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Study on Cold Recycled Asphalt Mixtures with Emulsified/Foamed Asphalt in the Laboratory and On-Site

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Abstract: Millions of tons of reclaimed asphalt pavement (RAP) and reclaimed aggregate or reclaimed inorganic binder stabilized aggregate (RAI) is produced every year in China. The cold recycled mixture (CRM) technology reduces fuel consumption, emissions, and cost and utilizes the high content of RAP. In this paper, six types of CRM with varying RAP/RAI composition and asphalt binders were investigated. The laboratory tests included strength indicators, high temperature stability, low temperature crack resistance, water stability, and dynamic modulus. A full-scale trial section was constructed after the laboratory tests. Except for low temperature failure strain without secondary compaction in the mixture design, test results illustrated that the performances of different CRMs met the specifications. The cement addition limited the thermo-viscoelastic behavior of the CRM. The RAI contents had reduced the water sensitivity of CRM, and the emulsified asphalt CRM had better performance than the foamed asphalt CRM. The performances of samples cored from the test section in the field met the specifications and were lower than that in the laboratory. The curing conditions in the field were not as effective as in the laboratory. The curing conditions and compaction method should simulate the conditions in the field to guide the CRM selection and mixture design.

Keywords: CRM; RAP; RAI; emulsified asphalt; foamed asphalt; performance; secondary compaction; cement

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1. Introduction

The rehabilitation and maintenance of stressed asphalt pavement would produce more than 100 million tons of reclaimed asphalt pavement (RAP) and reclaimed aggregate or reclaimed inorganic binder stabilized aggregate (RAI) [1,2] per year in China. This also creates a great need for considerable quantities of non–renewable natural aggregates and asphalt for renewing the stressed asphalt pavement [3,4]. RAP and RAI stockpiles would occupy a lot of deposition areas [5] and pose a threat to the environment [6].

The application of recycling technology for RAP and RAI brings excellent benefits in terms of economic, energetic, and environmental sustainability [7,8]. Cold recycling technology, which is mixed at ambient temperature, has decreased attention substantially due to its high utilization of RAP, lower construction costs [3,9], lower greenhouse gas emissions, and the ability to pave in cold–weathe conditions [10], lower fuel consumption [5,11], longer working time for transportation and placing [4,12], and asphalt consumption of only 50% of HMA [13]. This technology has the potential to utilize millions of tons of aged asphalt mixtures deposited at landfills [14] while still being largely pollution free [15]. The benefits associated with the use of RAP and RAI are related to the possibility of reducing the costs connected to the production processes and saving the natural aggregates and the virgin asphalt binder without negatively affecting its mechanical properties [4]. More recent studies [16,17] also assessed the possibility of incorporating up to 100% of RAP in fully recycled mixtures. As a result of these advantages, CRM is increasingly favored in pavement construction and rehabilitation [18].

The RAP/RAI and original aggregates (if needed) are bounded by stabilization agents to produce the CRM at ambient temperature without heating [19]. The most common stabilization agents include emulsified asphalt, foamed asphalt, and cement [14,20,21]. Factors influencing the volumetric and mechanical properties of CRM were intensively investigated by many researchers, e.g., curing time and temperature [22–24], compacting method [25], cement content and type [26–30], RAP source and content [31,32], asphalt content [27,33–35], gradation [21,25,36], water content [28,37], rejuvenator content [38], additive or active fillers [18,19,39,40], asphalt type, and extra aggregates [41]. At the same time, the effect of RAI or composite RAP/RAI on the performance, mechanical behavior, and small strain characteristic of CRM stabilized by emulsified asphalt or cement has been studied by many scholars [42,43]. These studies are all very significant in optimally designing CRM [44].

Although CRM is more environmentally friendly and economical than HMA and warm mix asphalt (WMA), CRM has been considered inferior to HMA [4,28]. There are three main concerns [45]: (a) high air–void content of the compacted mixtures, (b) weak strength at the initial stage [46], and (c) the long curing times needed to achieve final strength [40,47,48]. The long curing times put CMA at a disadvantage as compared to HMA and WMA, where the road can be opened to traffic after 24 h of construction. Marshall Stability values of CRM are significantly lower than HMA and WMA [49–52]. CRM has a good rutting resistance [46] because cement hydrates can greatly increase the stiffness of the asphalt binder [53]. However, because of the high void content and the addition of cement, CRM exhibits low tensile strength and low ductility [54,55], so its cracking resistance is weak compared to conventional HMA and hot recycling asphalt mixture [56]. CRM also has a high moisture susceptibility [39].

CRM is usually used as an alternative to base or sub–base courses [11,14,45,57] or bottom courses of asphalt layers [58,59]. Problems such as higher air voids, lower stability, lower ITS values [28], and high risks of cracking and moisture damage [60] mean that the CMA is not used for the surface course in heavy traffic conditions [61]. Therefore, the tensile strength, ductility, and moisture susceptibility of CRM should be further improved to achieve this ambitious goal [44].

It is not clear if the RAP/RAI content and the type of asphalt binder have a significant influence on the performance of the CRM [37]. This paper aims to deepen the study of the evaluation of the physical and mechanical properties of different types of CRM fabricated with RAP and RAI, emulsified, and foamed asphalt. Six types of CRM with different asphalt binders and RAP/RAI content were tested in the laboratory. Strength indicators (indirect tensile strength (ITS) and stability), high temperature stability (rutting test), low temperature crack resistance (low temperature bending test), water stability (dry and wet ITS ratio, residual stability ratio (M_0), and freeze–thaw ITS ratio), and dynamic modulus [31] were performed in the laboratory. Starting from the laboratory mix design, a full–scale trial section was constructed to evaluate the development of the mechanical and physical properties of the proposed CRMs. Additionally, samples were collected during the construction of the trial section and were tested in the laboratory to investigate the mechanical performance of different CRMs. This study will be very important in understanding the effect of RAP/RAI and asphalt type on pavement performance and providing a selection criterion for optimum cold recycling technologies.

2. Materials and Methods

2.1. Materials

2.1.1. RAP and RAI Materials

The recycled materials were derived from existing local asphalt pavement and acquired by milling of asphalt layers and cement stabilized base course layers. The recycled materials were representative of the material used in actual laboratory tests and pavement construction. The age of the RAP was unknown.

In previous studies [62–64], the aged asphalt binder in the RAP was considered to be inactive and a part of the RAP particles. No extra heating was used to melt the aged asphalt in the mixing of CRM, and RAP was employed as “black aggregates” [18]. In the RAP, mineral aggregates were coated with aged asphalt film which does not contribute to the internal cohesion of the mixture. The gradation of RAP materials before and after extraction should also be taken into consideration because some coarse particles in RAP are part of the assembly of fine RAP particles bonded by the aged asphalt [36,65]. After long-term service of pavement, the assembled RAP coarse particles will be gradually dispersed due to the influence of thermal radiation in the construction of the upper HMA layers and traffic load. As a result, the gradation of CRM may change as the service time progresses [21].

RAP and RAI materials used in this paper were sieved into three different fractions: fine RAP 0/5 (0–5 mm), medium RAP 5/10 (5–10 mm), and coarse RAP 10/20 (10–20 mm). The three RAP fraction gradations before and after extraction are presented in Figure 1a–c, and the three RAI fraction gradations are presented in Figure 1d.

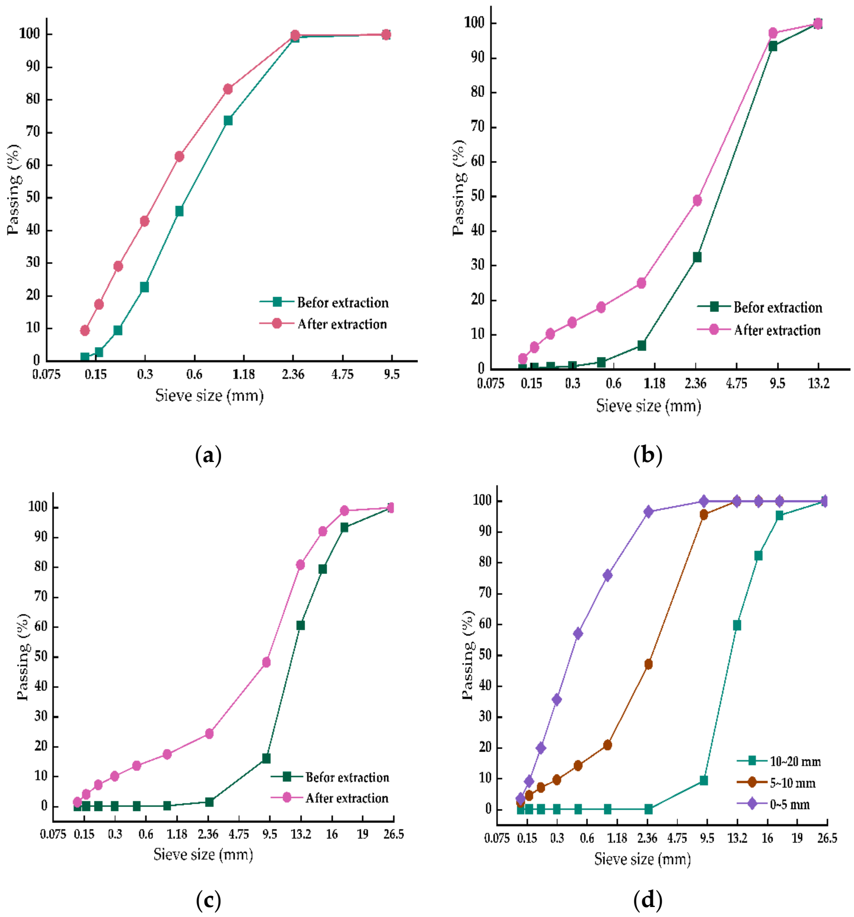


Figure 1. Particle size distribution of RAP and RAI materials. (**a**) RAP 0/5 (asphalt content 6.0%). (**b**) RAP 5/10 (asphalt content 4.0%). (**c**) RAP 10/20 (asphalt content 3.37%). (**d**) RAI.

2.1.2. Asphalts

The emulsified asphalt needs enough working time after being mixed with aggregates and filler. Considering the alkaline environment of cement hydration and the initial setting time requirement, as well as ensuring that emulsified asphalt can participate in the formation of cement paste structure after demulsification [66], a commercial cationic slow–cracking emulsified asphalt was used in this paper. The compatibility experiment between emulsified asphalt and aggregates was performed for assuring that the demulsification speed of the recycled mixture was about 2 to 3 h and compatible with aggregates. It has been previously explained by scholars [47] that the affinity between asphalt emulsion and aggregates can be affected by the surface charges of the aggregates. The indexes of emulsified asphalt are given in Table 1, which matched the requirements of the recycling specification (JTG/T 5521 2019) [57].

In this study, Wirtgen WLB10 laboratory foaming equipment was used to produce foamed asphalt. The critical foaming characteristics of foamed asphalt are expansion ratio and half–life. The expansion ratio is the ratio of the volume of a foamed liquid at any point relative to its original volume, and half–life is the time (in seconds) between the maximum expansion ratio and one–half of its value [35]. To achieve optimal values, the key foaming variables are asphalt temperature and foaming water content [67]. Generally, the expansion ratio increases with increasing asphalt temperature and foaming water content, while half–life is the direct opposite. An increase in expansion ratio and half–life promotes the dispersion of asphalt leading to a more complete coating of aggregates, hence improved mechanical properties.

The asphalt used for foamed asphalt was 70# road asphalt and subjected to evaluation of foaming performance conducted following the methodology described by [68]. The optimum temperature, which gives a larger expansion ratio and half–life, was determined to be 165–170 °C by measuring the expansion ratio and half–life of the foamed asphalt under different temperatures. The optimal foaming water content was about 3%. Under the optimum foaming temperature and water content, the maximum expansion ratio of foamed asphalt was larger than 12, and the half–life of foamed asphalt was about 10 s. The indexes of 70# road asphalt are shown in Table 2, which could meet the requirements of the construction specification (JTG F40–2004) in China [69].

Table 1. Test results of emulsified asphalt.

Test		Result	Requirements of Recycling Specification [57]	Requirements for Construction Specification [69]
Demulsification speed		Slow breaking	Slow or medium breaking	/
Particle charge		Cation (+)	Cation (+)	Cation (+)
Residue on the 1.18 mm sieve (%)		0.03	≤0.1	/
Evaporation residues	Content (%)	63.1	≥62	≥55
	Penetration (25 °C, 0.1 mm)	80	50–300	45–150
	Ductility (15 °C, cm)	60	≥40	≥40
Average particle size (μm)		3.28	/	/

Table 2. Test results of 70# road asphalt.

Test	Result	Requirements for Construction Specification [69]
Penetration (25 °C, 0.1 mm)	71	60–80
Softening point (°C)	47	≥44
Ductility (10 °C, cm)	33	≥15

2.1.3. New Aggregate, Cement, Mineral Powder, and Water

The new aggregates were limestone. The new aggregates and mineral powder (<0.075 mm) were utilized to improve the overall gradation of the mix and to control the variability of the gradation for a better dense skeleton structure in the mixture. The technical indicators of mineral powder met the construction specification (JTG F40–2004) [69] in China.

Portland cement (P.O.32.5) was employed to promote the demulsification of emulsified asphalt and improve the initial strength of the CRM under saturated conditions [70,71], and its content was determined by 1.5% by dry aggregate and mineral powder mass. These cement particles have a high surface area and high negative charge which helps in breaking the asphalt emulsion faster [26]. The hydration hydrates are mainly responsible for the ultimate strength of CRM, which can also help in accelerating the initial strength [72]. Adding a certain amount of cement can improve the performance of CRM, but excessive cement causes the deterioration of water stability and shrinkage characteristics of CRM. Therefore, it is suggested that the cement content should be no more than 1.8% in the recycling specification (JTG/T 5521 2019) [57].

According to the specification, the water used should be potable.

2.2. Methods

There were two different phases of the experimental program. In the first phase, laboratory studies of the mix designs and the physical and mechanical properties of six types of CRM were performed. In the second phase, four different CRMs were laid in a test section on a high–grad road featuring heavy traffic. Samples were collected from the test section on site for evaluating the mechanical properties of different CRMs.

2.2.1. Mix Design

The mixture design was based on the characteristic of the available RAP and RAI. Currently, there is no universally accepted mixture design for CRM. In this paper, the mixture design of CRM was conducted using a simplified cold–mixture design procedure, which involved several sequential steps: (a) RAP and RAI sampling on–site; (b) determine the gradation of RAP and RAI, and asphalt binder content of RAP; (c) determine an estimation of initial binder (emulsified, foamed asphalt or cement) content, and whether extra aggregates are needed; (d) design a reasonable recycled gradation; (e) with a fixed binder content, determine the optimum moisture content; (f) determine the optimum binder content; (g) carry out subsequent performance–verifying tests at full curing conditions.

In step e, under a fixed binder content and varied water contents, heavy compaction tests were performed to determine the optimum moisture content. According to the dry density curve corresponding to different water contents, the moisture content corresponding to the maximum dry density is taken as the basis of the optimum moisture content. For the optimum moisture content concept, the optimum moisture content assumes that all air voids should be fulfilled with water. If more water is added, the water may be squeezed out of samples during compaction. The fine particles might be flushed out with the squeezing of the water [6]. Insufficient or excessive moisture can lead to asphalt clots and compromise the coating of aggregates [73].

There is no accepted standard or specification for determining the optimum asphalt content. However, the optimum asphalt content should be the value when the CRM has the highest stability, the highest dry density, the most suitable air voids, and the aggregates skeleton within the regulation limits [74]. In the USA, different mixture design methods adopt varied asphalt binder contents based on the Marshall stability and flow values at 60 °C. In China's recycling specification (JTG/T 5521 2019) [57], the asphalt binder content is determined by using the ITS test at 15 °C or water immersion Marshall stability and void as control indexes. The ITS test could evaluate the cracking resistance of CRM, and for the water stability of CRM, the representation of the ITS test is very low. As a result, in this paper, we chose the $ITS_{Freeze–thaw}$ values and $TSR_{Freeze–thaw}$ to determine the asphalt binder. Under a fixed water content and varied asphalt contents, the optimum asphalt content is the asphalt binder content that referred to the maximum $ITS_{Freeze–thaw}$ values and $TSR_{Freeze–thaw}$.

Based on the recycling specification (JTG/T 5521 2019) [57], the compaction methods of CRMs in the laboratory must take the following steps: (a) for emulsified asphalt CRM, the Marshall samples must be compacted 50 times on both sides, and 25 times on both sides after curing to constant weight in a 60 °C blast oven; (b) for foamed asphalt CRM, the Marshall samples must be compacted 75 times on both sides, and cured to constant weight in a 60 °C blast oven.

In this paper, for both emulsified asphalt and foamed asphalt CRM, the Marshall samples should be compacted 75 times on both sides, and cured for 48 h in an air–circulating oven set at 60 °C with no humidity control to accelerate the emulsion breakage and water evaporation. One of the most difficult parts of mixture design is to simulate the field curing conditions in the laboratory [75]. This is because the field curing process is influenced by multiple factors, such as layer thickness, drainage conditions, construction sequence, ambient temperature, and humidity conditions [70,76]. This curing phase is a kind of accelerated curing that could better simulate the field conditions [77]. Before being demolded, the Marshall samples should be cooled for an additional 12 h at room temperature.

To fulfill the aims of the experiment, six distinct CRMs were designed as follows: emulsified asphalt CRM with RAP (labeled E/RAP), emulsified asphalt CRM with composite RAP and RAI (labeled E/RAP/I), emulsified asphalt CRM with RAI (labeled E/RAI), foamed asphalt CRM with RAP (labeled F/RAP), foamed asphalt CRM with composite RAP and RAI (labeled F/RAP/I), foamed asphalt CRM with RAI (labeled F/RAI). This selection facilitates a comparison between the mixtures concerning the asphalt type and recycled material type and their effect on the mixture performance separately.

In this method, the one–time compaction method is used to fabricate the samples to simulate the compaction during the paving process of cold recycled structural layer on the project site, without considering the compaction effect of the upper HMA [13].

The synthetic gradations of the different CRMs were continuous medium–sized gradations within the limits recommended by the recycling specification (JTG/T 5521 2019) [57] and shown in Figure 2. Following the mixture design steps, we obtained the details of different CRMs that are shown in Table 3. The optimum emulsified asphalt content was the total asphalt emulsion including water, and the optimum water content was the additional water added with fixed asphalt content.

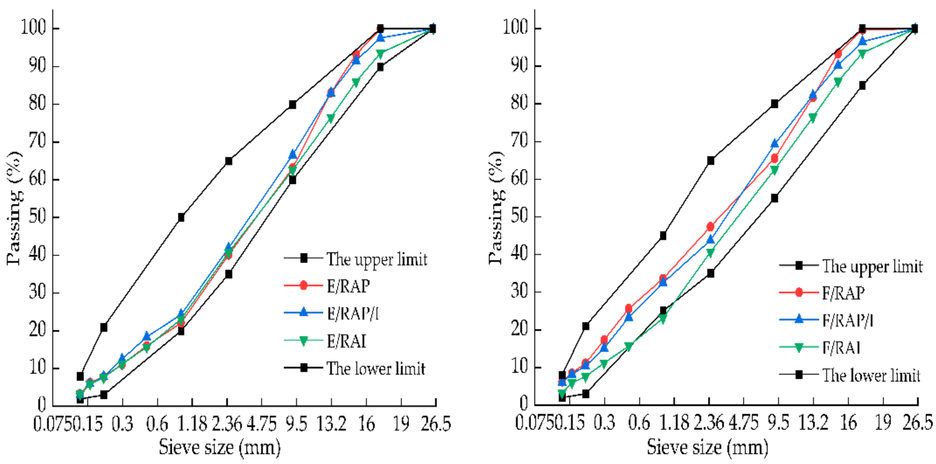


Figure 2. Design gradations of emulsified and foamed asphalt CRMs.

Table 3. Mixture design results of CRMs.

Mixture Type	Optimum Water Content (%)	Optimum Asphalt Content (%)	Cement Content (%)	Air Void (%)	Gradation Ratio (%)
E/PAP	4.8	3.8	1.5	9.8	RAP 0/5: 5/10: 10/20: lime 0–3: filler = 20: 28: 42: 8: 2
E/PAP/I	5.6	4.5	1.5	11.2	RAP 0/5: 5/10: 10/20: RAI 0/5: filler = 20: 28: 40: 11: 1
E/PAI	6.4	5	1.5	11.8	RAI 0/5: 5/10: 10/20: lime 0–3: filler = 20: 33: 42: 4: 1
F/PAP	5	3.2	1.5	10.6	RAP 0/5: 5/10: 10/20: lime 0–3: filler = 22: 20: 40: 15: 3
F/PAP/I	5.8	3.6	1.5	10.3	RAP 0/5: 5/10: 10/20: RAI 0/5: filler = 23: 28: 35: 11: 4
F/PAI	6.6	4.4	1.5	12.1	RAI 0/5: 5/10: 10/20: lime 0–3: filler = 20: 33: 42: 4: 1

2.2.2. Indirect Tensile Strength (ITS) Test

The CRM is used for the base course of the high–grade highway or the lower surface layer of the low–grade highway with two or more HMA layers above, so the requirements for road performance regarding cracking resistance and water stability are strict. In this position, the CRM layer may generate tensile stress under vehicle load. Therefore, it is reasonable to use splitting strength as the design parameter of pavement structure with the CRM. At the same time, water sensitivity is directly related to the behavior and durability of the CRM [78].

For evaluating the tensile strength and flexibility of the CRM, the ITS test was performed on both the unconditioned (ITS_{Dry}) and the conditioned specimens (ITS_{Wet}) at a controlled temperature of 15 °C, and the tensile strength ratio ($TSR_{Dry-wet}$) was also determined according to the splitting test method (JTG E20–2011) T0716 [79].

2.2.3. Freeze–Thaw ITS Test

The freeze–thaw ITS test was carried out to assess the CRM splitting strength before and after water damage, and to evaluate the moisture susceptibility according to the test method (JTG E20–2011) T0729 [79]. The ITS ratio of conditioned and unconditioned specimens ($TSR_{Freeze-thaw}$) was calculated as an indicator of moisture resistance. This indicator is more rigorous than $TSR_{Dry-wet}$ in evaluating the moisture resistance of the CRM. Eight specimens were prepared and divided into two groups; the first group is the unconditioned group, which was kept at room temperature for use. The second group is the conditioned group; the specimens of the second group were vacuum–saturated and kept for 15 min, then the specimens were stored in water for 0.5 h under natural pressure. The specimens of the second group were stored at −18 °C for 16 h. Then, the specimens were placed in a 60 °C water bath for 24 h. Before the freeze–thaw ITS test, all specimens of the two groups were immersed in a 25 °C water bath for more than 2 h. The specimens were subjected to a load at a speed of 50 mm/min in the ITS test.

2.2.4. Water Immersion Marshall Stability Test

The water immersion Marshall stability test was used to test the anti–stripping of the CRM after water damage, and evaluate the moisture damage resistance according to the test method (JTG E20–2011) T0709 [79].

2.2.5. High Temperature Rutting Tests

The high temperature rutting resistance of CRM is essential for mixture design, e.g., for a road with a CRM base course constructed in winter and opened to traffic, the rutting occurred in the next summer season [80].

The rutting test was performed to evaluate the high temperature rutting resistance of CRM at 60 °C according to the test method (JTG E20–2011) T0719 [79].

2.2.6. Low Temperature Bending Tests

The three–point flexural beam test was applied to evaluate the low temperature crack resistance of the CRM at −10 °C with a loading rate of 50 mm/min following the test method (JTG E20–2011) T0715 [79].

2.2.7. Dynamic Modulus Tests

The dynamic modulus test was used to evaluate the viscoelastic response of CRM with changes in loading frequency and temperature according to the test method (JTG E20–2011) T0738 [79].

2.2.8. In-Field Test Section

After the mixture design and the volumetric and mechanical properties of different CRMs were defined, the second phase of the research program was to devise a full–scale trial field. The designed pavement structure for the trial section was constructed in a typical maintenance work manner and subjected to heavy traffic in Shandong. The maintenance work had two lanes in one direction, and the cold recycling test section was performed in both directions; each CRM test section was about 500 m in length and 7.5 m in width. The original pavement structure comprised 10 cm HAM layers, 16 cm cement stabilized gravel base course, and 32 cm cement stabilized weathered sand (two layers).

During the maintenance work, the HMA layers and the cement stabilized gravel base course were removed by a milling operation and transported back to the recycling plant. The new CRM structure was a 12 cm HMA layer (two layers) and a 15 cm CRM layer (different types). After finishing the CRM upper base course, the 12 cm HMA layers were constructed as wearing courses. Samples were collected from the test section for laboratory testing before paving the HMA layers. The samples of foamed CRM structures were cored from the test section using coring machines after two days of curing. The samples of emulsified CRM structures were cored after five days of curing. The construction operation of CRM structures is shown in Figure 3. Samples of different CRM structures are shown in Figure 4. The samples were treated and tested in the laboratory.

(**a**) (**b**)

Figure 3. The construction operation of CRM structure test sections. (**a**) In-Field construction of emulsified asphalt CRM. (**b**) In-Field construction of foamed asphalt CRM.

Figure 4. Samples of different CRM structure test sections.

The RAI CRM structures were not included in the test section that was subjected to heavy traffic so as to guarantee the long-term service performance, on the advice of the administrators of this maintenance work.

3. Results

3.1. Indirect Tensile Strength (ITS) Test Result

Static mechanical characterization can be conducted by ITS test both in dry and wet conditions. After mixture design, we obtained the details of six kinds of CRM in the laboratory, and the splitting strengths were used to compare the strength of different CRMs based on the ITS test. The test results are shown in Figure 5.

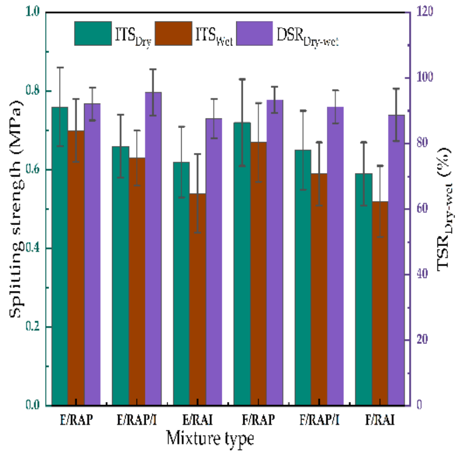


Figure 5. ITS test results of different CRMs.

3.2. Freeze–Thaw ITS Test Result

In this paper, the freeze–thaw ITS test was used to evaluate the water stability of the CRMs. The final splitting strength and freeze–thaw splitting strength ratio ($TSR_{Freeze–thaw}$) are shown in Figure 6.

The freeze–thaw splitting test was also used to determine the optimum asphalt binder content in this study; the splitting strength and freeze–thaw splitting strength ratio ($TSR_{freeze–thaw}$) of E/RAP and F/RAP are depicted in Figure 7.

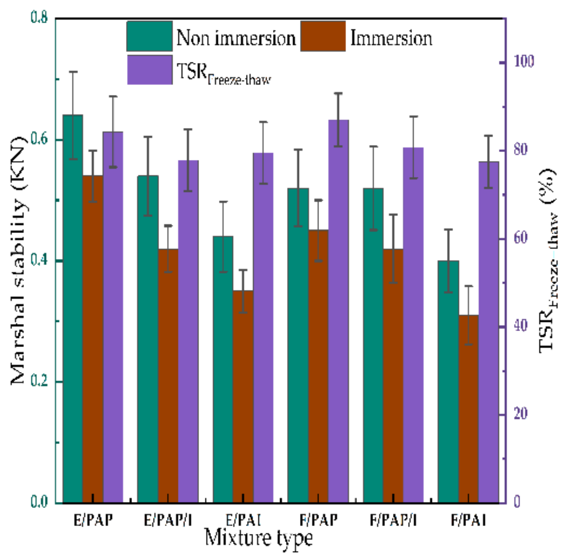


Figure 6. Freeze–thaw ITS test results of different CRMs.

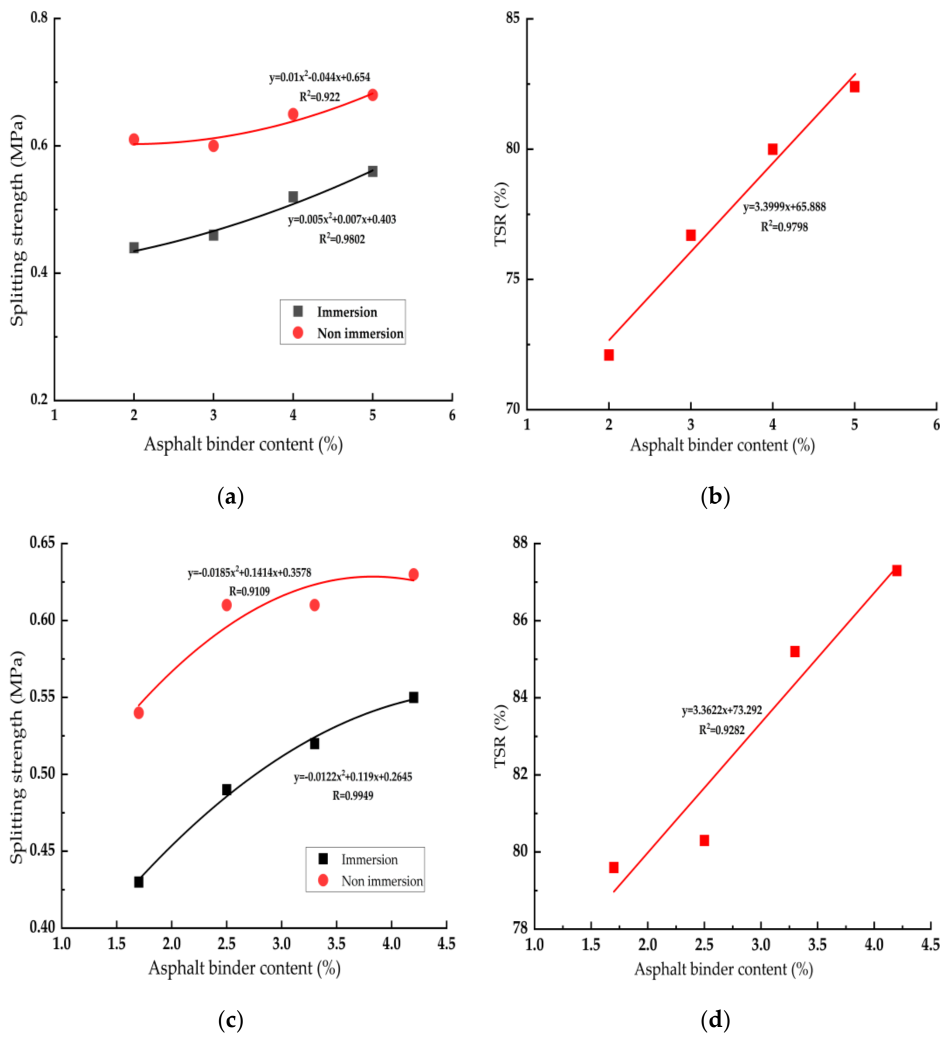


Figure 7. Freeze−thaw ITS test results of E/RAP and F/RAP. (**a**) Splitting strength of E/RAP with various asphalt binder contents. (**b**) $TSR_{Freeze–thaw}$ of E/RAP with various asphalt binder contents. (**c**) Splitting strength of F/RAP with various asphalt binder contents. (**d**) $TSR_{Freeze–thaw}$ of F/RAP with various asphalt binder contents.

3.3. Water Immersion Marshall Stability Test Results

The water immersion Marshall stability test was performed to evaluate the stability of different CRMs. The test results are depicted in Figure 8.

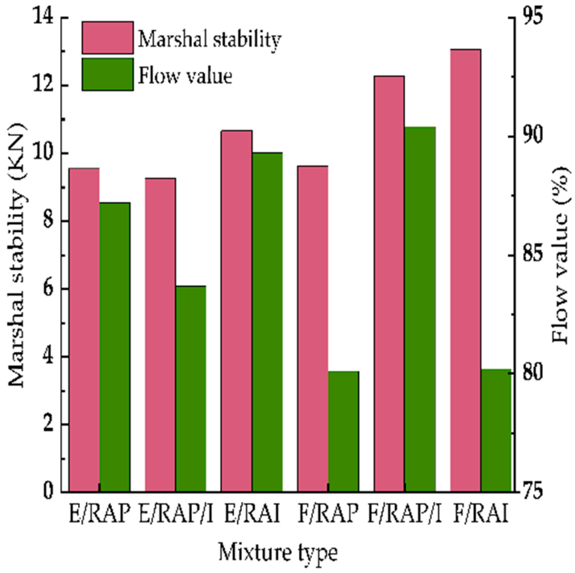


Figure 8. Water immersion Marshall stability test results.

The water immersion Marshall stability test was also used to determine the optimum asphalt binder content in this study. The Marshall stability and flow value of E/RAP and F/RAP are depicted in Figure 9.

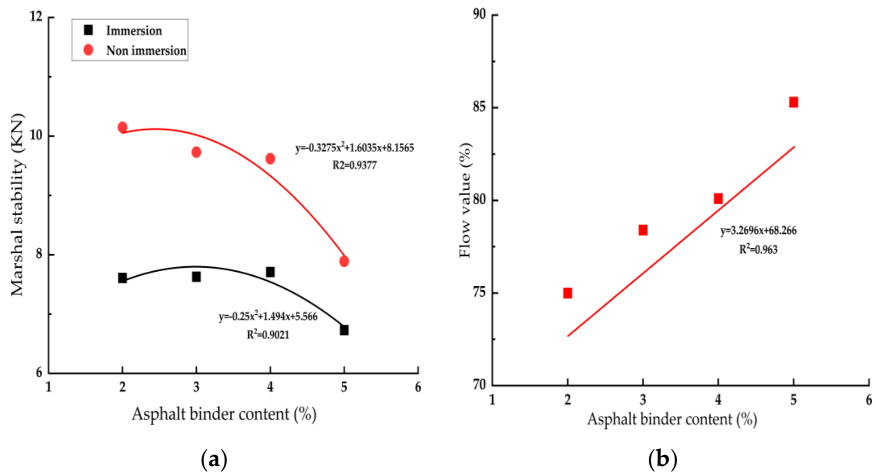
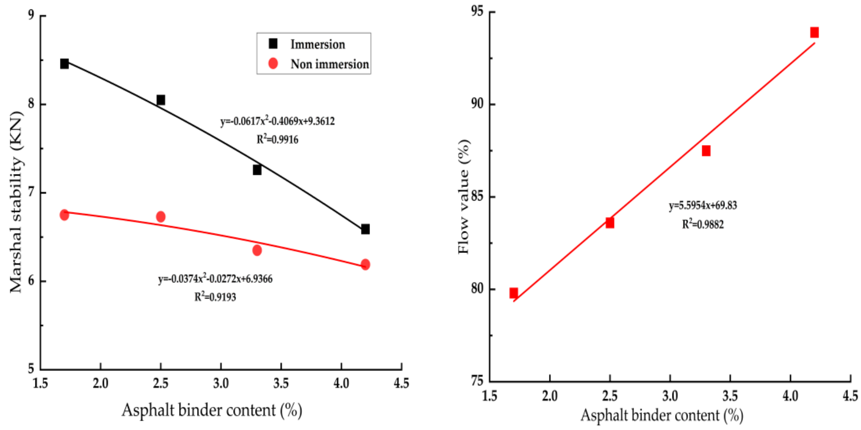


Figure 9. *Cont.*



(**c**) (**d**)

Figure 9. Water immersion Marshall stability test results of E/RAP and F/RAP. (**a**) Water immersion Marshall stability of E/RAP with various asphalt binder contents. (**b**) Flow value with various asphalt binder contents. (**c**) Water immersion Marshall stability of F/RAP with various asphalt binder contents. (**d**) Flow value of F/RAP with various asphalt binder contents.

3.4. High Temperature Rutting Test Results

The high temperature rutting test was adopted to evaluate the rutting resistance of different CRMs by using the parameter of dynamic stability. The dynamic stability of six kinds of CRM are listed in Table 4.

Table 4. Dynamic stability of different CRMs.

Mixture Type	Dynamic Stability (Times/mm)
E/RAP	12,535
E/RAP/I	7684
E/RAI	5172
F/RAP	12,584
F/RAP/I	No deformation
F/RAI	No deformation
Specification requirement≥	800 (traditional asphalt mixture)

3.5. Low Temperature Bending Test Results

For evaluating the low temperature cracking resistance, the small size beam samples were fabricated. Figure 10 shows the failure strain results of different CRMs.

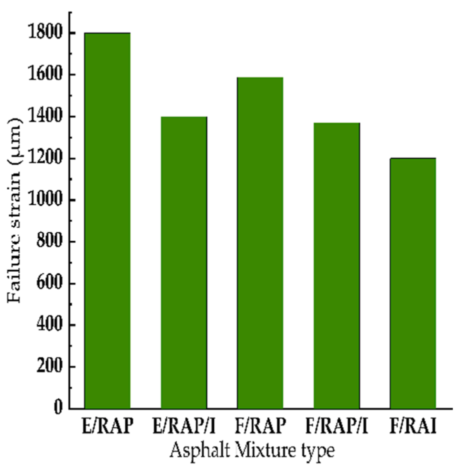


Figure 10. Low temperature bending test results of different CRMs.

3.6. Dynamic Modulus Test Results

The dynamic modulus test was performed to measure the dynamic modulus of CRM. The dynamic modulus of F/RAP at 15 °C and 20 °C is shown in Figure 11.

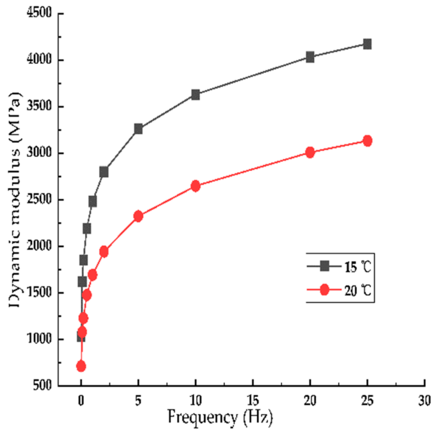


Figure 11. Dynamic modulus test results of F/RAP CRM.

3.7. In-Field Samples Test Results

Four CRMs were constructed by mixing, paving, compacting, and curing. During construction, core specimens of the four CRMs were collected from the trial section of the cold recycled upper base course under one–time compaction before paving HMA and tested to verify their road performance. Core specimens collected from the trial section were investigated by employing the dry–wet ITS test, freeze–thaw ITS test, and Marshall stability test (residual stability ratio (MS_0)). The test results are shown in Table 5 and Figure 12.

Table 5. Dry–wet ITS results of core specimens from construction field.

Mixture Type	Relative Density of Bulk Volume	Compaction Degree (%)	Splitting Strength (MPa)	$TSR_{Dry\text{–}wet}$ (%)
E/RAP	2.33	91.5	0.68	91.7
F/RAP	2.322	105.2	0.78	94.7
F/RAP–I (14.3% RAI)	2.314	103.6	1	96.1
F/RAP–II (53.8% RAI)	2.264	106.4	0.82	84.7
Recycling Specification requirement≥		E/RAP, 90 F/RAP, 98	base/subbase, 0.4 lower surface layer, 0.5	75

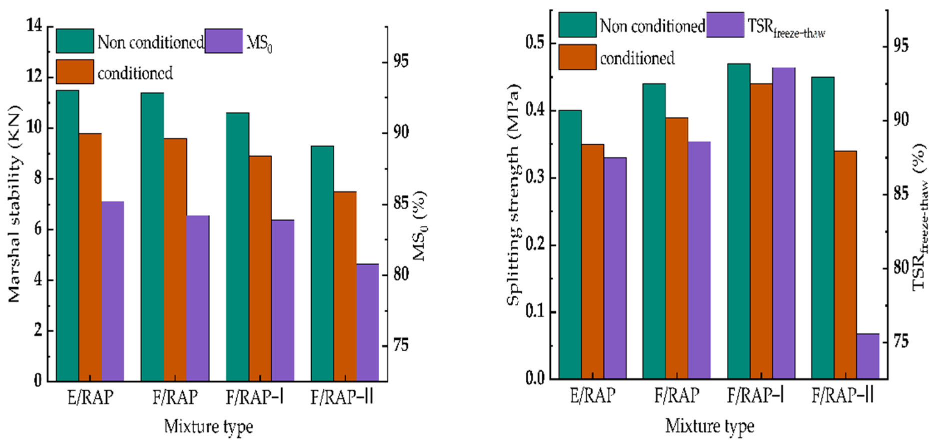


Figure 12. Test results of core specimens from the construction field. (**a**) Freeze–thaw test results. (**b**) Marshall stability test results.

4. Discussion

4.1. Mix Design

The secondary compaction method was used to simulate the compaction procedure when the HMA layer is paved in the specification, and has been discussed in many studies. During paving of the HMA layer, the temperature of the CRM layer is increased by the HMA mixture, and the CRM layer is further compacted during the compaction of the HMA layer. The total voids of CRM essentially comprise two parts: the voids formed after the first compaction, and the voids formed by water evaporation [28]. When the secondary compaction effort is not large enough to reduce all the void content due to water evaporation, or the water evaporation process is not finished when the secondary compaction is performed, the number of voids formed due to water evaporation in the hardened state is very high [48,81,82]. The high void content reduces the internal friction resistance of the aggregate skeleton, and the mechanical properties of the CRM are also decreased [44]. Because of the high void content, a large amount of water can easily permeate the interior of the CRM layer, which affects the adhesive ability of the asphalt binder and leads to aggregate stripping [83]. Rutting will also occur after opening to traffic [80].

Thus, in the mixture design of CRM, the volumetric and mechanical indexes should meet the specification after the first compaction procedure. The secondary compaction during HMA layer paving should: (a) further enhance the compaction degree; (b) reduce the air void after the moisture evaporation; (c) enhance the primary mechanical properties and reduce the air void of CRM compared with that of mixture design. The period between paving the HMA layer and CRM layer is uncertain in the suitable site, as the effect of secondary compaction cannot be guaranteed if the cement hydration is too high or the asphalt binder is stable. The secondary compaction is not taken into consideration in this study.

The total moisture content helps in: (a) reducing the viscosity of the clod recycled mixture; (b) providing suitable conditions for cement hydration; (c) the homogeneous distribution of asphalt droplets; (d) enhancing its workability and compatibility. It is important to emphasize that the total moisture content comprises additional water added before compaction and emulsion water, which is further divided into water absorbed by aggregates and intergranular water.

4.2. Indirect Tensile Strength (ITS) Test

The tensile strength is a good indicator of the cracking potential of pavement [84]. An asphalt mixture with a high tensile strain at failure can tolerate higher strains before failing. Furthermore, the ITS strength value is an indicator of strength and adherence against fatigue, temperature cracking, and rutting [84,85].

The ITS strength and $TSR_{Dry-wet}$ values in all different CRMs were higher than the ITS limit (0.4 MPa) and $TSR_{Dry-wet}$ limit (75%) imposed by the recycling specification (JTG/T 5521 2019) [57].

Compared with RAI materials, the RAP materials have higher strength and performance, and have good compatibility with added asphalt because RAP materials are coated with aged asphalt. Based on the performance of RAP, the splitting strength of the RAP CRM was greater than that of the CRM with RAI. The addition of RAI materials could decrease the splitting strength, so the CRM with RAI had the lowest $TSR_{Dry-wet}$ values.

4.3. Freeze–Thaw ITS Test Result

Moisture damage–related distress is a primary concern that limits the application of CRM as an alternative to HMA in the field [86]. The main concerns of moisture damage take the form of stripping due to loss of bonding between asphalt binder and aggregate [12]. Two mechanisms lead to moisture damage in cold mix asphalt: one is the potential incomplete coating as a result of the charge incompatibility between asphalt and aggregate; the other is the presence of water in the mixture [12].

The $TSR_{Freeze–thaw}$ values of all CRMs were higher than the limit (70%) imposed by the recycling specification (JTG/T 5521 2019) [57]. The $ITS_{Freeze–thaw}$ and $TSR_{Freeze–thaw}$ values of the CRM with RAP were higher than those of the CRM with composite RAP and RAI, the CRM had the lowest $ITS_{Freeze–thaw}$ and $TSR_{Freeze–thaw}$ values. The addition of RAI materials could reduce the moisture damage resistance of the CRM.

The $TSR_{Freeze–thaw}$ values of all CRMs are much lower than the $TSR_{Wet–dry}$ values. This is because the $TSR_{Freeze–thaw}$ is more rigorous than the $TSR_{Wet–dry}$ as an indicator in evaluating the moisture susceptibility of the CRM.

It can be seen from Figure 7 that the $ITS_{Freeze–thaw}$ strength of emulsified and foamed asphalt CRM with RAP would increase with the rise in asphalt content. The combination of asphalt cement and RAP materials is achieved by the bond between the asphalt and RAP materials. The bond would be enhanced with the increase in asphalt content.

The $TSR_{Freeze–thaw}$ values of emulsified and foamed asphalt CRM with RAP under different asphalt contents were higher than the limit (70%) imposed by the recycling specification (JTG/T 5521 2019) [57]. The strength of asphalt cement and the bond between the asphalt and RAP material could be reinforced by the increase in asphalt, which can prevent water damage under freeze–thaw conditions [42,66,87,88].

4.4. Water Immersion Marshall Stability Test Results

Marshall stability is related to the resistance of asphalt materials to distortion, displacement, rutting, and shearing stresses. The test results were compared to the limits provided by the recycling specification (JTG/T 5521 2019) [57] (4 KN for base or subbase layers, 5 KN for lower surface layer) and the construction specification (JTG F40 2004) [69] (8 KN for asphalt mixture). According to the results, it can be seen that all the tested mixtures complied with the specifications.

It can be seen from Figure 8 that the Marshall stability would be enhanced with the addition of RAI because the Marshall stability is mainly based on internal friction and cohesion. Cohesion is the binding force of binder material, and internal friction is the interlocking and frictional resistance provided by aggregates [89]. The RAI materials had a coarser texture than the RAP materials, and the RAI materials could provide more frictional resistance. Thus, the CRM with RAI added had higher Marshall stability.

It should be noted from Figure 9 that the Marshall stability of emulsified and foamed asphalt CRM with RAP before and after water immersion would decrease with the increase in asphalt content, and the residual Marshall stability (M_0) would linearly decrease with the rise in asphalt content. This phenomenon could be explained by the fact that the increase in asphalt content would result in more free asphalt which leads to instability of CRM due to the lubricating effect of the excess asphalt causing a lower angle of friction [34].

4.5. High Temperature Rutting Test Results

High temperature stability is used to evaluate the durability and ascertain the structural capacity of HMA [34]. Rutting tests were conducted to reflect the resistance of CRMs to deformation at high temperatures. Permanent deformation was taken as the main failure mode of CRM [90].

The required dynamic stability value for the CRM in heavy traffic pavement structures is more than 2000 times/min in the recycling specification (JTG/T 5521 2019) [57]. Except for emulsified asphalt RAI CRM (5172 times/min), the dynamic stability of all CRMs exceeded the level of 6000 times/min and met the construction specification (JTG F40 2004) [69], which means that the high temperature resistance of emulsified and foamed asphalt CRMs is acceptable under one–time compaction.

The viscosity and stiffness of asphalt in RAP materials would be enhanced by the aging of asphalt in RAP materials during a long period of service life, and the increase in viscosity and stiffness of aged asphalt in RAP materials could improve the high temperature performance of CRM. The effect of aged asphalt in RAP material did not act like the newly added asphalt in the CRM and did not significantly reduce the high temperature performance of the CRM. At the same time, the addition of cement can greatly reduce the temperature susceptibility of CRM [91]. The hydrates from cement are rigid materials. Therefore, hydration hydrates have lower temperature stability and higher stiffness than asphalt mortar [53]. The high temperature performances of CRM, e.g., high temperature stability and deformation resistance ability, were improved by the hydration hydrates [4,30,66,92,93].

4.6. Low Temperature Bending Test Results

The low temperature performance indicators and standards of CRM are not included in the current recycling specification (JTG/T 5521 2019) [57]. Therefore, it is necessary to study the low temperature performance of CRM to promote the application of this technology at a high level.

The failure strain is usually used to evaluate the cracking resistance at a low temperature of HMA. The low temperature bending failure strains of the different CRMs could not meet the minimum limit (2000 μm for traditional asphalt mixture) of the construction specification (JTG F40 2004) [69]. As a result, the implication of emulsified and foamed CRM with RAP and RAI in the lower surface layer should be carefully considered. With the addition of RAI, the failure strain of CRM would decrease, which means that the addition of RAI harms the cracking resistance at low temperatures.

4.7. Dynamic Modulus Test Results

The dynamic modulus has been proved to better reflect the mechanical responses and deformation resistance of asphalt pavement structures under traffic loads. The CRM contains a certain amount of aged and newly added asphalt and also has viscoelastic properties; it is very reasonable to use dynamic modulus for evaluating the rheological behavior of the CRM [94–97].

The dynamic modulus of foamed asphalt CRM with RAP would increase with the rise in loading frequency, and decrease with the rise in test temperature. This phenomenon complies with the validity of the time–temperature superposition principle of traditional HMA. We could conclude that the CRM with RAP exhibits viscoelasticity and thermo–rheological behavior [98]. In the structure design of the CRM with RAP, the CRM with RAP should be treated as a viscoelastic material. Compared with the dynamic modulus of asphalt stabilized gravel base course fabricated with 70# matrix asphalt, the dynamic modulus of foamed asphalt CRM with RAP was about half of its values at the same test temperature. These findings are in line with the studies of [29,99], which found that the addition of cement reduced the viscoelastic response of the CRM. Dolzycki et al. [100] also revealed that the cement hydrates would play a more important role in increasing the stiffness of the CRM and the effect of asphalt binder would be significantly diminished. Thus, the cement plays an important role in limiting the thermo–viscoelastic behavior [101]. Compared to HMA, the dynamic modulus characterization of CRM mixtures must consider additional composition–related issues and is less sensitive to temperature [59].

4.8. In-Field Samples Test Results

The compaction degree, splitting strength, and $TSR_{Dry-wet}$ of four kinds of CRM met the requirements of the recycling specification (JTG/T 5521 2019) [57]. Some of the compaction degrees of core samples were larger than 100%, and these results could be explained by the compaction difference between laboratory and field construction. The addition of RAI materials could enhance the splitting strength of foamed asphalt CRM with RAP, but the splitting strength and $TSR_{Dry-wet}$ would be decreased with the rise in RAI content, and the water stability of CRM with RAP was damaged with the addition of RAI materials. The splitting strength and $TSR_{Dry-wet}$ of E/RAP and F/RAP CRM samples cored from the trial section were similar to the test results from the laboratory.

The $TSR_{Freeze-thaw}$ of different CRMs was above the limit (70%) applied by the recycling specification (JTG/T 5521 2019) [57] and the limit (75%) applied by the construction specification (JTG F40 2004) [69]. The splitting strength of emulsified and foamed asphalt CRM with RAP before and after water immersion from the field was smaller than that from the laboratory. The ITS test results of samples cored from the field also confirmed that the splitting strength at 25 °C (freeze–thaw ITS test) was lower than that at 15 °C (dry–wet ITS test), and the addition of RAI did not affect this regularity. The freeze–thaw test splitting strength of samples cored from the test trial was smaller than the test results from the laboratory.

The Marshall stability and residual stability ratio (M_0) of different CRMs met the requirements of the recycling specification (JTG/T 5521 2019) [57] at 40 °C and the construction specification (JTG F40 2004) [69] at 60 °C. The Marshall stability of samples cored from the field was smaller than that from the laboratory, and the addition of RAI could reduce the Marshall stability and residual stability ratio (M_0).

The test results of freeze–thaw and Marshall stability of samples cored from the trial section were smaller than that from the laboratory. This phenomenon could be explained by the insistent curing and compaction between laboratory and field [102]. According to the recycling specification (JTG/T 5521 2019), after the CRM layer was paved, samples could be cored when the moisture was lower than 3% or the samples could be obtained completely. The CRM layer was cured under natural conditions. These were all different from the conditions in the laboratory tests.

5. Conclusions

This paper presented a mixture design of different kinds of CRM, comprising emulsified and foamed asphalt CRMs each with RAP, composite RAP and RAI, and RAI. After mixture design, road performance tests, that is, dry–wet ITS test, freeze–thaw ITS test, water immersion Marshall stability test, high temperature rutting test, low temperature bending test, and dynamic modulus test, were conducted to verify the performance of different kinds of CRM in the laboratory. The samples collected from the trial section were also tested to verify the CRMs with RAP and RAI. The following are some of the noteworthy conclusions made during the mixture design and paving of the trial sections with different kinds of CRM.

(1) During the mixture design of CRM, the dry–wet ITS, freeze–thaw ITS, Marshall stability, and high temperature resistance of different kinds of CRM all met the limits applied by the specifications without considering the second compacting procedure. Thus, during the CRM mixture design in the laboratory, the second compaction procedure is not required. The second compaction procedure could not completely simulate the real compaction effect or the curing conditions in the field.
(2) The volumetric index and high temperature resistance of CRM should meet the limits applied by the specifications after the one–time compaction to resist rutting at high temperatures. The second compaction procedure during the paving of HMA layers should be used to reduce the air voids after the water evaporation and enhance the performance of CRM, and not used as the assurance of the basic volumetric index or mechanical properties.
(3) The low temperature bending failure strain was lower than the lowest requirement of construction specifications for the traditional asphalt mixture, so the application of CRM with RAP in the lower surface layer should be carefully checked. The low temperature crack resistance of the CRM should be improved to improve its application level.
(4) The addition of cement limited the thermo–viscoelastic behavior of the CRM with RAP, which should be treated as a viscoelastic material in highway structure design.
(5) The addition of RAI would reduce the water stability of the CRM with RAP, and the emulsified asphalt CRM had better performance than the foamed asphalt CRM.
(6) All samples cored from the field cold recycled asphalt mixture structure could meet the requirements of recycling and construction specifications.

The emulsified and foamed asphalt cold recycled asphalt mixture with RAP or RAI had good road performance in the laboratory and field and could meet the related requirements of recycling and construction specifications. The application of CRM is proved to be an effective way to recycle RAP and RAI materials.

However, the addition of RAI materials could significantly reduce the water stability and strength of CRM with RAP; RAI materials should not be incorporated into CRM with RAP. The CRM studied in this paper did not meet the lowest requirements of construction specification regarding the low temperature bending failure strain, we should develop a new kind of CRM with a higher performance that could be used in the lower surface layer and be recycled in more valuable ways.

The CRM with RAP exhibits viscoelastic properties (time and temperature–dependent behavior) [103,104] and the highway structure design should be adjusted with the CRM layers. The viscoelastic properties should be taken into consideration during structure design with CRM layers. The transition of the structure system may occur with the application of CRM with RAP. The CRM structure may withstand tensile stress, and the control parameters of the CRM structure should change to the bending strain at the bottom of the layer and permanent deformation. The asphalt mixture layer on the CRM should be specially designed for rutting and fatigue resistance, which could provide protection for the CRM and prolong its service life.

We will analyze the dynamic response of highway structure with CRM in a future study. The phase interface bond between emulsified asphalt film and RAP aggregates is a kind of poor phase interface, and the inner cohesion of emulsified asphalt is weaker than the phase interface bond, which could significantly influence the strength of emulsified asphalt cold recycled asphalt mixture. We will develop higher–performance emulsified asphalt to improve the phase interface bond between emulsified asphalt film and RAP aggregates and the inner cohesion of emulsified asphalt film. The goal of studying the CRM is that the CRM layer should have the same quality as the traditional base layer or the bottom asphalt layer.

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