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Research Article

Measurement of the Promoting Effect of Complex Conditions on the Adhesion Development in Curing Process of Cold Recycling Mixture with Emulsified Asphalt

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The curing process of cold recycling mixture with emulsified asphalt is a process of emulsion breaking, water evaporation, and cement hydration, resulting in adhesion development and strength formation. There are many factors that affect this process, including curing temperature, curing time, reclaimed asphalt pavement (RAP) contents, and cement contents. However, the evaluation of the promoting effect of each factor is still not quite clear. Hence, in this paper, the curing temperature, curing time, and RAP contents were discussed to find out the dominating factor in this process. The development of moisture loss and indirect tensile strength (ITS) was measured and analyzed through establishing prediction models between them and curing time. Besides, the functional relationship between moisture loss and ITS was also analyzed to evaluate the promoting effect of each factor. The results showed that the curing temperature has a certain impact on the development of moisture loss and ITS and an increase in curing temperature would accelerate the reaction rate, while RAP contents can hardly affect this process. Through functional relationship between moisture loss and ITS, it was found that the development of early strength and adhesion was dominated by ITS despite the increase of curing temperature and RAP contents. Expanding the hydration effect of cement could promote the curing process. However, this dominating role weakened at higher temperature and moisture loss should be treated more carefully.

1. Introduction

The cold recycling (CR) technology of asphalt pavement refers to the technology of milling, crushing, and screening the old asphalt pavement to make it into recycled aggregates (reclaimed asphalt pavement, RAP), adding new aggregates in a certain proportion, mixing with emulsified asphalt or foamed asphalt, cement, etc., at room temperature, and then paving the pavement structure layer. According to construction technology, the reclamation depth and the processing place, it can be divided into three methodologies: cold in-place recycling (CIR), cold central-plant recycling (CCPR), and full-depth reclamation [1].

CR with emulsified asphalt is a multiphase composite and thermodynamically incompatible semiloose system composed of emulsified asphalt evaporation residue, cement hydration products, RAP materials, new aggregates, and water [2]. Usually, 1.5%–2.5% cement would be added in CR with emulsified asphalt as an activator to accelerate breaking and improve the comprehensive performance. Due to the significant differences in properties between cement and bitumen emulsion in the stabilization agent of CR mixtures, it results in the diversity of influence factors in the process of adhesion development and strength formation, such as the amount of RAP materials, cement dosage, curing temperature, and curing time [3]. Besides, water is an essential component, it contributes to the homogeneous distribution of asphalt emulsion within the mixture, cement hydration, and convenient construction at room temperature [4–7].

Due to its increasingly widespread application worldwide [8–15], numerous studies have shown that the process of curing and adhesion development of CR mixtures are key issues in this field. The development of adhesion is a prerequisite for its

strength formation, and its strength is an important basic mechanical indicator in its application.

To figure out the process of adhesion development and strength formation, researchers have conducted extensive research. Lin et al. [3] emphasized the curing time and the macroscopic performance changes of CR mixtures. It was found that cement can promote the demulsification of emulsified asphalt in CR mixtures, while hydration products can increase internal friction, thereby improving the early and long-term macroscopic strength of the mixture. The curing temperature and moisture content have important effects on the early strength. Nassar et al. [16] evaluated curing temperature, cement content, and humidity through indirect tensile stiffness modulus and studied their influence on the process of strength formation. Kuchiishi et al. [17] conducted dynamic modulus tests on CR mixtures with different component contents and found that the content and type of asphalt and cement have important effects on the performance of the mixture. Kumar et al. [18] investigated the impact of different curing temperatures and curing periods and found that curing regime profoundly impacts the moisture loss and rate of evolution of the CR-Mix's stiffness properties. Ji et al. [19] studied the influence of different factors of cement content, water content, and cement–water ratio on the early strength of the cold recycled emulsified asphalt mixtures.

From the above, extensive research on the influencing factors has been conducted. However, these factors were simultaneously influencing the curing process and adhesion development of cold recycled mixtures. In order to study the impact of a certain variable, the method of controlling variables is usually used. However, the adhesion of emulsified asphalt mastic in cold recycled mixtures is mainly composed of emulsion demulsification and cement hydration [20, 21] and it is difficult to determine whether these variables affect the adhesion development process through affecting emulsion demulsification or cement hydration and which factor was the dominate one in this process only by controlling the variables. Emulsion demulsification or cement hydration both involve water transferring and the influence of these factors on the developing process of adhesion is mostly achieved by affecting the moisture content, resulting difficulty in relating these factors to demulsification and hydration directly. Therefore, it is necessary to explore a method that can directly connect them, deepen the understanding of adhesive development process, and figure out the dominate factor. Thus, many researchers are committed to conducting research in this area.

Saadoon et al. [22] investigated cold asphalt mixture samples with different contents and types of cement and proposed a new model to predict the contribution of cement hydration products to the total stability of cold asphalt mixtures. Orosa et al. [23] evaluated the short-term resilient behavior and found water loss during curing and stiffness increase were related. Ogbo et al. [24] explored the relationship between the amount of moisture in CIR and the mechanical properties of CIR. Raj et al. [25] evaluated the curing rate using moisture loss monitoring of mixture and strength development using indirect tensile strength (ITS) testing and wheel tracking testing. It revealed that curing period and temperature have a significant impact on the rate of moisture loss and strength gain. Graziani et al. [7] measured the evolution of water loss by evaporation and ITS and analyzed results using the method for biochemical reaction study, however, without considering effects of influencing factors. Since the process of adhesion development and strength formation is complicated, more influencing factors should be considered. Tedla et al. [26] designed cold mix containing 40% virgin aggregates and 60% RAP at varying air voids and determined the evolution of water loss, drying process based on rate of evaporation, moisture content, bulk density, air voids, and ITS for cured samples. A model using these parameters was established, and the relationship between the process of adhesion development and effects of influencing factors was analyzed. However, influencing factors analyzed were air voids and bulk density rather than universally acknowledged influencing factors such as curing temperature, cement content, and RAP materials content.

Therefore, in this paper, in order to explore the development laws of moisture loss and adhesion of cold recycled mixtures with emulsified asphalt and link various influencing factors to moisture loss, Michaelis–Menten model was applied to analyze the development of moisture loss and ITS growth under different curing temperatures, curing times, and RAP materials contents. Besides, the development of moisture loss and ITS were related through formula derivation, and the promoting effect of these influencing factors was measured. Hence, the dominate factor was determined. In addition, relevant studies have shown that there is a significant positive correlation between the early adhesion development of CR mixtures and their long-term performance [27]. Thus, this paper also made suggestions to improve long-term performance of CR mixture with emulsified asphalt.

2. Experimental Program

2.1. Raw Materials. CR mixture with emulsified asphalt mainly consists of RAP materials, emulsified asphalt, water, cement, and new aggregate.

2.1.1. RAP Materials. The composition of the crushed RAP materials is relatively complex, including coarse aggregate, fine aggregate, and aged asphalt blocks. Hence, the RAP materials were screened into 10−30, 5−10, and 0−5 mm, and the results are shown in Figure 1.

The asphalt content of aged asphalt wrapped on the surface of RAP materials was measured, and the results are shown in Table 1.

Penetration, ductility, and softening point of aged asphalt wrapped on the surface of RAP materials were measured, and the results are shown in Table 2. The experiments were based on Chinese Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (hereinafter referred to as Standard Test Methods).

In Table 2, it was found that penetration and ductility significant decreased and softening point increased. It indicates

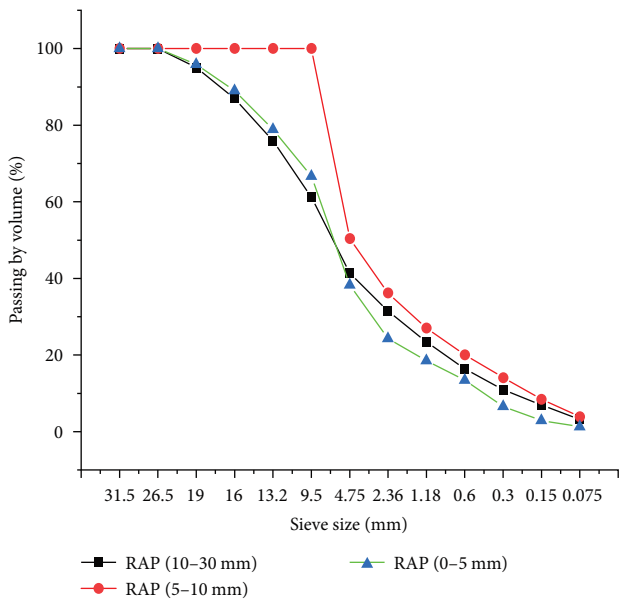


Figure 1: RAP grading composition.

Table 1: The asphalt content of aged asphalt.

	RAP (10–30 mm)	RAP (5–10 mm)	RAP (0–5 mm)
Aged asphalt content	4.02	4.71	6.24

Table 2: Results of penetration, ductility, and softening point of aged asphalt.

	Results	Standard
Penetration 25°C (0.1 mm)	22.7	60–80
Ductility 15°C (cm)	12.4	>100
Softening point (°C)	63.8	≥46

that the asphalt wrapped on the surface of RAP materials has been aged, and hence in this paper RAP materials would be used as "black aggregates."

2.1.2. Emulsified Asphalt. The adhesion ability to RAP materials, the softening ability to aged asphalt materials, and the compatibility with stone are the main considerations when selecting the type of emulsified asphalt. In China, at present, the selection for suitable emulsified asphalt is usually based on the analysis of RAP and engineering experience considerations. The technical requirements for emulsified asphalt applied in this research are shown in Table 3 and all technical indicators meet the specification requirements. The tests were based on Standard Test Methods. The evaporation residue of emulsified asphalt is shown in Figure 2, and the mixing of emulsified asphalt and RAP materials is shown in Figure 3.

2.1.3. Cement. Cement is used as an active filler to accelerate the demulsification process and effectively improve the early strength of the mixture. In this paper, PC32.5 composite Portland cement was applied, and the test results are shown in Table 4.

2.1.4. New Aggregates. It is probable that using RAP materials alone would not make the gradation of recycling asphalt mixture meet the specification requirements. Therefore, it is often necessary to add a certain amount of new aggregates to improve the gradation of recycling asphalt mixture. In this paper, the particle size of the added new aggregate is 10–20 mm, and the screening results are shown in Figure 4. The test results are listed in Table 5.

2.1.5. Filler. The mineral powder should be added when the grading composition of RAP materials does not meet the design grading requirements. Its purpose is to adjust the grading, reduce voids, and absorb water in cold recycled asphalt mixture. The general dosage of mineral powder is 0%–5%. The test results of filler are listed in Table 6.

2.2. Mixture Design. In this paper, according to Chinese Technical Specifications for Highway Asphalt Pavement Recycling (JTG/T 5521—2019), which referred to as Specifications for Highway Asphalt Pavement Recycling, the modified Marshall test method was adopted for the design of CR mixture with emulsified asphalt. This method is to estimate the approximate amount of emulsified asphalt according to the recommended empirical formula after selecting RAP materials, new aggregates, and emulsified asphalt. Then, the range of water content that meets the adhesion is determined based on different mixing water consumption. Finally, the amount of emulsified asphalt is changed to determine the optimal asphalt content of the mixture based on indicators such as Marshall stability, flow value, and voids. The design steps are as follows:

(1) Analysis and evaluation of RAP materials.

The indicators that need to be analyzed and evaluated are asphalt content of RAP materials, physical indicators of aged asphalt including penetration, ductility, softening point, and viscosity, chemical components of aged asphalt and grading of RAP materials.

(2) Selection of emulsified asphalt.

Emulsified asphalt is selected based on the Standard Test Methods and the testing index contains demulsification rate, particle charging, evaporation residue content, etc.

(3) Selection and determination of the proportion of RAP materials.

The proportion of RAP materials is the percentage of RAP materials in the total recycled mixture, and its determination should comprehensively consider the following factors: (1) the technical properties of RAP materials, including the degree of aging of aged asphalt, the gradation of RAP materials, asphalt content; (2) the purpose of applying recycled asphalt mixtures, namely application of structure position, application for different levels of traffic volume,

Table 3: The results and technical requirements for emulsified asphalt.

	Results	Standard
Demulsification rate	Slow breaking	Slow breaking or medium breaking
Particle charging	Cation (+)	Cation (+)
Evaporation residue content (%)	62.8	≥62
The remaining amount on the sieve (1.18 mm), not greater than (%)	0.04	0.1
Viscosity	5	2–30
Mixing test with mineral materials	Uniformly, wrapping area greater than 2/3	Uniformly, wrapping area not less than 2/3
Mixing test with cement, residue on sieve (%)	41.2	—
Storage stability (1 day) (%)	0.6	≤1

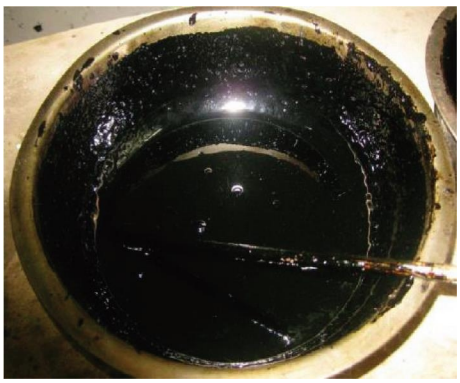


Figure 2: The evaporation residue of emulsified asphalt.

Figure 3: The mixing of emulsified asphalt and RAP materials.

Table 4: The results and technical requirements for cement.

	Results	Standard
Fineness (%)	2.4	≤10.0
Standard consistence (%)	28.1	—
Setting time		
Initial setting time (min)	198	≥45
Final setting time (min)	395	≤600
Stability	Qualified	Qualified
Strength		
3-day flexural strength	4.2	≥2.5
3-day compressive strength	19.1	≥11.0
28-day compressive strength	36.8	≥32.5

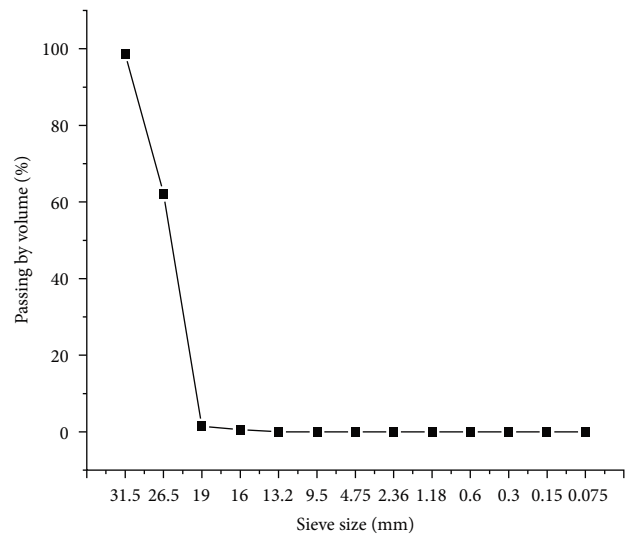


Figure 4: The screening results of new aggregates.

Table 5: The results and technical requirements for new aggregate.

	Results	Standard
Crushing value (%)	19.2	≤30
Abrasion loss (%)	8.2	≤35
Apparent relative density (t/m^3)	2.52	≥2.45
Water absorption rate (%)	0.6	≤3.0
Needle like content (%)	9.8	≤18
Mud content (%)	0.6	≤1

Table 6: The results and technical requirements for filler.

	Results	Standard
Screening, <0.075 (%)	82.8	75–100
Hydrophilicity coefficient	0.73	<1
Plasticity index (%)	2.5	<4
Density (g/cm^3)	2.570	—

etc.; (3) the technical level of construction; (4) socioeconomic benefits. Overall, the basic principle for determining the proportion of RAP materials is to maximize the savings of asphalt and gravel materials while ensuring the quality of

Table 7: Proportions of materials for different RAP dosages.

RAP content (%)	New aggregate (10–20 mm, %)	RAP (10–30 mm, %)	RAP (5–10 mm, %)	RAP (0–5 mm, %)	Filler (%)
90	10	41	13	34	2
80	20	31	13	34	2
70	30	12	22	34	2

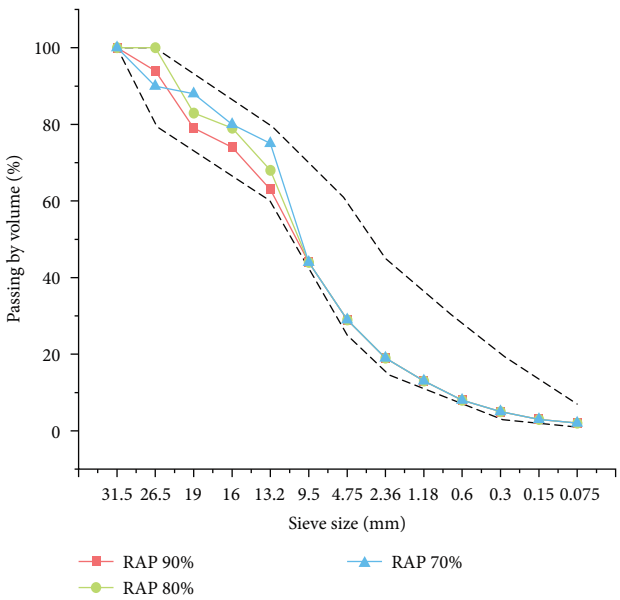


Figure 5: Grading curves cold recycling mixture for different RAP dosages.

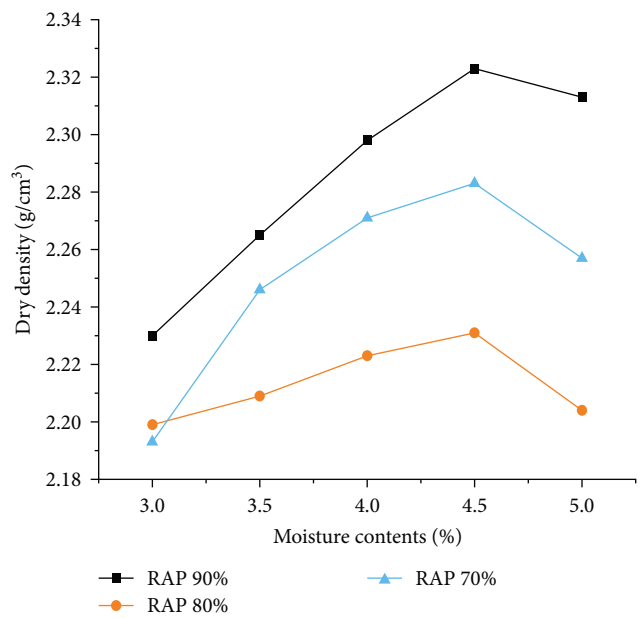


Figure 6: Dry density with five different moisture contents for three dosages of RAP.

recycled asphalt mixture and meeting road performance requirements and strive for the economic benefits as high as possible. In this paper, proportion of RAP materials was 70%, 80%, and 90%.

(4) Grading design of CR mixture.

According to the proportion of RAP materials, appropriately graded new aggregates were added to design the structure of the mixture, so that the recycling asphalt mixture has a good grading curve, ensuring the mixture could meet the Marshall index requirements, such as voids, density, etc. Besides, 2% filler was also added in the mixture to optimize grading curve and meet the Marshall index requirements. In this paper, the grading design is shown in Table 7 and Figure 5.

(5) Determination of the optimal water consumption.

The optimal fluid content (OFC) is used as an indicator to control all fluid contents in the mixture. Different amounts of emulsified asphalt are selected, and the water content is determined by calculating the OFC.

In this paper, soil compaction tests were conducted on recycling asphalt mixtures with five different moisture contents (3%, 3.5%, 4%, 4.5%, and 5%) to determine the maximum dry density. The mass ratio of water to emulsified asphalt is 1 : 1. The results are shown in Figure 6.

In Figure 6, it could be found that when the moisture content is 4.5%, the dry density of recycling asphalt mixtures reaches the peak. The dry density of 70% RAP, 80% RAP, and 90% RAP is 2.283, 2.231, and 2.323 g/cm^3, respectively. Therefore, 4.5% is the optimal moisture content for the three dosages of RAP.

(6) Determination of the optimal emulsified asphalt content.

Based on the preliminary formulation of the water consumption and emulsified asphalt content, specimens with different amounts of emulsified asphalt were formed. The optimal emulsified asphalt content is determined through Marshall stability, flow number, voids, etc., and optimum asphalt content (OAC) calculation methods in the Standard Test Methods.

In this paper, cold recycled specimens are formed with different emulsified asphalt contents (2.5%, 3.0%, 3.5%, 4.0%, and 4.5%), 1.5% cement and 4.5% water content and relevant indicators were tested. The test results are summarized in Table 8.

In Table 8, it can be seen that based on the maximum density, maximum voids, maximum Marshall stability, as well as the requirement of voids and ITS not less than 0.7 MPa, the OAC value is calculated. Based on the above results, the recommended content of emulsified asphalt for 90% RAP is 3.8%, 80% RAP is 4.1%, and 70% RAP is 4.3%.

Table 8: Test results of cold recycling asphalt mixture with different emulsified asphalt content.

RAP content (%)	Emulsified asphalt content (%)	Relative density (g/cm^3)	Voids (%)	Marshall stability (kN)
90	2.5	2.303	7.57	18.62
	3.0	2.292	7.26	20.9
	3.5	2.290	6.40	22.76
	4.0	2.319	5.07	23.37
	4.5	2.320	5.35	23.41
80	2.5	2.334	6.77	22.81
	3.0	2.333	6.44	21.91
	3.5	2.328	7.61	25.71
	4.0	2.328	7.05	27.14
	4.5	2.334	7.54	27.03
70	2.5	2.333	6.92	12.51
	3.0	2.323	7.44	23.98
	3.5	2.317	7.19	23.25
	4.0	2.333	8.40	28.64
	4.5	2.322	7.97	29.25
Technical requirement	—	—	7–12	≥8

Table 9: The mixture design results.

Number	RAP content (%)	New aggregate (10–20 mm, %)	RAP (10–30 mm, %)	RAP (5–10 mm, %)	RAP (0–5 mm, %)	Filler (%)	Cement content (%)	Emulsified asphalt content (%)	Water content (%)
1	90	10	41	13	34	2	1.5	3.8	4.5
2	80	20	31	13	34	2	1.5	4.1	4.5
3	70	30	12	22	34	2	1.5	4.3	4.5

Above all, the mixture design results in this paper are shown in Table 9.

2.3. Variable Selection and Testing Method

2.3.1. Variable Selection.

(1) Internal Conditions. The internal factors that affect the adhesion development of cold recycled mixtures with emulsified asphalt are mainly the amount of RAP materials, cement dosage, water content, emulsified asphalt content, etc.

RAP materials, as an important component of cold recycled mixtures, have a significant impact on their adhesion development. The surface of RAP materials is coated with aged asphalt, which combines with new asphalt to develop adhesion. When using different amounts of RAP materials, the proportion of aged asphalt in the mixture varies and hence the adhesion of the mixture will change. Based on this, this study uses RAP dosage as one of the variables. According to Xiao et al. [1] and Giani et al. [28], theoretically all of the RAP materials can be reused in new blended mixture, especially in CIR technology. However, in this way, there will be some mechanical properties and durability losing. To avoid this situation as much as possible and maintain the advantage of high RAP materials usage in CR technology, in this paper, 90%, 80%, and 70% RAP materials were chosen.

In addition, some internal factors have been optimized during the mix design, and the optimal dosage has been selected, such as water content and emulsified asphalt content. Lin et al.'s [3] study has shown that maximum ITS can be achieved under the optimal content of these factors. The experimental research results are shown in Figure 7.

According to the experimental results shown in Figure 7, as the emulsified asphalt content and water content increase, the trend of ITS showed a continuous increase and then a continuous decrease and reached the peak value at 4% emulsified asphalt content and 3.6% water content. From this, although the emulsified asphalt content and water content have a significant impact on the early adhesion development of cold recycled mixtures, after the mix design, it is already at the optimal amount and the ITS can reach the maximum value. Therefore, in this study, the emulsified asphalt content and water content will not be discussed anymore.

Meanwhile, for the cement content, Lin et al.'s [3] study has shown that as the cement content increases, the early strength continues to improve, and there is no optimal cement content to achieve a maximum ITS value. From this, when economic factors are not considered, the more cement is used, the higher ITS of the cold recycled mixture can be obtained. However, engineering practice has shown that the cement content should be strictly controlled. A higher cement dosage may counteract the flexibility provided by emulsified asphalt and RAP materials and increase the probability of dry shrinkage and temperature shrinkage of the mixture. Therefore, in Specifications for Highway Asphalt Pavement Recycling, the cement dosage exceeding 1.5% is inadvisable

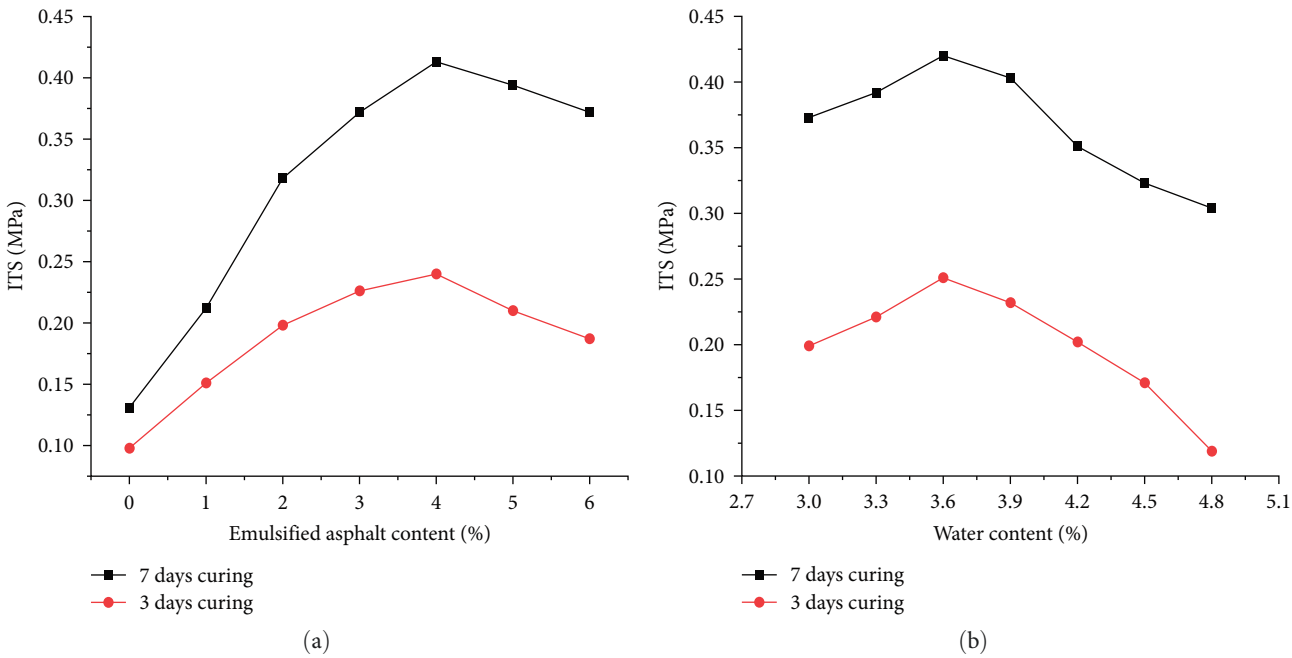


Figure 7: (a, b) ITS under different emulsified asphalt content or different water content [3].

and should not be more than 1.8%, in the mix design process. Therefore, in the mix design process of this study, a 1.5% cement dosage was used, and this factor will not be discussed anymore.

(2) External Conditions. The external factors influencing the adhesion development of cold recycled mixtures with emulsified asphalt mainly include curing temperature, curing time, and curing humidity.

Currently, many scholars have conducted research on the effect of curing temperature on the ITS of cold recycled mixtures, and results are shown in Figure 8.

In Figure 8, as the curing temperature increases, values of ITS continuously increase with the prolongation of curing time. The increase in curing temperature can promote water evaporation, accelerate the demulsification of emulsified asphalt, and accelerate the cement hydration reaction. Therefore, in this study, the impact of curing temperature would be discussed and the temperatures of 20 and 40°C were chosen.

In addition, changes in curing humidity will also affect the adhesion development rate of cold recycled mixtures with emulsified asphalt [29, 30]. In Specifications for Highway Asphalt Pavement Recycling, there is no regulations about curing humidity. Therefore, in this paper, curing humidity will not be discussed.

Curing is a process in which the adhesion slowly develops, and strength continuously improves. In Figure 8, adhesion during this process is closely related to the curing time. Therefore, in this study, the effect of curing time on the adhesion will also be discussed and tests would be conducted at 1, 3, 7, 14, and 28 days.

2.3.2. Testing Method. In this paper, moisture loss and ITS were conducted to analyze the process of emulsion breaking and strength formation, namely the curing process.

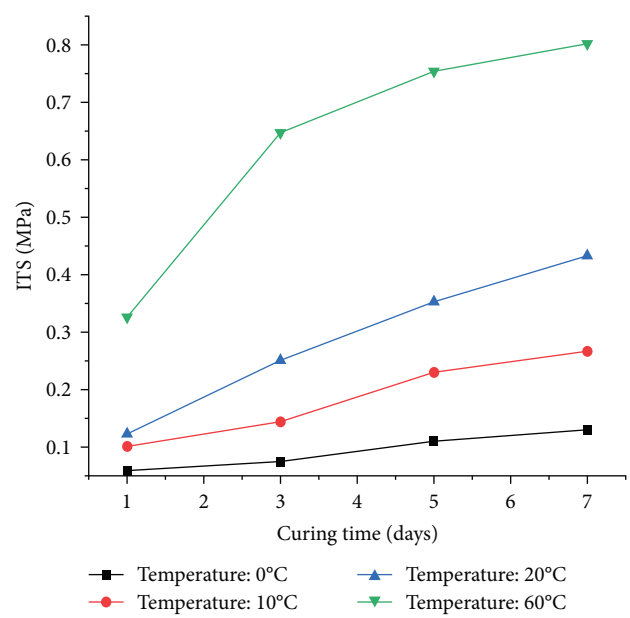


Figure 8: Influence of curing temperature on ITS [3].

Moisture loss was measured by carefully weighing each specimen in this process before ITS tests. ITS tests were conducted based on Standard Test Methods (T 0716-2011). In the curing process, both the moisture loss tests and ITS were conducted at 1, 3, 7, 14, and 28 days.

2.4. Compaction and Curing. In this paper, the compaction method used is the Marshall compaction method. In the process of mixture design, according to Specifications for Highway Asphalt Pavement Recycling, when determining

Table 10: Results of moisture loss under 20 and 40°C curing temperature.

Temperature (°C)	Time (days)				
	1	3	7	14	28
			90% RAP		
20	0.52%	0.95%	1.54%	1.90%	2.22%
	0.52%	0.94%	1.55%	1.92%	2.18%
	0.54%	0.90%	1.58%	1.85%	2.17%
40	1.19%	2.11%	2.71%	3.28%	3.45%
	1.18%	2.10%	2.70%	3.29%	3.50%
	1.20%	2.15%	2.73%	3.33%	3.48%
			80% RAP		
20	0.60%	1.10%	1.78%	2.25%	2.50%
	0.61%	1.09%	1.78%	2.17%	2.45%
	0.60%	1.12%	1.76%	2.23%	2.54%
40	1.30%	2.18%	2.69%	3.12%	3.28%
	1.28%	2.20%	2.68%	3.08%	3.27%
	1.31%	2.21%	2.70%	3.13%	3.30%
			70% RAP		
20	0.55%	0.99%	1.62%	2.10%	2.34%
	0.53%	1.01%	1.60%	2.16%	2.32%
	0.55%	0.99%	1.63%	2.08%	2.28%
40	1.29%	2.24%	2.83%	3.36%	3.54%
	1.28%	2.25%	2.85%	3.30%	3.50%
	1.31%	2.26%	2.86%	3.28%	3.48%

the optimal amount of emulsified asphalt, evenly mixed mixtures were loaded into the test mold and placed on the Marshall compactor. The required compaction frequency is 50 times on both sides. Then, the sample and test mold together were placed in a 60°C blast oven for curing until they reached constant weight. After this, the sample and the test mold were taken out of the oven and immediately placed on the Marshall compactor to compact 25 times on both sides.

In the process of moisture loss and ITS tests, mixed mixtures were placed on the Marshall compactor to compact 50 times on both sides. Then, the sample and test mold together were placed in 20 or 40°C ovens for curing. At 1, 3, 7, 14, and 28 days, samples were taken out to measure moisture loss first and then measure ITS.

3. Results and Analysis

3.1. Evaluation of Moisture Loss. In the processes of emulsified asphalt demulsification and cement hydration, the former will release water while the latter absorbs water. Therefore, the water content during the strength formation process of CR asphalt mixture is an important observation point. The moisture loss during the process of emulsion breaking and strength formation under 20 and 40°C curing temperature is shown in Table 10.

In Table 10, it can be seen that as the curing process continues, the moisture loss of specimens with 90%, 80%, and 70% RAP contents continues to increase both at the curing temperature of 20 and 40°C.

In addition, in Table 10, it can also be observed that there is no significant difference in moisture loss of recycled mixtures with 90%, 80%, and 70% RAP contents at the same curing time, regardless of whether the curing temperature is 20 or 40°C. It is probable that during the mixture design, the recycled mixtures with three different RAP contents applied the same moisture content and cement content.

Comparing the moisture loss under 20 and 40°C conditions, it can be seen that high temperature will significantly increase the rate and amount of moisture loss. Taking the recycled mixture with a 90% RAP dosage as an example, the moisture loss at 28 days under 20°C is 2.18% on average, while at 40°C conditions, it is 3.48% at 28 days on average.

In order to further analyze the water loss during this process and lay a foundation for the analysis of promoting effects of complex conditions in curing process, the results of moisture loss were used to establish a prediction model in Section 3.3, and it will be illustrated thoroughly in that section.

3.2. Evaluation of Indirect Tensile Strength. Results of ITS during the process of emulsion breaking and strength formation under 20 and 40°C curing temperature are shown in Table 11.

In Table 11, it can be seen that as the curing time continues, the results of ITS of the cold recycled mixture gradually increase. This pattern exists at both curing temperatures of 20 and 40°C and also exists at RAP content of 90%, 80%, and 70%. This characteristic is consistent with the variation

Table 11: Results of ITS under 20 and 40°C curing temperature (MPa).

Temperature (°C)	Time (days)				
	1	3	7	14	28
			90% RAP		
20	0.31	0.58	0.78	0.95	1.04
	0.31	0.56	0.80	0.89	1.03
	0.33	0.57	0.82	0.88	1.00
40	0.45	0.76	0.95	0.98	1.15
	0.44	0.77	0.92	1.02	1.14
	0.46	0.76	0.96	0.96	1.12
			80% RAP		
20	0.35	0.65	0.85	1.00	1.11
	0.34	0.66	0.83	0.98	1.09
	0.33	0.68	0.86	0.95	1.13
40	0.49	0.78	0.99	1.05	1.21
	0.50	0.79	0.98	1.06	1.22
	0.51	0.76	1.01	1.05	1.26
			70% RAP		
20	0.37	0.69	0.91	1.11	1.21
	0.37	0.71	0.90	1.05	1.22
	0.39	0.71	0.92	1.06	1.25
40	0.53	0.88	1.08	1.16	1.31
	0.52	0.86	1.05	1.15	1.28
	0.55	0.89	1.06	1.14	1.33

pattern of moisture loss during the curing process. For further analysis of the development of ITS, SEM tests were conducted, and results are shown in Figure 9.

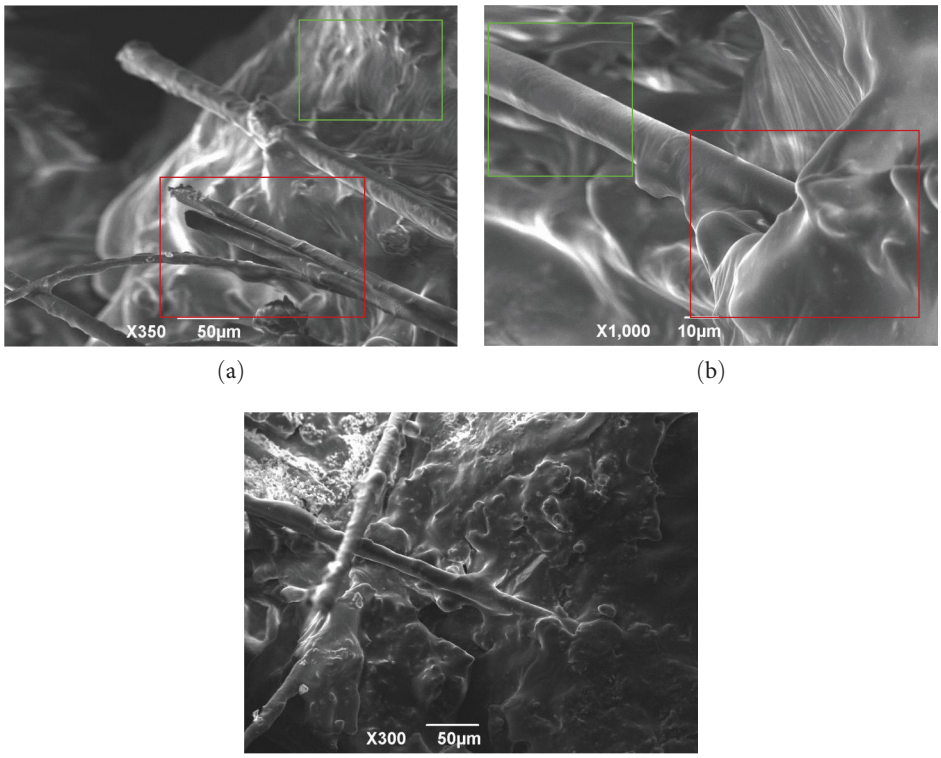
Figure 9 shows morphology of cement hydration products and demulsification state of emulsified asphalt in the process of ITS development. In Figure 9(a), dendritic cement hydration products could be seen (area in red box) and at this time emulsified asphalt have not yet wrapped around the hydration products (area in green box). Hence, at this time, the ITS of the cold recycled mixture mainly relied on cement hydration rather than the demulsification of emulsified asphalt.

In Figure 9(b), it could be found part of the emulsified asphalt mastic has been wrapped around the hydration products (area in red box), and some hydration products were still independent of emulsified asphalt mastic (area in green box). Compared with Figure 9(a), it indicates that the development of ITS of cold recycled mixture with emulsified asphalt still mainly relied on cement hydration. However, the combination of cement hydration and emulsified asphalt demulsification developed at this time. With the increase of time, this combination gradually developed and when the cement hydration products are fully combined with the emulsified asphalt mastic (as shown in Figure 9(c), almost all of cement hydration products are wrapped with emulsified asphalt mastic on the surface), the ITS of the cold recycled mixture with emulsified asphalt will be provided by both of them.

Comparing the ITS results under the same curing temperature condition and different RAP contents, it can be seen that as the RAP content increases, the ITS of the cold recycled mixture gradually decreases, and the ITS is approximately linearly related to the RAP content. It is illustrated that the application of RAP has a certain adverse effect on the ITS. Therefore, in many engineering practices, cold recycled mixtures are only applied on base or subbase course [1] in low-volume and medium-volume traffic [10, 11, 31] and seldom in high-volume traffic. Moreover, under the three RAP contents, the results of ITS are all greater than 0.6 MPa, which meets the specification requirements for the lower layer of surface course and base course of high-grade asphalt pavement. Therefore, the RAP content can be 90% or more if CR mixture with emulsified asphalt were intended for use on highways.

Compared with the same RAP content, the ITS test results under different curing temperature conditions show that as the temperature increases, the growth rate of ITS results accelerates. At the same curing time, the ITS of the recycled mixture at curing temperature of 40°C is higher than that at 20°C.

According to Specifications for Highway Asphalt Pavement Recycling, CR layer should be cured immediately after construction and curing time was inadvisable to be less than 7 days and should not be less than 48 hr. It also stipulated that ITS should be greater than 0.6 MPa when CR mixtures with emulsified asphalt are applied to heavy traffic load highways. From results in Table 11, when curing temperature was at 20°C, ITS at 7 days, all met this standard and some of ITS at 3 days met this standard. When the RAP materials content was 90%, 3 days ITS was less than 0.6 MPa. When RAP



(a) (b) (c)

Figure 9: Results of SEM tests in the process of ITS development: (a) 1 day, (b) 14 days, and (c) 28 days.

materials contents were 80% and 70%, 3 days ITS was greater than 0.6 MPa. When curing temperature at 40°C, regardless of the amount of RAP used, 3 days ITS meets this requirement. In this case, when constructed in hot season, the environment temperature is high, and effects of 48 hr curing can fully achieve that of 7 days curing at low-temperature season. Hence, it can further provide theoretical support for the requirement in the specification.

3.3. Establishment and Analysis of Prediction Model. Curing is a process of continuous moisture loss and gradual strength formation over time. The test results shown in Tables 10 and 11 indicate that the rate of moisture loss and ITS gradually decreases during the curing process, which can be divided into three stages [22]. The trends of moisture loss and ITS in curing process have similarity to the trend of speed of enzymatic reactions. Hence, this trend of moisture loss and ITS can be predicted and analyzed through Michaelis–Menten equation [32]. Michaelis–Menten equation is shown in Equation (1):

$$f(t) = \frac{y_A \cdot t}{K_m + t}, \tag{1}$$

where t(days) is the curing time, y_A is the value when the reaction approaches saturation and for moisture loss and ITS tests, y_A is the asymptotic value at the end of the reaction which is the long-term results of moisture loss and ITS, and K_m, also known as the Michaelis constant, is the value of t when the function reaches half of its asymptotic value.

It could be found that the development of moisture loss and ITS gradually stabilized from Tables 10 and 11. Since the adhesion development of cold recycled mixtures mainly relied on the demulsification of emulsified asphalt and cement hydration and it could be represented by moisture loss and ITS; hence, the adhesion development of cold recycled mixtures would gradually stabilize too. Besides, according to Tedla et al. [26] and Xuan et al. [30], the adhesion development of emulsified asphalt has exceeded 80% of the final adhesion after 28 days. Therefore, in this paper, it assumes that y_A is infinitely close to the results of moisture loss and ITS tests at curing time of 28 days and K_m equals to the curing time when the results of moisture loss and ITS tests reach half of the value of results at curing time of 28 days.

3.3.1. Establishment of Prediction Model. Prediction model of moisture loss and ITS were estimated, and results are shown in Figures 10 and 11. y_A and K_m of different conditions and regression parameters are listed in Table 12.

3.3.2. Model Reliability Analysis. To check the adequacy of the regression model, the following methods were used.

Assuming the Michaelis–Menten regression model is as follows:

$$Y = f(t, x_1, x_2) + \varepsilon, \tag{2}$$

where t(days) is time, x_1 and x_2 is y_A and K_m, respectively, Y is the calculation value of moisture loss or ITS for cold

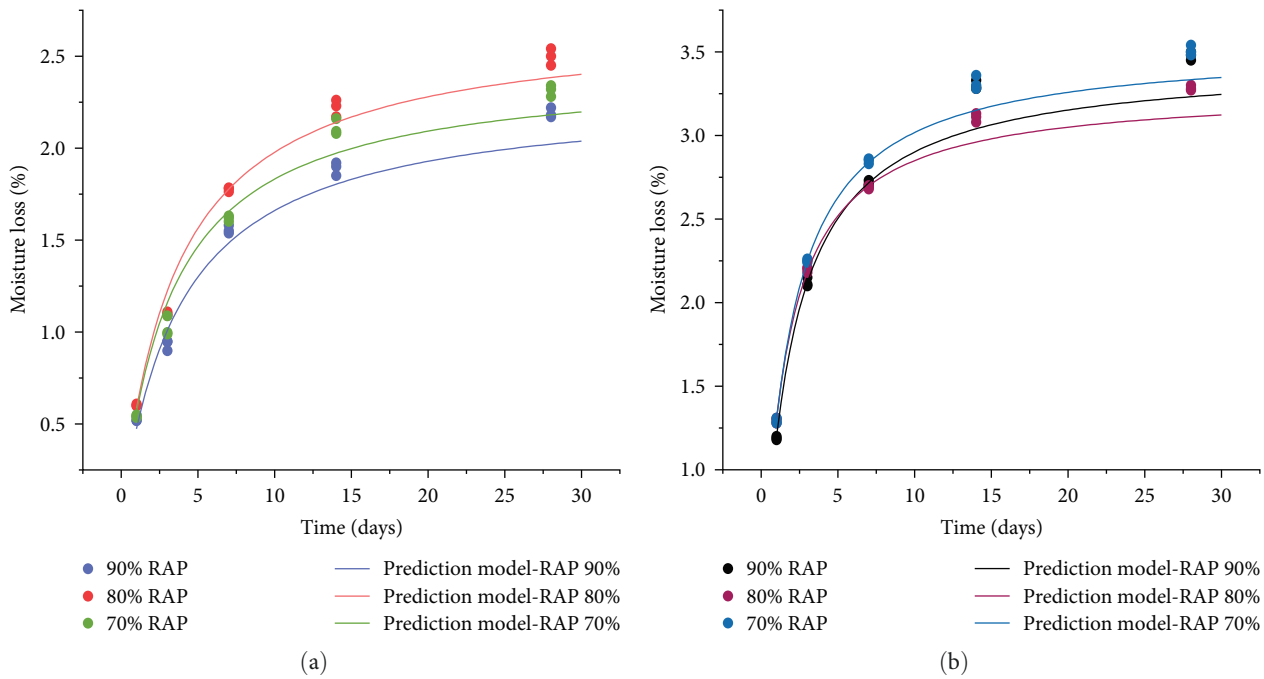


Figure 10: (a, b) Results of moisture loss at the curing temperature of 20 and 40°C.

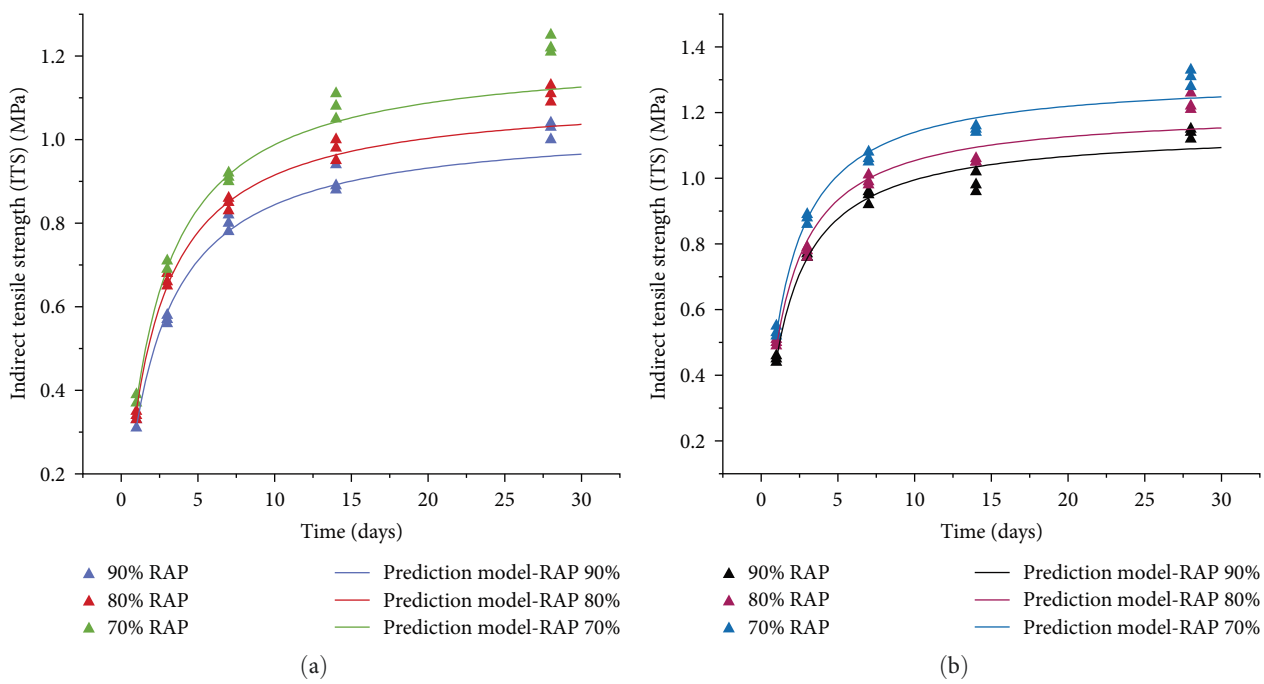


Figure 11: (a, b) Results of ITS at the curing temperature of 20 and 40°C.

recycled mixture with emulsified asphalt, and ε obeys normal distribution $N(0, \sigma^2)$.

Moisture loss or ITS tests were conducted 90 times, respectively, and 180 sets of measured values were obtained. They could be recorded as $(t_i, Y_i) i = 1, 2 \ldots, n,\ n = 90$ for moisture loss test and $(t_i, Y_i) i = 91, 92, \ldots, 2n$ for ITS.

Substituting the independent variable with the measured value:

$$Y_i' = \mathrm{f}(t). \tag{3}$$

The average experimental results of moisture loss and ITS of cold recycled mixture are $\overline{Y}_1 = \frac{1}{n}\sum_{i=1}^{n} Y_i$ and $\overline{Y}_2 = \frac{1}{n}\sum_{i=91}^{2n} Y_i$, respectively.

Hence, taking moisture loss results as examples to describe the reliability testing framework.

Table 12: y_A and K_m of different conditions and regression parameters.

Temperature (°C)	(a) y_A and K_m of moisture loss and regression parameters		
	y_A (%)	K_m (days)	R^2
	90% RAP		
20	2.18	3.85	0.9739
40	3.48	1.89	0.9659
	80% RAP		
20	2.50	3.60	0.9845
40	3.28	1.51	0.9751
	70% RAP		
20	2.32	3.32	0.9695
40	3.51	1.73	0.9685
Temperature (°C)	(b) y_A and K_m of ITS and regression parameters		
	y_A (MPa)	K_m (days)	R^2
	90% RAP		
20	1.04	2.32	0.9697
40	1.15	1.56	0.9710
	80% RAP		
20	1.11	2.13	0.9753
40	1.22	1.48	0.9739
	70% RAP		
20	1.21	2.25	0.9669
40	1.35	1.49	0.9834

$$Q_T = \sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2 = \sum_{i=1}^{n}\left[\left(Y_i - Y_i'\right) + \left(Y_i' - \overline{Y}\right)\right]^2 = \sum_{i=1}^{n}\left(Y_i - Y_i'\right)^2 + \sum_{i=1}^{n}\left(Y_i' - \overline{Y}\right)^2 + 2\sum_{i=1}^{n}\left(Y_i' - \overline{Y}\right)\left(Y_i' - \overline{Y}\right). \quad (4)$$

Equation (5) could be obtained through simplifying Equation (4):

$$Q_T = \sum_{i=1}^{n}\left(Y_i - Y_i'\right)^2 + \sum_{i=1}^{n}\left(Y_i' - \overline{Y}\right)^2. \quad (5)$$

Hence,

$$Q_{\mathrm{SSE}} = \sum_{i=1}^{n}\left(Y_i - Y_i'\right)^2. \quad (6)$$

$$Q_{\mathrm{ESS}} = \sum_{i=1}^{n}\left(Y_i' - \overline{Y}\right)^2. \quad (7)$$

$$Q_T = Q_{\mathrm{SSE}} + Q_{\mathrm{ESS}}. \quad (8)$$

Assuming H_0: The regression effect of the model is not significant.

Transforming Equations (6)–(8), Equation (9) can be obtained as follows:

$$\frac{1}{\sigma^2}Q_T = \frac{1}{\sigma^2}Q_{\mathrm{SSE}} + \frac{1}{\sigma^2}Q_{\mathrm{ESS}}. \quad (9)$$

The left side of Equation (9) follows a degree of freedom of $(n-1)$ χ^2 distribution. The degree of freedom of $\frac{1}{\sigma^2}Q_{\mathrm{SSE}}$ is $(n-p-1)$ and the degree of freedom of $\frac{1}{\sigma^2}Q_{\mathrm{ESS}}$ is p. Due to the independence of $\frac{1}{\sigma^2}Q_{\mathrm{SSE}}$ and $\frac{1}{\sigma^2}Q_{\mathrm{ESS}}$, the following equation can be obtained as follows:

$$F = \frac{Q_{\mathrm{ESS}}/p}{Q_{\mathrm{SSE}}/(n-p-1)}. \quad (10)$$

Equation (10) follows a degree of freedom of $(p, n-p-1)$ F distribution. When significance level $\alpha = 10\%$, Equation (11) can be obtained:

$$P = \{F \geq F_\alpha(p, n-p-1)\} = \alpha. \quad (11)$$

If $F \geq F_\alpha(p, n-p-1)$, H_0 would be rejected, and it could be concluded that the model regression was significant, and the model was reliable. Otherwise, the model regression was not significant.

The measured values of moisture loss and ITS of the cold recycled mixture were compared with the calculated values of the Michaelis–Menten regression model. The calculation results are shown in Table 13.

In Table 13, the regression on the moisture loss and ITS was significant through Michaelis–Menten model. Hence, the Michaelis–Menten model can be used to predict the

Table 13: Analysis of model regression.

(a) Moisture loss						
	20°C			40°C		
RAP material contents	90%	80%	70%	90%	80%	70%
Q_T	1.6395	2.1629	1.7748	2.8628	2.2129	2.8406
Q_{SSE}	0.0570	0.0384	0.0712	0.1050	0.0540	0.0890
Q_{ESS}	1.5825	2.1245	1.7034	1.7034	2.7578	2.7517
n	15	15	15	15	15	15
F	27.7773	55.3062	23.9157	26.2752	39.9831	30.9242
F_α $(p, n-p-1)$	5.46	5.46	5.46	5.46	5.46	5.46
H_0	Rejected	Rejected	Rejected	Rejected	Rejected	Rejected
Results	Significant	Significant	Significant	Significant	Significant	Significant
(b) ITS						
	20°C			40°C		
RAP material contents	90%	80%	70%	90%	80%	70%
Q_T	0.2850	0.3095	0.3823	0.2757	0.2939	0.3437
Q_{SSE}	0.0087	0.0075	0.0127	0.0068	0.0067	0.0050
Q_{ESS}	0.2763	0.3020	0.3696	0.2689	0.2873	0.3387
n	15	15	15	15	15	15
F	31.8472	40.1594	29.1031	39.6626	43.1855	67.8251
F_α $(p, n-p-1)$	5.46	5.46	5.46	5.46	5.46	5.46
H_0	Rejected	Rejected	Rejected	Rejected	Rejected	Rejected
Results	Significant	Significant	Significant	Significant	Significant	Significant

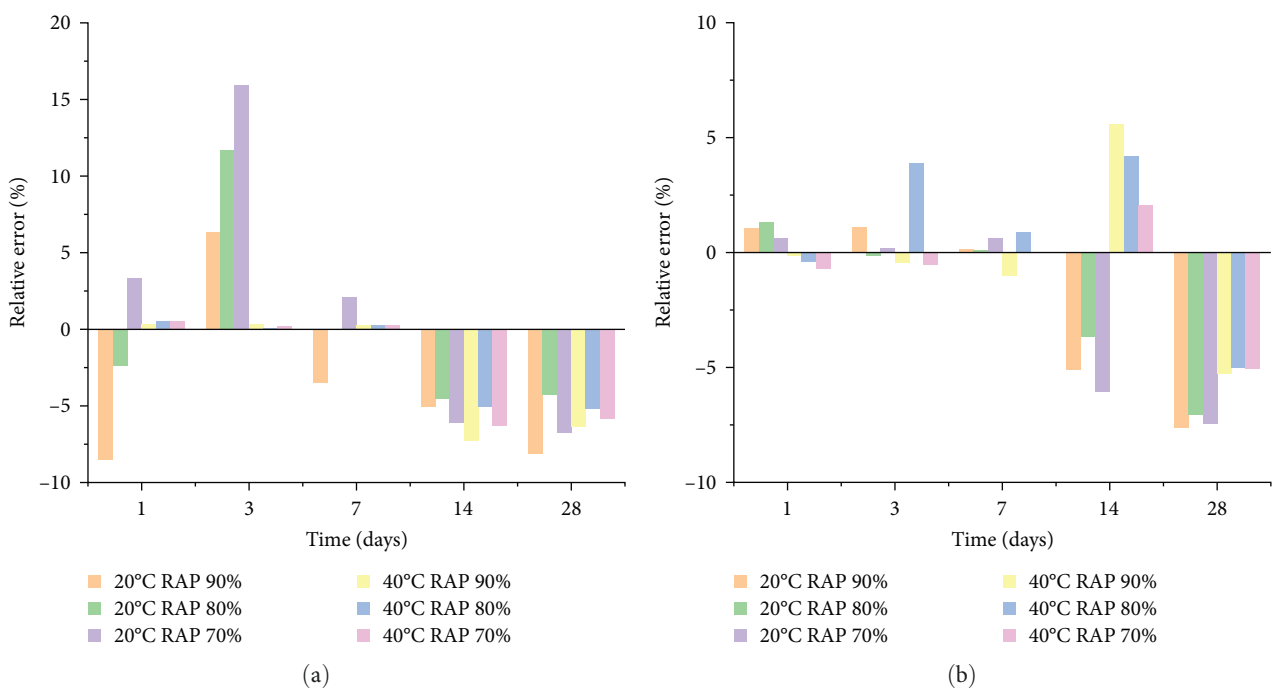


Figure 12: The relative errors of fitting curves. (a) Moisture loss. (b) ITS.

development of moisture loss and ITS. The model parameters shown in Table 12 were reliable.

Besides, the relative error of fitting curve is shown in Figure 12.

In Figure 12, it could be found that the relative errors of moisture loss and ITS were quite small generally. For moisture loss in Figure 12(a), the relative error of 3 days was relatively larger than others. Under 20°C and 70% RAP materials, the relative error was the largest and the value was 15.95%. Under 20°C and 80% RAP materials, the relative error was the second largest and the value was 11.69%. Other relative errors were all less than 10%. For ITS in Figure 12(b), the relative errors were all quite small and they are all less than 10%. Hence, it indicates that the

regression effect is significant, and the prediction model was reliable.

3.3.3. Analysis and Discussion of Prediction Model. In Sections 3.1 and 3.2, it has already been found that high temperature will significantly increase the rate of moisture loss and ITS; however, this rate of growth decelerates with the curing time increases. In Table 12 and Figures 10 and 11, this pattern can be seen more directly. Taking the recycled mixture with a 90% RAP dosage as an example, at curing temperature of 20 and 40°C for moisture loss K_m is 3.85 and 1.89 days, respectively, and for ITS K_m is 2.32 and 1.56 days, respectively. This rule has been applied to some studies to shorten the curing time by increasing the curing temperature.

Also, in Sections 3.1 and 3.2, it was found that with the increase of curing temperature, the amount of moisture loss and ITS increases. Also taking the recycled mixture with a 90% RAP dosage as an example, at curing temperature of 20 and 40°C for moisture loss y_A is 2.18% and 3.48%, respectively, and for ITS y_A is 1.04 and 1.15 MPa, respectively. For moisture loss, it is possible that an increase in temperature will accelerate the evaporation of water under the same other conditions which indirectly promotes the breaking of emulsified asphalt. For ITS, results also slightly increase under the condition of curing temperature increasing and it is probable that the increase of temperature accelerates the cement hydration reaction, which is an effective promoting factor for the early strength of CR asphalt mixtures. Therefore, increasing curing temperature is an effective method to shorten curing time and increase early strength.

3.4. Promoting Effects of Complex Conditions on the Adhesion Development. The curing process is a process of emulsion breaking, water evaporation, cement hydration, and strength formation. Since cement hydration is one of the important factors to promote early strength formation, the development of ITS in the early stage could be used to evaluate the development of cement hydration. Hence, it is important to evaluate the promoting effects by analyzing moisture loss and ITS.

To clarify the promoting effects of complex conditions (in this paper, the curing temperature and RAP contents were discussed) on the adhesion development of recycling mixture with emulsified asphalt, the relationship between moisture loss and ITS under different curing temperatures and RAP contents was analyzed.

Prediction model established in Section 3.3.1 described the relationship between moisture loss or ITS and curing time. Due to the fact that variables are all curing time, and hence the functional relationship between moisture loss and ITS can be derived through analysis.

From Equation (1), Equations (12) and (13) can be obtained:

$$f(t_{\text{moisture loss}}) = \frac{y_{A,\text{moisture loss}} \cdot t}{K_{m,\text{moisture loss}} + t}. \tag{12}$$

$$f(t_{\text{ITS}}) = \frac{y_{A,\text{ITS}} \cdot t}{K_{m,\text{ITS}} + t}. \tag{13}$$

Observing Equations (12) and (13), it could be found that if $K_{m,\text{moisture loss}} < K_{m,\text{ITS}}$, the rate of moisture loss was faster than that of ITS, and in this case, the development of early strength formation was dominated by moisture loss. If $K_{m,\text{moisture loss}} > K_{m,\text{ITS}}$, the rate of ITS was faster than that of moisture loss, and the development of early strength formation was dominated by cement hydration.

t was obtained from Equation (12), and hence we get the following equation:

$$t = \frac{K_{m,\text{moisture loss}} \cdot f(t_{\text{moisture loss}})}{y_{A,\text{moisture loss}} - f(t_{\text{moisture loss}})}. \tag{14}$$

Substituting Equation (14) into Equation (13), we get the following equation:

$$f(t_{\text{ITS}}) = \frac{y_{A,\text{ITS}} \cdot \frac{K_{m,\text{moisture loss}} \cdot f(t_{\text{moisture loss}})}{y_{A,\text{moisture loss}} - f(t_{\text{moisture loss}})}}{K_{m,\text{ITS}} + \frac{K_{m,\text{moisture loss}} \cdot f(t_{\text{moisture loss}})}{y_{A,\text{moisture loss}} - f(t_{\text{moisture loss}})}}. \tag{15}$$

Organizing Equation (15) and making its form into Equation (1), Equation (16) was obtained:

$$f(t_{\text{ITS}}) = \frac{\alpha \cdot f(t_{\text{moisture loss}})}{\beta + f(t_{\text{moisture loss}})}, \tag{16}$$

where

$$\alpha = \frac{y_{A,\text{ITS}} \cdot K_{m,\text{moisture loss}}}{K_{m,\text{moisture loss}} - K_{m,\text{ITS}}}. \tag{17}$$

$$\beta = \frac{K_{m,\text{ITS}} \cdot y_{A,\text{moisture loss}}}{K_{m,\text{moisture loss}} - K_{m,\text{ITS}}}. \tag{18}$$

Hence, the values of ITS and moisture loss could be linked through a Michaelis–Menten type equation, and this relationship is reported in Figure 13. Since $y_{A,\text{moisture loss}}$, $K_{m,\text{moisture loss}}$, $y_{A,\text{ITS}}$, and $K_{m,\text{ITS}}$ are all positive, α and β would be both positive when $K_{m,\text{moisture loss}} > K_{m,\text{ITS}}$ and they would be both negative when $K_{m,\text{moisture loss}} < K_{m,\text{ITS}}$ obviously. Therefore, when $K_{m,\text{moisture loss}} > K_{m,\text{ITS}}$, the development of early strength formation was dominated by cement hydration, and α and β would be both positive. When $K_{m,\text{moisture loss}} < K_{m,\text{ITS}}$, the development of early strength formation was dominated by moisture loss, and α and β would be both negative.

In Figure 13, it could be found that curvature at different temperatures was significantly different. The curvature of Equation (16) at 20°C was convex and that of 40°C was concave and almost straight. In addition, the curvature at the same temperature with different RAP contents has similarity. To analyze the curvature of Equation (16) at different temperatures with different RAP contents, the second derivative was calculated and listed in Equation (19).

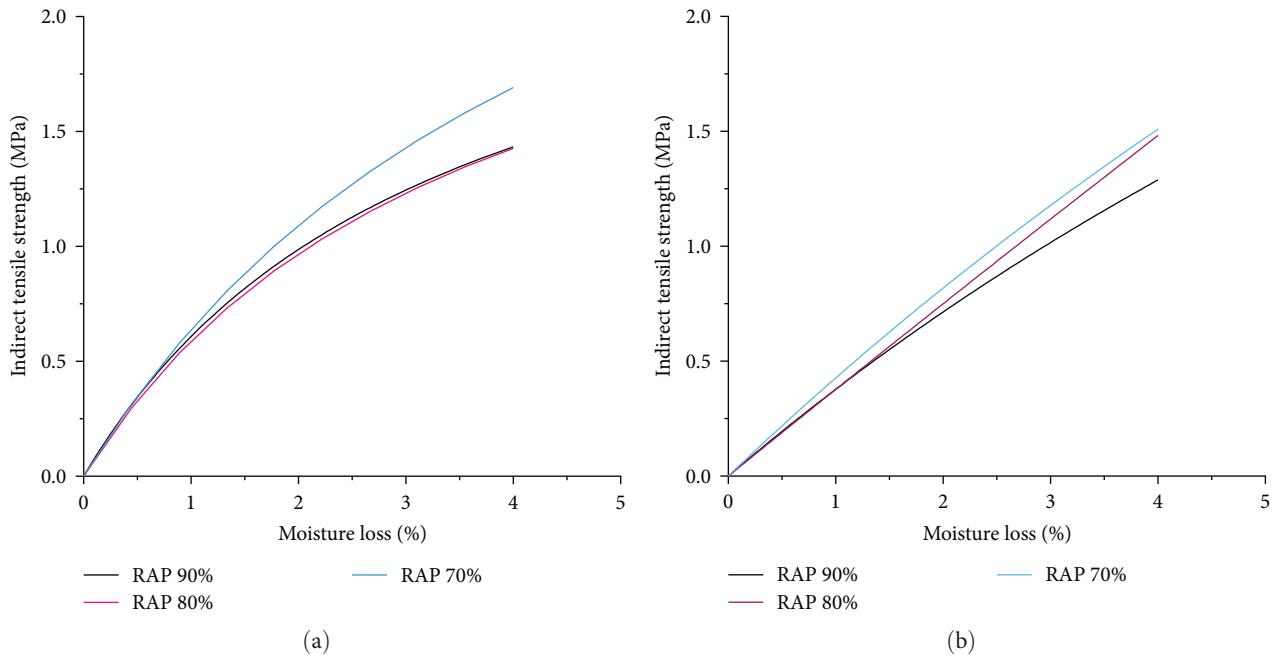


Figure 13: The relationship between moisture loss and ITS: (a) at the temperature of 20°C and (b) at the temperature of 40°C.

$$f''(t_{\mathrm{ITS}}) = \frac{d^2 f(t_{\mathrm{ITS}})}{df(t_{\mathrm{moisture\,loss}})^2} = \frac{-2 \cdot \alpha \cdot \beta}{(\beta + f(t_{\mathrm{moisture\,loss}}))^3}. \quad (19)$$

Observing Equation (19), it could be found that if the value of Equation (19) was positive, the curvature would be concave. In this case α and β were both negative and $|\beta|$ should be greater than $f(t_{\mathrm{moisture\,loss}})$. As for the development of early strength formation, it was dominated by moisture loss. Besides, if the value of Equation (19) was negative, the curvature would be convex. In this case, α and β were both positive and the development of early strength formation was dominated by ITS. In this way, the development of early strength and adhesion is linked with the value of α and β and the curvature of Equation (16).

Observing Figure 13 again, the curvature of Equation (16) at 20°C with three contents of RAP was convex. Hence, it indicates that at temperature of 20°C, the development of early strength and adhesion was dominated by ITS, and this result is independent of the amount of RAP used. In addition, at the temperature of 40°C despite the fact that α and β were both positive, the curvature was smaller than that at the temperature of 20°C. It indicates that with the increase of curing temperature, although the development of early strength and adhesion was still dominated by ITS, the degree has weakened. Also, with the increase of the content of RAP, the curvature increased at this temperature. It shows that the increase of the RAP content would enhance the dominating role of ITS in the process of adhesion development.

Due to the close relationship between long-term performance and early strength of CR mixture with emulsified asphalt [27], the way of improving early strength can enhance long-term performance to some extent. Hence, when cured at 20°C, long-term performance can be improved by expanding the hydration effect of cement. When cured at 40°C, moisture loss should be treated more carefully compared with that at a lower curing temperature. Also, when RAP content is higher, long-term performance can be enhanced by ensuring cement hydration.

4. Conclusions

The curing process of CR mixture with emulsified asphalt is a process of emulsion breaking, water evaporation, and cement hydration, resulting in adhesion development and strength formation. There are many factors that affect this process, including curing temperature, curing time, RAP contents, and cement contents.

In this paper, the curing temperature (20 and 40°C), curing time (1, 3, 7, 14, and 28 days), and RAP contents (90%, 80%, and 70%) were discussed to find out the dominating factor in this process. The development of moisture loss and ITS were analyzed through establishing prediction models between them and curing time. Besides, the functional relationship between moisture loss and ITS was also analyzed to evaluate the promoting effect of each factor. It can be concluded that:

(1) For moisture loss, there is no significant difference with the increase of RAP contents as the curing process continues, regardless of the curing temperature. Besides, high temperature will significantly increase the rate and amount of moisture loss.

(2) For ITS, under the same curing temperature, as the RAP content increases, it gradually decreases, and the application of RAP has a certain adverse effect on it. Under 90%, 80%, and 70% RAP contents, the results of ITS are all greater than 0.6 MPa, which

meets the specification requirements for the lower layer of surface course and base course of high-grade asphalt pavement. Therefore, the RAP content can be 90% or more if CR mixture with emulsified asphalt were intended for use on highways. Besides, as the temperature increases, the growth rate of ITS results accelerates.

(3) Prediction models were established using Michaelis–Menten equation, characterizing the relationship between moisture loss and curing time, ITS and curing time under different curing temperature and RAP contents, respectively.

(4) Functional relationship between moisture loss and ITS was established and organized into the form of Michaelis–Menten equation. If the value of Equation (11) was positive, the curvature of Equations (6–8) would be concave, and the development of early strength formation was dominated by moisture loss. If the value of Equation (11) was negative, the curvature would be convex, and the development of early strength formation was dominated by ITS.

(5) At curing temperature of 20°C, the development of early strength and adhesion was dominated by ITS and this result is independent of the amount of RAP used. Besides, at curing temperature of 40°C, the curvature was smaller than that at the temperature of 20°C. It indicates that with the increase in curing temperature, although the development of early strength and adhesion was still dominated by ITS, the degree has weakened.

(6) When cured at 20°C, long-term performance can be improved by expanding the hydration effect of cement. When cured at 40°C, moisture loss should be treated more carefully compared with that at lower curing temperature.

(7) When ITS was used as evaluation index, it indicates that effects of 3-day curing at 40°C can achieve that of 7-day curing at 20°C. In this case, when constructed in hot season, effects of 48 hr curing can fully achieve that of 7 days curing at low temperature season. Hence, it can further provide theoretical support for the requirement in the specification.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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