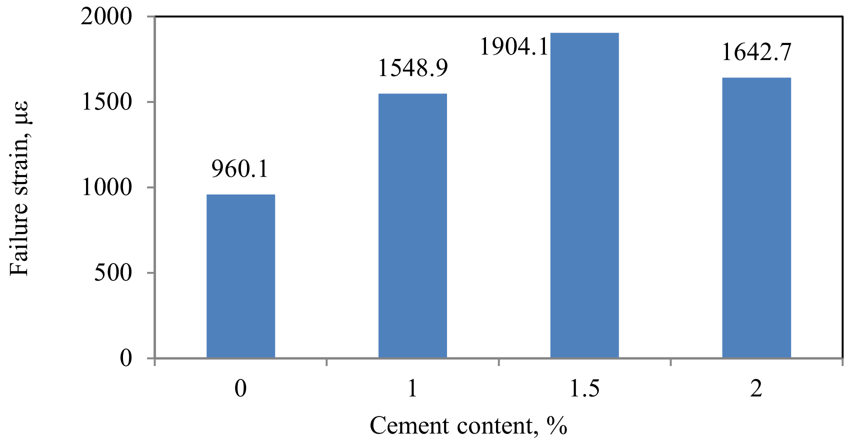

FIGURE 8 Results of low-temperature cracking resistance test

3.3 Correlation Analysis between Early-age Strength and Long-term Performance

Based on the results of raveling test and cohesion test, the linear correlation between raveling loss rate and cohesion force was developed as shown in Figure 9. In consideration of the relatively good correlation between cohesion force and raveling loss, as evidenced by a correlation coefficient (R^2) of 0.613, only one of these two variables, the cohesion force, was selected to develop the correlation models between the early-age strength and long-term performance of cold recycled mixes.

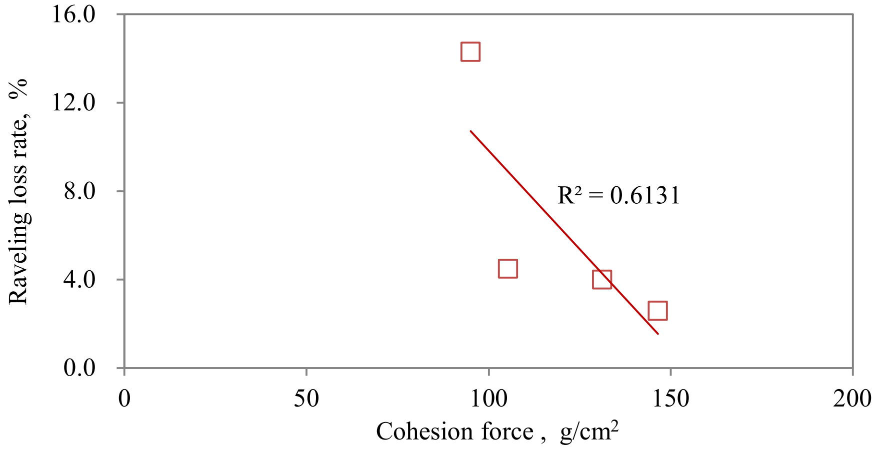

FIGURE 9 The correlation between cohesion force and raveling loss rate

Figures 10, 11 and 12, present the linear correlation models between the early-age strength and the long-term performances of asphalt emulsion cold recycled mixes. The correlation coefficients between cohesion force and Marshall stability, IDT strength, TSR_{d-w}, RS, TSR, dynamic stability, and failure strain are 0.990, 0.734, 0.904, 0.871, 0.904, 0.904 and 0.871, respectively. The high correlation coefficients indicate that the cohesion force has strong linear relation with various long-term performance characteristics of asphalt emulsion cold recycled mixes. The highest correlation coefficients were achieved between the cohesive force and IDT strength, TSR_{d-w}, and DS, which were all above 0.9. It is worth noting that the correlation between cohesive force and failure strain is different from others, since the relation between failure strain and cement content is not linear. But in general, strong linear correlations between the early-age strength property and various long-term performance properties of asphalt emulsion cold recycled mixes could be developed based on the linear correlation analysis.

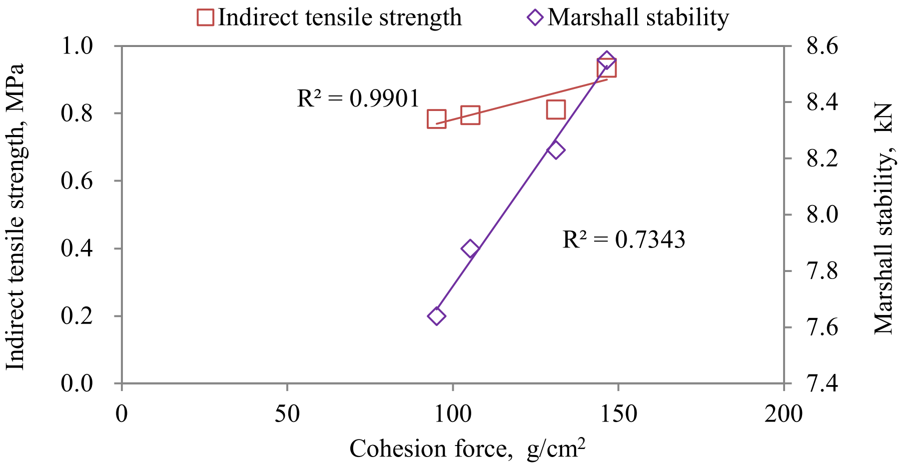

FIGURE 10 Linear correlation between cohesion force and long-term strength

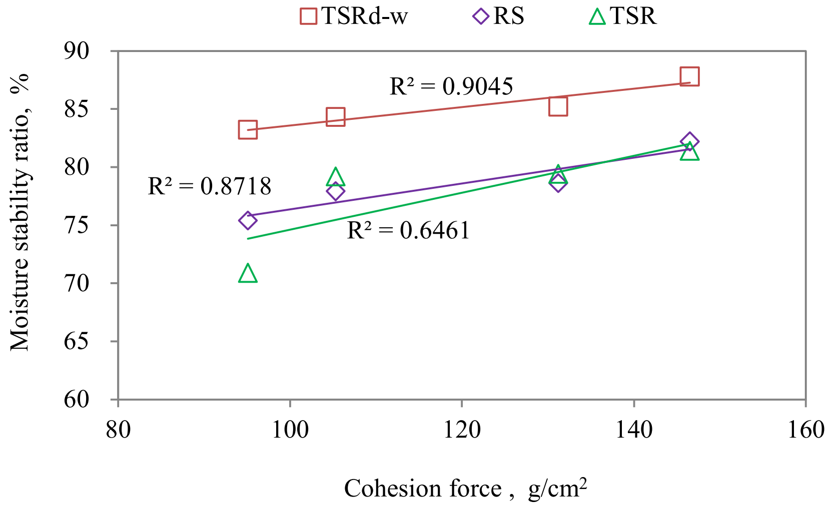

FIGURE 11 Linear correlation between cohesion force and moisture stability

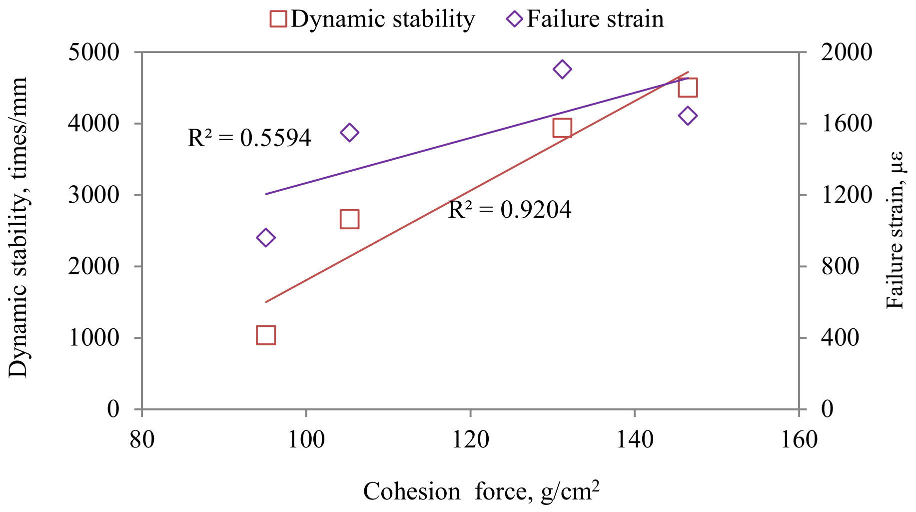

FIGURE 12 Linear correlation between cohesion force and DS and failure strain

4 CONCLUSIONS

This study investigated the early-age strength and long-term performance of asphalt emulsion cold recycled mixes with various cement contents, as well as their correlation. The following summarizes the major findings of this study:

1. The results of the Hveem cohesion test and raveling test indicated that a higher cement content results in a higher cohesive force and a lower raveling loss of the asphalt emulsion cold recycled mixes.
2. In general, adding cement in asphalt emulsion cold recycled mix improved its early-age strength, moisture stability, high-temperature stability and low-temperature cracking resistance.
3. With the increase of cement content, the moisture stability, high-temperature stability

and strength of cold recycled mixes increase, while the low-temperature cracking resistance increases first and then decreases.

4. A strong linear correlation between the early-age strength and long-term performance of cold recycled mixes with full curing exists based on the linear correlation analysis, and the correlation coefficients between IDT strength, $TSR_{d\text{-}w}$, DS and the cohesive force exceed 0.9.

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