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The Impact of Cement Contents on the Properties of Asphalt Emulsion Stabilized Cold Recycling Mixtures

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Abstract: This paper studied how the content of Portland cement in emulsion stabilized cold recycling (CR-Emulsion) mixtures impacts the properties of asphalt. The properties (i.e., the rate of increase in initial strength, moisture susceptibility, rut resistance, and crack resistance) of asphalt CR-Emulsion mixtures with varying cement content and different curing histories were tested using indirect tensile strength (ITS) tests, bending beam tests at -10℃, and dynamic stability rutting tests at 60℃. The test results showed that ITS values linearly increased as the cement content and curing time increased. Increasing the cement content lead to better moisture resistant properties and the strength increased at a higher rate. Specimens with a cement content lower than 0.5% by weight exhibited relatively poor water resistance properties and a poor rate of increase in initial strength. The ITS values of the wet condition samples (ITS_{wet}) were more significantly affected by cement content than the ITS values of the dry condition samples (ITS_{dry}). Specimens with 1.5% cement by weight exhibited better rut resistance properties than specimens with 0%, 0.5%, and 2.5% cement content. As the cement content increased, the maximum bending strength at -10℃ increased, whereas the maximum bending strain at -10℃ decreased. The cement in CR-Emulsion mixtures requires a certain amount of curing time to improve the mixture properties; thus, curing methods that use an accelerated process cannot reflect the real conditions of CR-Emulsion mixtures. It was concluded that Portland cement is necessary to enhance the rate of increase in initial strength and to improve both the moisture resistance properties and high temperature properties of CR-Emulsion mixtures. However, too high of a cement content leads to brittleness at low temperatures. The optimal cement content for CR-Emulsion mixture was suggested to be around 1.5%.

Key words: *Asphalt emulsion; Cold recycling; Indirect tensile strength; Pavement; Portland cement.*

Introduction

In the last 10 years, the use of Asphalt Emulsion Stabilized Cold Recycling (CR-Emulsion) mixtures has seen a dramatic growth in China and throughout the world. While normally used in low-volume roads, CR-Emulsions are commonly used in high-volume roads and expressways in mainland China, typically with only 6-15 cm of hot mix asphalt (HMA) on top; therefore, CR-Emulsion mixtures are required to have the following properties:

(1) A rapid rate of increase in strength after construction.
(2) Excellent rut-resistant properties to sustain overweight loads that are prevalent in China.
(3) Good crack-resistant properties to resist the harsh climate conditions of China.

Cement is usually added to asphalt stabilized mixtures to enhance properties by improving the retained strength, improving the resistance to moisture, and increasing initial strength [1]. Cement accelerates the break-up of the asphalt emulsion and enhances the adhesion between the asphalt and aggregate. Adding cement in cold recycling mixtures is considered innovative [2]; however, in China, it is a common practice to add cement to CR-Emulsion mixtures to enhance their properties. The tendency has been to increase cement content to produce mixes that have a high strength and a strong a bond between particles to improve the aforementioned properties. In general, cement contents of no less than 1.5% have been used. However, there are now concerns regarding the negative effects of cement. Thus, finding the optimal cement content of a CR-Emulsion mixture has become important.

In this study, the objectives were to investigate the impact of cement content in CR-Emulsion mixtures and to find the optimal cement content.

Literature Review

Adding cement to asphalt emulsion mixtures to enhance performance dates back to the early 1970's. [3-5]. Valkonen and Nieminen [6] found that a small amount of Portland cement improved cold in-place recycling (CIR) initial strength and water resistance. Using electron microscopy observations, James *et al*. [7] found that there were differences in the state of the binder between solvent-free dense graded bituminous emulsion mixtures with or without cement. Issa *et al*. [2] found that the Hveem stability increased with cement content, and the optimum cement content likely ranged between 1% and 2%. Berthelot *et al*. [8] found that adding cement to emulsified asphalt stabilization systems significantly improved the mechanistic-climatic durability of the marginal granular base aggregate. Long *et al*. [9] found that both the indirect tensile strength (ITS) and the unconfined compressive strength (UCS) increased with an increase in cement content. Wang

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Table 1. Gradation of Cold Recycling Mixtures.

Sieve Size （mm）	Percentage Passing Each Sieve by Weight（%）					
	RAP	Virgin Aggregate	Mineral Filler	Combined Gradation	Gradation Band of Chinese MOT Spec. JTG F41 [11]	
					Low Limit	High Limit
26.5	100	100	100	100	100	100
19	89	100	100	91.8	90	100
9.5	56.6	100	100	67.5	60	80
4.75	31.6	85.3	100	45.8	35	65
2.36	18.9	60.4	100	31.3	20	50
0.3	6.3	17.7	100	13.3	3	21
0.075	3	5.4	90	7.8	2	8
Proportion （%）	75	20	5	-	-	-

Table 2. Asphalt Emulsion Formulation.

Ingredient		Percentage (%)
Asphalt (60/90 pen, From CNOOC)		63
Water phase	Emulsifier (PC-55, from MeadWestvaco)	1.6
	Water	35.4
	Hydrochloric acid	Until pH value of water phase reaches 2.0

Table 3. Asphalt Emulsion Test Results.

Items		Test results	Requirements of China MOT Spec. JTG F41 [11]
Particle charge		Positive	Positive
Set speed		Slow set	Slow or medium set
Sieve test, %		0	≤ 0.1
Angler Viscosity at 25℃, s		7.1	2-30
Tests on residue	Residue percentage,%	63.2	≥ 62
	Penetration, 25℃, 100 g, 5 s	51	50-300
	Softening Point(R&B), ℃	49.5	-
	Ductility, 15℃, 5 cm/min, cm	61	≥ 40
Storage stability test (5days), %		0.3	≤ 5

et al. [10] found that cement in asphalt emulsion mixtures displayed four effects: promoting emulsion break, forming a net structure with the cement hydration products and asphalt film, creating inner deficiencies in mixtures and enhancing adhesion between the asphalt and the aggregate.

Specifications from the Chinese Ministry of Transport (MOT) [11] require that the cement content of CR-Emulsion mixtures should not exceed 1.5%, as suggested by Wirtgen Cold Recycling Manual [12]. The South Africa Bitumen Stabilized Material Guidelines [1] suggests that less than 1.0% should be used for asphalt emulsion stabilized mixtures, and the ARRA Basic Asphalt Recycling Manual cites that the typical content of Portland cement has been 1% to 2 % [13].

Although previous studies have shown that adding cement to asphalt emulsion mixtures produces significant benefits, the studies did not address the impact of cement on CR-Emulsion rut-resistant properties and low-temperature crack resistance properties, and many previous studies focused on virgin aggregates and high-float emulsions. Also, the cement content limits suggested by different agencies are different.

Experimental Procedures

Gradation

In previous research, the suitability between continuously graded aggregates for cold treatment and foamed bitumen has been verified. Aggregates with this type of gradation are also commonly used in pavement structures, either as granular, cemented or asphaltic base or sub-base layers. Thus, continuously gradation bonds as specified in China's MOT JTG F41 [11] were used in this study.

Materials

Reclaimed asphalt pavement (RAP) samples were milled from Beijing 5th East Ring Road. The RAP samples were dried outside for two days (around 30℃), and then placed in a 60℃ oven until a constant weight was reached. Afterwards, sieve analyses of the RAP were performed.

One type of 0-5 mm sized crashed lime stone chip and one type of lime stone filler, which was manufactured in Beijing, were used in this study. These materials are commonly used in the recycling process in Beijing. The samples were dried to constant weight in a 110℃ oven, and sieve analyses were performed. Sieve analyses of the extracted aggregate from the RAP samples were not performed because the RAP samples are more like "black aggregates" in CR-Emulsion mixtures.

The cement used in this study was 32.5 MPa, P.S.A type Portland blast furnace-slag cement produced in Tangshan. This cement type is commonly used in the recycling process in China. The samples were dried to constant weight in a 110℃ oven, and sieve analyses were performed.

All the aforementioned granule materials were blended proportionally to meet China's MOT JTG F41 grading band, as tabulated in Table 1. To minimize the variability of gradation, RAP particles larger than 26.5 mm were discarded. The remaining RAP particles were then divided into three stockpiles that were retained on one of the following sieves: 9.5 mm, 4.75 mm and those that passed through the 4.75 mm sieve. The particles were then re-blended according to the designed gradation to produce the mixtures.

A cationic slow set solvent-free emulsion produced with 60/90 penetration grade asphalt and a slow-set emulsifier was used in this study. The asphalt emulsion formula and its properties are shown in Table 2 and Table 3. This kind of asphalt emulsion is also commonly used in the recycling process in north China.

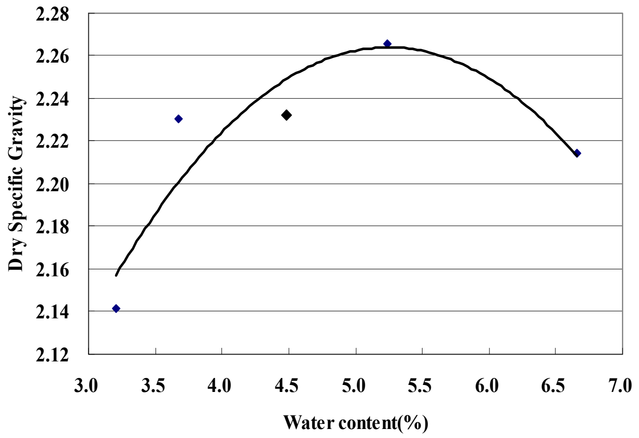


Fig. 1. Relationships Between Dry Specific Gravity and Water Content.

Table 4. Determine of Optimum Asphalt Content.

Asphalt content, %	2	2.2	2.5	3
ITS_{dry}, MPa	0.61	0.76	0.72	0.71
ITS_{wet}, MPa	0.53	0.73	0.69	0.67
$ITS_{retained}$, %	86.9	96.1	95.8	94.4

Laboratory Testing

Optimum Moisture Content

The optimum moisture content (OMC) is one of the most important mixture design criteria of CIR-Emulsion mixtures. Water is necessary to soften and break down agglomeration in the aggregates and to aid the asphalt dispersion during mixing and compacting. The modified proctor test was run in accordance with China's MOT JTG E40-2007 T0131 [14], which is similar to the ASTM D 1557 "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56000 ft-lbf/ft^3 or 2700 kN-m/m^3)." Following the JTG E40-2007 T0131, the OMC was determined to be 5.2%, as shown in Fig. 1.

Optimal Asphalt Content

The optimum asphalt content (OAC) is also an important mixture design criteria of CIR-Emulsion mixtures. Mix designs were performed using standard methods specified in China's MOT JTG F41 [11], and the selection of the binder content was based on both the ITS_{dry} and ITS_{wet}. Four binder contents, 2.0%, 2.2%, 2.5%, and 3.0%, were used, and the specimens were cured in a 60℃ oven. The optimum asphalt content was determined to be 2.2%, as shown in Table 4.

Experimental Specimen Preparation

All specimens were prepared at the optimum moisture content (5.2%) and the optimum residual asphalt binder content (2.2%) but with different levels of cement content (0%, 0.5%, 1.5%, and 2.5%) to provide an equivalent basis for comparison. Mineral filler was used to offset the change in cement content to ensure consistent total filler content.

Specimen preparation consisted of four steps: material preparation, mixing, molding and compacting, and finally curing. The predetermined amounts of the dried solid materials (aggregates, mineral filler, RAP and cement) were placed in a mechanical mixer and thoroughly mixed. Next, the predetermined amount of water was added and mixed until all aggregate particles were uniformly wet. Then, the predetermined amount of emulsion was added and mixed for 50 seconds. Finally, the newly mixed materials were placed in molds to be compacted and cured. All mixing and compacting procedures were performed at room temperature.

Five types of specimens were prepared:

(1) Oven-curing Marshall specimen: Newly-mixed loose materials were placed in a 101.6 mm diameter Marshall mold, and 75 blows were applied on each side of the specimen at room temperature (23℃-28℃). Without being removed from the mold, each specimen was placed in a 60℃ oven until a constant weight was reached. Then, the specimen was cooled to room temperature and extruded from the mold. This curing process was selected to simulate the final condition of CR-Emulsion mixtures in a pavement structure. Four specimens were prepared for each cement content.

(2) Partly-sealed-short-term-curing Marshall specimen: The specimen preparation was the same as that of the oven-curing Marshall specimen except the curing process was changed. After compaction, the specimen, which was still in its mold, was placed in a plastic bag with one side sealed and the other side left open and cured at room temperature (23℃-28℃) for 1 day, 3 days, 5 days, and 7 days, respectively, before finally being extruded from the mold. This curing procedure was adopted to simulate a CR-Emulsion job-site curing process before overlay. Four specimens were prepared for each condition.

(3) Sealed-28-day-curing Marshall specimen: The specimen preparation procedure was the same as that of the oven-curing Marshall specimen except the curing process was changed. The Marshall specimen was sealed in a plastic bag immediately after compaction with the mold un-extruded, cured for 28 days at room temperature (23℃-28℃), and then extruded from mold. This curing procedure was adopted to simulate the early stages of a CR-Emulsion mixture job-site curing process. Four specimens were prepared for each condition.

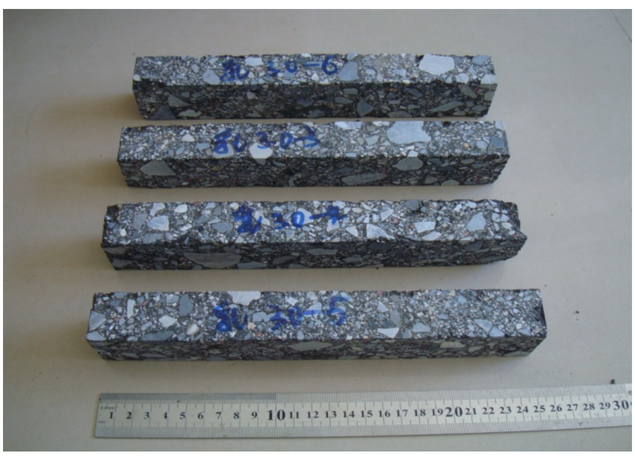


Fig. 2. Bending Beam Test Specimens.

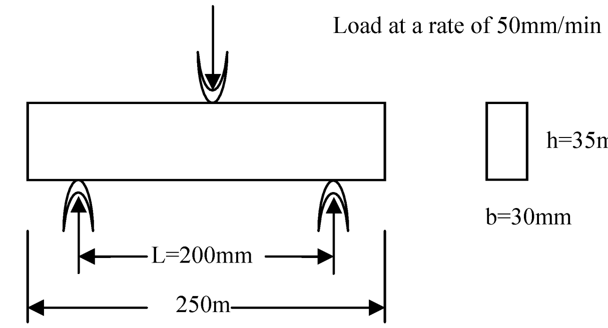


Fig. 3. Sketch Map of Bending Beam Tests.

(4) 300 mm wide×300 mm long×40 mm thick specimen: Newly-mixed loose materials were placed in a rut resistance specimen mold, and a 30000 N/m load was applied using a minimized steel roller; the specimen was then placed in a 60℃ oven until a constant weight was reached. Finally, the specimen was cooled to room temperature and extruded from mold. The specimen was used for rut resistance tests. Three specimens were prepared for each condition.

(5) 30 mm wide×250 mm long×35 mm thick specimen: This specimen, shown in Fig. 2, was produced by cutting a 300 mm wide×300 mm long×40 mm thick specimen. The specimen was used in bending beam tests at -10℃. Eight specimens were prepared for each condition.

Test Methods

Table 5 gives a complete list of the laboratory tests.

(1) ITS tests at 15℃ were performed on the 101.6 mm diameter Marshall samples in accordance with China's MOT JTJ 052-2000 T0716 [15], using a Marshall machine and a 100 mm diameter indirect tensile breaking head. The indirect tensile strength and the tensile strength ratio of the CIR-Foam mixtures were computed as follows:

$$ITS = \frac{0.006287 \times P_{\max}}{h} \tag{1}$$

where

P_{max} = maximum load, N

h = specimen height, mm

The ITS test results obtained from specimens that were immersed in a 15℃ water bath for 1 hour prior to the ITS test, were termed ITS_{dry}. The ITS test results obtained from specimens that were immersed in a 25℃ water bath for 23 hours and then placed in a 15℃ water bath for an additional 1 hour prior to the test were termed ITS_{wet}. The ratio of ITS_{wet} to ITS_{dry}, expressed as a percentage, was termed $ITS_{retained}$, as defined in Eq. (2).

$$ITS_{retained} = \frac{ITS_{wet}}{ITS_{dry}} \tag{2}$$

where

$ITS_{retained}$= the ratio of ITS_{wet} to ITS_{dry}, %

ITS_{wet} = indirect tensile strength at wet condition, MPa

ITS_{dry} = indirect tensile strength at dry condition, MPa

(2) Rut-resistance tests at 60℃ were performed in accordance with China's MOT JTJ 052-2000 T0719 to evaluate the high temperature performance of CR-Emulsion mixtures. The 300 mm wide×300 mm long×40 mm thick specimen was placed in a 60℃±1℃ chamber on the rut test apparatus, for 5 to 24 hours or until the specimen reached the test temperature; then loads of 0.7 MPa were applied for more than 1 hour through a 200 mm diameter rubber tire moving forward and backward 42 times per minute on the specimens. The dynamic stability (DS) was defined as the rut depth generated by every load between 45 minutes and 60 minutes, as defined in Eq.(3). The overall rut depth at 60 minutes was also used to evaluate rut resistance properties.

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \tag{3}$$

where

DS—dynamic stability，times/*mm*.

d_1— rut depth after 45 min loading, *mm*.

d_2— rut depth after 60 min loading, *mm*.

t_1, t_2—loading time, 45 min and 60 min, respectively.

N—loading frequency, typically 42 times per minute.

(3) Bending beam tests at -10℃ were performed in accordance with China's MOT JTJ 052-2000 T0715 to evaluate low temperature performance. Specimens were placed on supports that were 200 mm apart, and a concentrated center load was applied on top at the mid-span at a speed of 50 mm/min, as shown in Fig. 3. The bending strength at failure, R_B, and bending strain at failure, ε_B, calculated using Eqs. (4, 5), were adopted to evaluate the low temperature performance of CR-Emulsion mixtures.

$$R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2} \tag{4}$$

$$\varepsilon = \frac{6 \times h \times d}{L^2} \tag{5}$$

where

R_B—bending strength at failure, MPa.

L—the span length, mm.

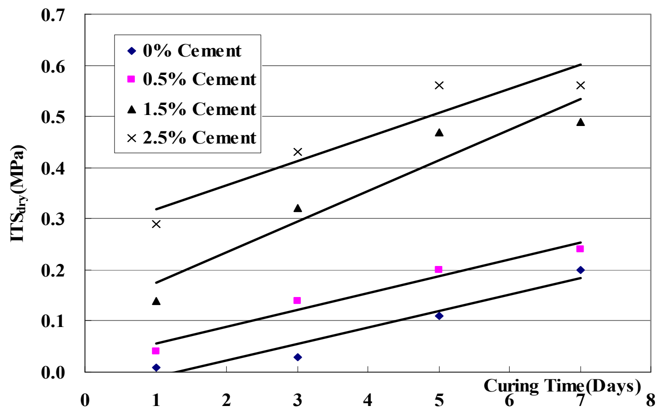
P_B—maximum concentrated center load at failure, N.

b—beam width, mm.

h—beam height, mm.

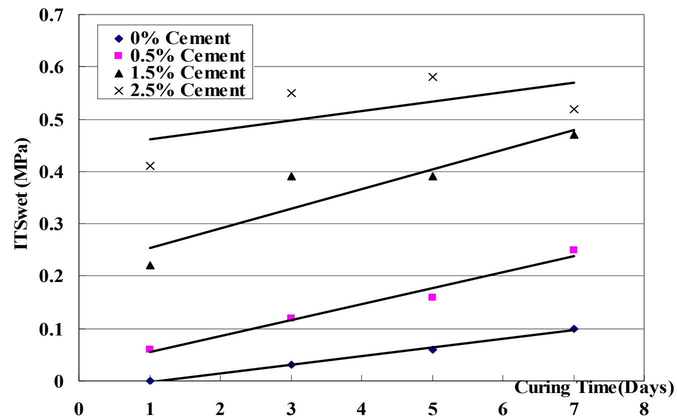
Table 5. A List of the Laboratory Tests Performed.

Cement Content(%)	0						0.5						1.5						2.5					
Curing Methods	1d	3d	5d	7d	28d	60℃ Oven	1d	3d	5d	7d	28d	60℃ Oven	1d	3d	5d	7d	28d	60℃ Oven	1d	3d	5d	7d	28d	60℃ Oven
ITS_{dry}	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ITS_{wet}	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Bending Beam Tests												×						×						×
Rutting Tests						×						×												×



Cement Content	Linear Regression	Coefficient of Determination, R^2	Note
0.00%	$y = 0.0325x - 0.0425$	0.94	y- ITS_{dry} x-Curing time
0.50%	$y = 0.033x + 0.023$	0.96	
1.50%	$y = 0.06x + 0.115$	0.913	
2.50%	$y = 0.047x + 0.272$	0.887	

Fig. 4. Relationship between ITS_{dry} and Curing Time.



Cement Content	Linear Regression	Coefficient of Determination, R^2	Note
0.00%	$y = 0.0165x - 0.0185$	1	y- ITS_{wet} x-Curing time
0.50%	$y = 0.0305x + 0.0255$	1	
1.50%	$y = 0.0375x + 0.2175$	0.8	
2.50%	$y = 0.018x + 0.443$	0.4	

Fig. 5. Relationship between ITS_{wet} and Curing Time.

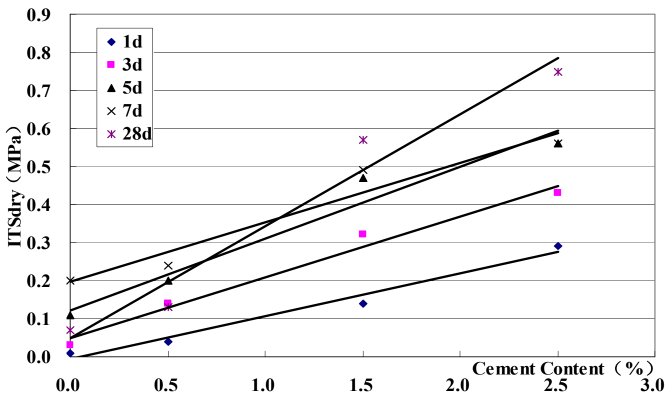
The test results of all specimens were averaged and used in the analysis.

Results and Discussion

ITS_{dry}, ITS_{wet}, $ITS_{retained}$

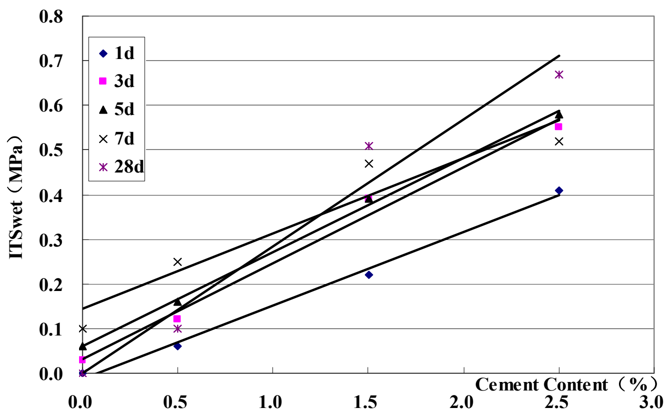
Fig. 4 shows the relationship between ITS_{dry} and the curing time of CR-Emulsion specimens with different cement contents. The values of ITS_{dry} increased when the curing time and cement content increased.

Using Excel, linear regression trend lines were fit to the data. The slope of the ITS_{dry}-curing time curve increased from 0.0325 to 0.06 as the cement content increased from 0% to 1.5%, and then declined



Curing Times	Linear Regression	Coefficient of Determination, R^2	Note
1 day	$y = 0.1125x - 0.0066$	0.9771	y- ITS_{dry} x-Cement content
3 days	$y = 0.16x + 0.05$	0.9813	
5 days	$y = 0.1892x + 0.1222$	0.9581	
7 days	$y = 0.1569x + 0.1959$	0.9435	
28 days	$y = 0.2942x + 0.049$	0.9627	

Fig. 6. Relationship Between ITS_{dry} and Cement Content.



Curing Times	Linear Regression	Coefficient of Determination, R^2	Note
1 day	$y = 0.1651x - 0.0132$	1	y- ITS_{wet} x-Cement content
3 days	$y = 0.2153x + 0.0303$	1	
5 days	$y = 0.2105x + 0.0607$	1	
7 days	$y = 0.1688x + 0.1451$	0.9	
28 days	$y = 0.2847x - 0.0003$	1	

Fig. 7. Relationship Between ITS_{wet} and Cement Content.

to 0.047 as the cement content was further increased to 2.5%. This result indicates that CR-Emulsion mixtures with the correct amount of cement content increased in strength faster than mixtures with too much or too little cement. Too much cement (2.5%) lead to poor workability, making the mixture too stiff to be compacted effectively, which was apparent during specimen preparation.

The relationships between the ITS_{wet} and curing time, shown in Fig. 5, were similar to the ITS_{dry} results, indicating that within the range of 0% to 1.5% cement content, the water resistance properties of the CR-Emulsion mixtures were enhanced with a higher cement content. The ITS_{wet} results of specimens that contained 2.5% cement and cured for 7 days were abnormally lower than the specimens that

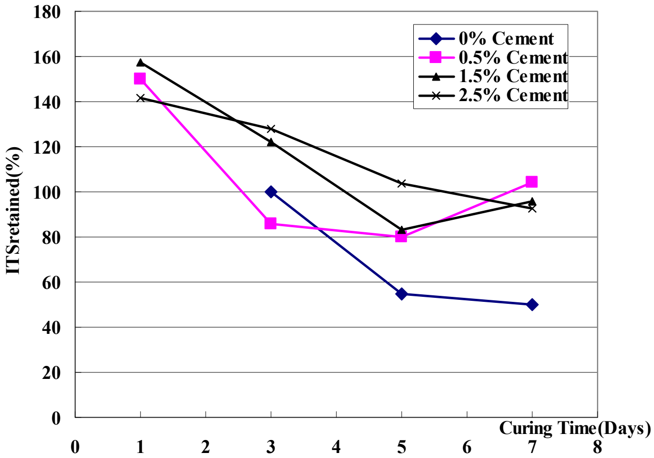


Fig. 8. Relationship Between $ITS_{retained}$ and Cement Content.

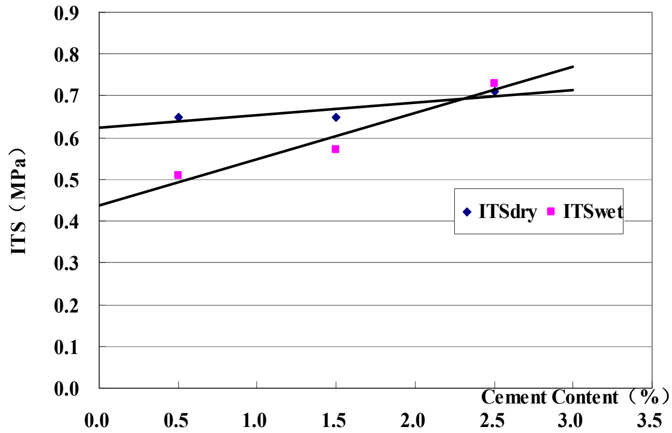
were cured for 5 days. This result was due to an electric power failure that resulted in too long of a time interval between the mixing and compacting of the specimens cured over 7 days. Consequently, the hydration of cement hindered effective compaction. The slopes of the ITS_{dry}-curing time linear regression line were higher than the corresponding slopes of the ITS_{wet}-curing time curves, indicating that being soaked in water produced an adverse effect on initial strength gain.

Fig. 6 and Fig. 7 show plots of the cement content versus ITS_{dry} and ITS_{wet} for various curing time mixtures. Both the ITS_{dry} and ITS_{wet} exhibited a good linear relationship with cement content. The slope of the ITS-cement content curve increased as the curing time increased from 1 day to 28 days, indicating that the cement needed a certain amount of curing time in the CR-Emulsion mixtures; the longer the curing time, the greater the strength benefit that can bedeveloped from the higher cement content. This result also implies that, to some extent, the curing methods using an accelerated process do not reflect the real conditions of CR-Emulsion mixtures. The data of 7 days curing specimens were an exception because of the electric power failure mentioned above.

The ITS_{dry} and ITS_{wet} values of specimens with no cement were much lower than the values from specimens with cement, indicating that cement effectively enhanced the initial strength of the mixtures. The specimens without cement that were cured for 1 day disintegrated during the soaking procedure before the ITS_{wet} tests, indicating that cement is necessary in CR-Emulsion mixtures.

Fig. 8 shows the relationships between the $ITS_{retained}$ and the curing time of mixtures with varying cement content. The higher the cement content, the higher the $ITS_{retained}$ values were. This result also indicates that cement can effectively enhance the moisture resistance properties of CR-Emulsion mixtures.

For specimens cured over 28 days with 0.0% and 0.5% cement, the ITS_{dry} and $ITS_{retained}$ values were even lower than the specimens that were cured for 5 days. Also, specimens without cement that were cured for 28 days disintegrated during soaking. However, one reason for this phenomenon is that the specimens cured for 28 days were completely sealed, whereas the specimens cured for 5 days were half sealed; the data still indicate that a cement content of less than 0.5% leads to a relatively poor rate of increase in strength. For specimens cured for over 5 days with 1.5% and 2.5% cement, the



ITS	Linear Regression	Coefficient of Determination, R^2	Note
ITS_{dry}	$y = 0.03x + 0.625$	0.75	*y*- *ITS*
ITS_{wet}	$y = 0.11x + 0.4383$	0.936	*x*-Cement content

Fig. 9. ITS_{dry} and ITS_{wet} of Oven Curing Specimens with Different Cement Content.

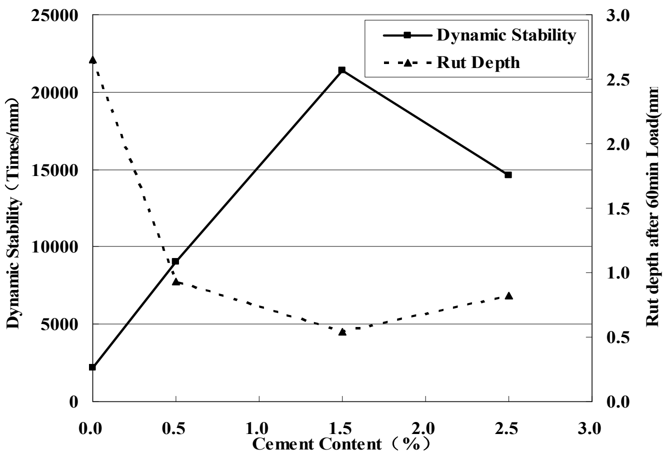


Fig. 10. Relationship Between DS and Cement Content.

ITS_{dry} and ITS_{wet} values were more than 70% of the specimens that were cured for 28 days, which is a satisfactory rate of increase in strength.

Fig. 9 shows the ITS_{dry} and ITS_{wet} results for CR-Emulsion specimens that were oven-cured at 60℃ with varying cement content. The ITS_{wet} results increased more rapidly with an increase in cement content than the ITS_{dry} did, indicating that cement has a more obvious benefit on water resistant performance. The $ITS_{retained}$ increased as the cement content increased, implying that the higher the cement content, the better the final moisture resistance.

From these ITS_{dry} and ITS_{wet} test results, it can be seen that cement is absolutely necessary in CR-Emulsion mixtures, and the optimal cement content is around 1.5%.

Rut Resistance Tests

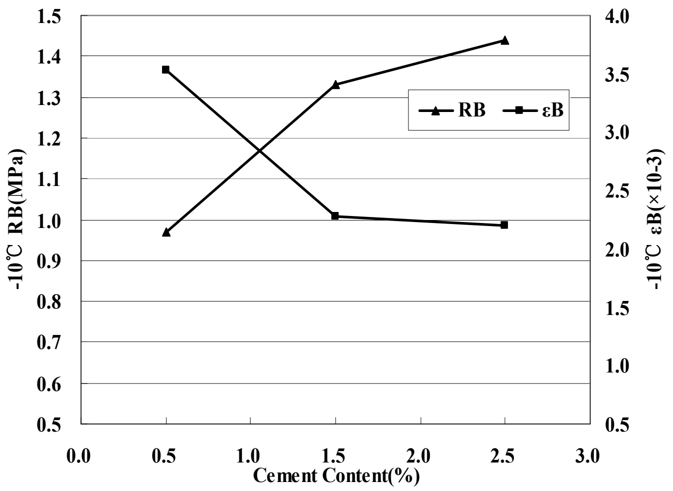


Fig. 11. Bending Beam Test Results of CR-Emulsion Mixtures with Different Cement Content.

Fig. 10 shows the rut resistance test results for CR-Emulsion mixtures with varying cement content. The rut depth value decreased and DS increased as the cement content increased from 0% to 1.5%; however, adding a cement content greater than the aforementioned levels did not enhance the rut resistant properties any further. Specimens with 2.5% cement content showed a relatively poor workability during specimen preparation. Too much cement resulted in the mixture becoming too stiff to be compacted effectively.

The DS values of all specimens with cement were even much higher than China's specifications for both HMA and polymer modified asphalt mixtures used in hot areas [16], implying that the CR-Emulsion high temperature performance is adequate to be used as a substitute for HMA layers.

From these rut resistance test results, it can be seen that cement is necessary for CR-Emulsion mixtures, and the optimal cement content is around 1.5%.

Low Temperature Bending Beam Tests

Fig. 11 shows low temperature (-10℃) bending beam test results for CR-Emulsion mixtures with varying cement content. The bending strength at failure (R_B) increased, while the bending strain at failure (ε_B) decreased as the cement content increased.

Assuming that failures in cold recycling layers are caused by excessive strain, high cement content is not a good choice. The values of R_B and ε_B change much more significantly as the cement content reaches 1.5%; afterwards, adding any more than 1.5% cement content is not necessary.

Conclusions

From the data obtained and the analysis performed, the following conclusions are made:

1. Increasing the cement content leads to better moisture resistant properties and a higher rate of increase in strength. Specimens with lower than 0.5% cement showed relatively poor water resistance properties and a poor rate of increase in initial strength.
2. Both the ITS_{dry} and ITS_{wet} results exhibited a good linear relationship with cement content and curing time. ITS_{wet} is more significantly affected by cement content than ITS_{dry}.
3. The cement requires a minimum curing time in CR-Emulsion mixtures to improve properties; thus, the curing methods that use an accelerated process did not reflect the real conditions of CR-Emulsion mixtures.
4. The delayed compaction has negative effects on the properties of CR-Emulsion mixtures.
5. Adding cement enhances the rut resistant properties of CR-Emulsion mixtures. However, when the cement content exceeds 1.5%, there is no improvement in rut-resistant properties. This result is because too much cement makes the mixture too stiff and thus difficult to compact effectively.
6. The DS values of all specimens containing cement met the requirements of China's MOT specifications for HMA and polymer modified asphalt mixtures used in hot areas, implying that CR-Emulsion mixtures have excellent high temperature performance.
7. Increasing the cement content lead to a higher maximum bending strength and lower maximum bending strain at low temperatures. If we suppose that failures in cold recycled layers are caused by excessive strain, then high amounts of cement content is not a good choice.

Therefore, Portland cement is absolutely necessary in CR-Emulsion mixtures because it enhances the rate of increase in strength, moisture resistant properties, and high temperature performance. However, too high a cement content leads to brittleness at low temperatures and poor workability. The optimal cement content for CR-Emulsion mixture is around 1.5%.

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