IMPACTS OF CEMENT CONTENT ON PROPERTIES OF FOAMED ASPHALT COLD RECYCLING MIXTURES

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Abstract

This paper studied how the Portland cement content impacts the properties of foamed asphalt stabilized cold recycling (CR-Foam) mixtures. The properties of CR-Foam 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□. It is concluded that Portland cement is absolutely necessary to enhance the rate of increase in initial strength and to improve both the moisture resistance properties and high temperature properties of CR-Foam mixtures. However, too high cement content leads to bad rut resistance properties and brittleness at low temperatures. The optimal cement content for CR-Foam mixture is suggested to be around 1.5%.

1. INTRODUCTION

In the last 10 years, the use of Foamed Asphalt Stabilized Cold Recycling (CR-Foam) mixtures has seen a dramatic growth in China and throughout the world. While normally used in low-volume roads, CR-Foam mixtures are commonly used in high-volume roads and expressways in China mainland, typically with only 6-15 cm of hot mix asphalt (HMA) on top; therefore, CR-Foam mixtures are required to have the following properties:
(1) A rapid rate of increase in strength after construction.
(2) Good rut-resistant properties to sustain overweight loads which 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 (AASA, 2009). However, Adding cement in cold recycling mixtures is considered innovative (Rita et al, 2001). In China, the tendency has been to add more than 1.5% cement to cold recycling mixtures to produce mixes that have a high strength and a strong a bond between particles to improve the aforementioned properties. There are now concerns regarding the negative effects of cement. Thus, finding the optimal cement content of a CR-Foam mixture has become important.

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

2. LITERATURE REVIEW

F M Long et al conducted a research on foamed asphalt treated sand materials with various binder contents and active filler content by adopting UCS, ITS, and erosion tests etc, found that the cement added strength to the mix but reduced the flexibility, increase in the cement content resulted in a decrease in the strain-at-break, and the higher the binder and filler content, the higher the resistance to the durability(F M Long et al, 2005). Castedo-Franco found that moisture sensitivity of foamed asphalt mixtures could be reduced by adding 1-2% Portland cement(Castedo et al, 1983). Valkonen and Nieminen found that a small amount of Portland cement improved cold in-place recycling (CIR) early strength and water resistance(Valkonen, A., and Nienminen, P., 1995).

Specifications from the Chinese Ministry of Transport (MOT, 2008) require that the cement content of CR-Foam mixtures should not exceed 1.5%, as suggested by Wirtgen Cold Recycling Manual(Wirtgen, 2004). The South Africa Bitumen Stabilized Material Guidelines suggests that less than 1.0% should be used for foamed asphalt stabilized mixtures, and the ARRA Basic Asphalt Recycling Manual cites that the typical content of Portland cement has been 1% to 2 % (ARRA, 2002).

Although previous studies have shown that adding cement to foamed asphalt mixtures produces significant benefits, the studies did not address the impact of cement on CR-Foam rut-resistant properties and low-temperature crack-resistance properties. Also, the cement content limits suggested by different agencies are different.

3. EXPERIMENTAL PROGRAM

3.1 Gradation

In previous research, the suitability between continuously graded aggregates for cold treatment and foam asphalt 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 (MOT, 2008) were used in this study.

3.2 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-Foam 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.

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	
					Low limit	High limit
26.5	100	100	100	100.0	100	100
19	89	100	100	91.8	90	100
9.5	56.6	100	100	67.5	60	85
4.75	31.6	85.3	100	45.8	35	65
2.36	18.9	60.4	100	31.3	30	55
0.3	6.3	17.7	100	13.3	10	30
0.075	3	5.4	90	7.8	6	20
Proportion（%）	75	20	5	-	-	-

A 60/90 penetration grade asphalt was used to produce foamed asphalt. Its foamability was tested by using Wirtgen WLB10 laboratory plant. The asphalt temperature and water added for producing foamed asphalt were determined as 160℃ and 2.5%, when the foamed asphalt got its optimized expansion ratio and half-life. The test results were shown in Table 2.

Table 2 Characteristics of foamed asphalt

Percentage water added(%)	Asphalt temperature					
	150℃		160℃		170℃	
	expansion ratio(times)	half-life(s)	expansion ratio(times)	half-life(s)	expansion ratio(times)	half-life(s)
1.5	16	26	15	31	13	30
2	20	22	19	26	18	26
2.5	25	16	24	24	21	19
3	28	12	27	22	22	15

3.2 Laboratory Testing

3.2.1 Optimum moisture content

The optimum moisture content (OMC) is one of the most important mixture design criteria of CIR-Foam 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 (MOT, 2007), 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%.

3.2.2 Optimal asphalt content

The optimum asphalt content is also an important mixture design criteria of CIR-Foam mixtures. Mix designs were performed using standard methods specified in China’s MOT JTG F41 (MOT, 2008), 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 optimum asphalt content was determined to be 2.2%.

3.2.3 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 foamed asphalt 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-Foam 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- Foam 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- Foam mixture job-site curing process. Four specimens were prepared for each condition.

(4) 300 mm wide×300 mm long×40 mm thick specimen. Newly-mixed 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 Figure 1, 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.

Figure 1 Sketch Map of Bending Beam Test Specimens

3.2.4 Test methods

Table 3 gives a complete list of the laboratory tests.

Table 3 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
ITSdry	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ITSwet	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Bending Beam tests												×						×						×
Rutting tests						×						×												×

(1) ITS tests at 15 ℃ were performed on the 101.6 mm diameter Marshall samples in accordance with China's MOT JTJ 052 T0716 (MOT, 2000), using a Marshall machine and a 100 mm diameter indirect tensile breaking head, as shown in Figure 4. The indirect tensile strength and the tensile strength ratio of the CIR-Foam mixtures were computed as follows:

$$ITS = \frac{0.006287 \times P_{\max}}{h} \qquad \text{(Eq.1)}$$

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 $ITS_{retained}$, see Equation 2.

$$ITS_{retained} = \frac{ITS_{wet}}{ITS_{dry}} \qquad \text{(Eq.2)}$$

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-Foam 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, see Equation 3. The overall rut depth at 60 minutes was also used to evaluate rut resistance properties.

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \qquad \text{(Eq.3)}$$

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

(4) 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 Figure 2. The bending strength at failure, R_B, and bending strain at failure, ε_B, see Equation 4 and 5, were adopted to evaluate the low temperature performance of CR-Foam mixtures.

$$R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2} \qquad \text{(Eq.4)}$$

$$\varepsilon = \frac{6 \times h \times d}{L^2} \qquad \text{(Eq.5)}$$

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

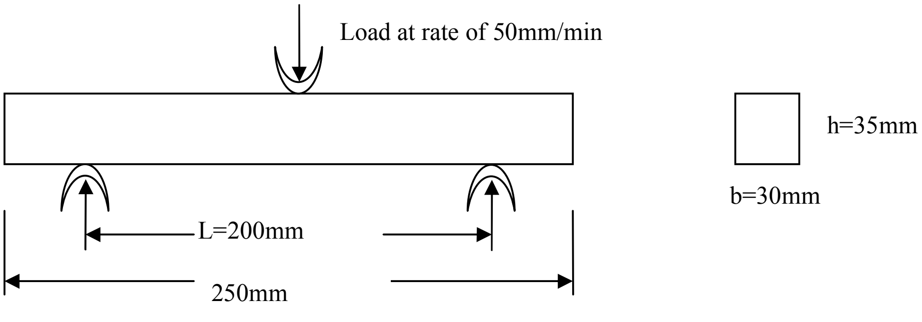


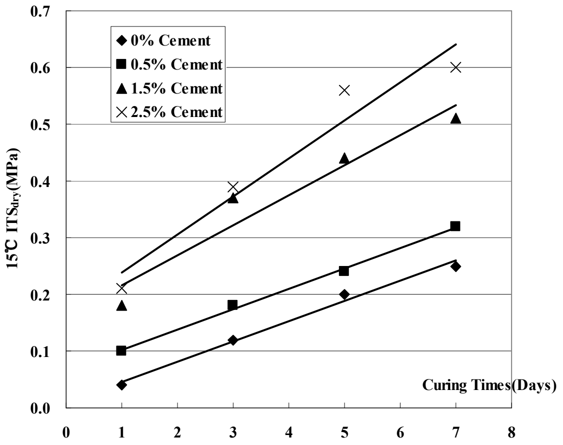
Figure 2 Sketch Map of Bending Beam Tests

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

4. RESULTS AND DISCUSSION

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

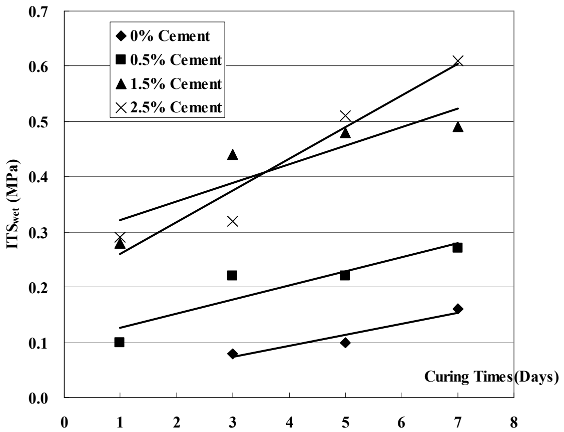
Figure 3 shows the relationship between ITS_{dry} and the curing time of CR-Foam specimens with different cement contents. The values of ITS_{dry} increased when the curing time and cement content increased. Using Excel, linear regression trend lines were fit to the data. The slope of the ITS_{dry}-curing time curve increased from 0.0355 to 0.067 as the cement content increased from 0% to 2.5%. This result indicates that CR-Foam mixtures with higher amount of cement content increased in strength faster than mixtures with lower cement content.



Cement Content	Linear Regression	Coefficient of Determination, R^2
0.0%	y = 0.0355x + 0.011	0.9894
0.5%	y = 0.036x + 0.066	0.9969
1.5%	y = 0.053x + 0.163	0.9286
2.5%	y = 0.067x + 0.172	0.9411
Note	y- ITS_{dry}, x-Curing time	

Figure 3 Relationship between ITS_{dry} and curing time

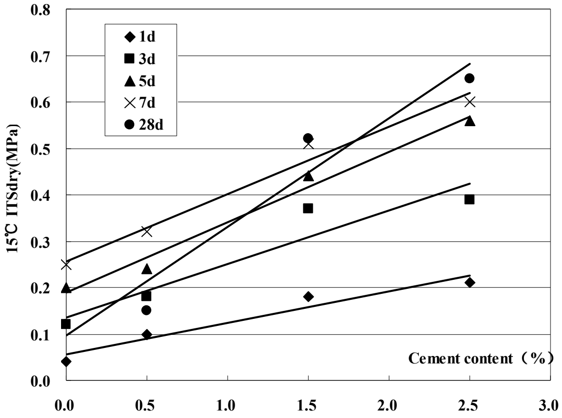
The relationships between the ITS_{wet} and curing time, shown in Figure 4, were similar to the ITS_{dry} results, indicating that within the range of 0% to 2.5% cement content, the water resistance properties of the CR-Foam mixtures were enhanced with a higher cement content. The slopes of the ITS_{dry}-curing 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.



Cement Content	Linear Regression	Coefficient of Determination, R^2
0.0%	y = 0.0200x + 0.0133	0.9231
0.5%	y = 0.0255x + 0.1005	0.8297
1.5%	y = 0.0335x + 0.2885	0.7882
2.5%	y = 0.0575x + 0.2025	0.9383
Note	y- ITS_{wet}, x-Curing time	

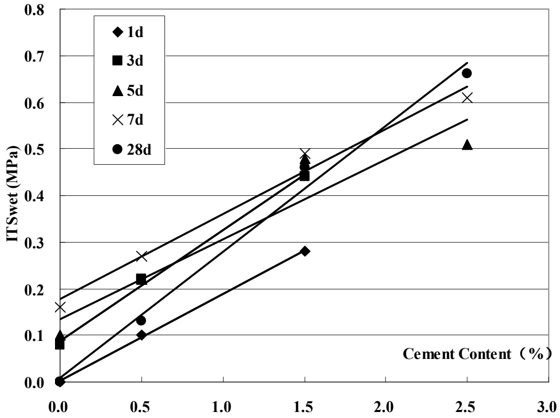
Figure 4 Relationship between ITS_{wet} and curing time

Figure 5 and Figure 6 show plots of the cement content versus ITS_{dry} and ITS_{wet} for various curing time mixtures. Both the ITS$_{\mathrm{dry}}$ and ITS$_{\mathrm{wet}}$ exhibited good linear relationships with cement content. The slope of the ITS$_{\mathrm{dry}}$-cement content curve generally increased as the curing time increased from 1 day to 28 days, and the slope of the ITS$_{\mathrm{wet}}$-cement content curve of 28 days curing specimens was much higher than others, indicating that the cement needed a certain amount of curing time to work. This result also implies that the accelerated curing methods can not reflect the real conditions of CR-Foam mixtures.



Curing Times	Linear Regression	Coefficient of Determination, R^2
1 day	y = 0.0675x + 0.0566	0.9387
3 days	y = 0.1159x + 0.1346	0.9028
5 days	y = 0.1519x + 0.1892	0.9843
7 days	y = 0.1451x + 0.2568	0.9776
28 days	y = 0.2332x + 0.0976	0.9488
Note	y- ITS$_{\mathrm{dry}}$, x-Cement Content	

Figure 5 Relationship between ITS$_{\mathrm{dry}}$ and cement content



Curing Times	Linear Regression	Coefficient of Determination, R^2
1 day	y = 0.1857x + 0.0029	0.9993
3 days	y = 0.2371x + 0.0886	0.9961
5 days	y = 0.1712x + 0.1349	0.9015
7 days	y = 0.1827x + 0.1769	0.9811
28 days	y = 0.2708x + 0.0078	0.9892
Note	y- ITS$_{\mathrm{wet}}$, x-Cement Content	

Figure 6 Relationship between ITS$_{\mathrm{wet}}$ and cement content

The ITS$_{\mathrm{dry}}$ and ITS$_{\mathrm{wet}}$ 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 and cured for 1 day disintegrated during the soaking before the ITS$_{\mathrm{wet}}$ tests, indicating that cement is necessary in CR-Foam mixtures.

For specimens cured over 28 days with 0.0% and 0.5% cement, the ITS$_{\mathrm{dry}}$ and ITS$_{\mathrm{retained}}$ 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$_{\mathrm{dry}}$ and ITS$_{\mathrm{wet}}$ values were more than 70% of the specimens cured for 28 days, which is a satisfactory rate of increase in strength.

Figure 7 shows the relationships between the $ITS_{retained}$ and the curing time of mixtures with varying cement content. The $ITS_{retained}$ values of specimens with cement are much higher than specimens without cement, indicating that cement can effectively enhance the moisture resistance properties of CR-Foam mixtures.

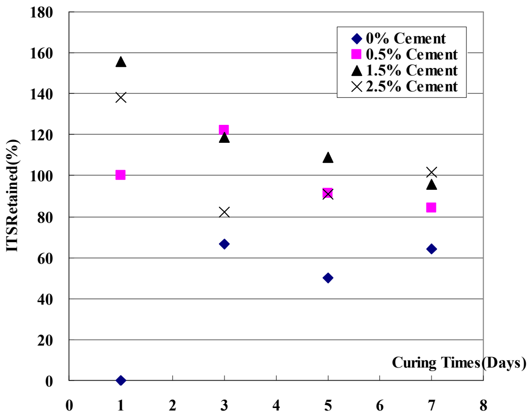
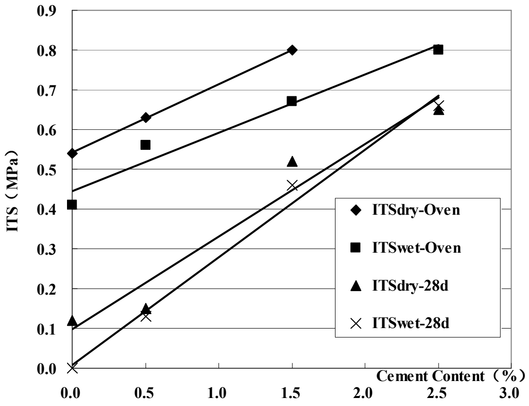


Figure 7 Relationship between $ITS_{retained}$ and cement content

Figure 8 shows the ITS_{dry} and ITS_{wet} results for CR-Foam specimens that were cured for 28 days and oven-cured at 60℃ with varying cement content. The slopes of the ITS-cement content curve of 28 days curing specimens were much higher than those of oven curing specimens, which also indicates that the curing methods using an accelerated process do not reflect the real conditions of CR-Foam mixtures.



Curing Method	Linear Regression	R^2	Note
oven	y = 0.1729x + 0.5414	0.9998	y- ITS_{dry} x-Cement Content
28 days	y = 0.2332x + 0.0976	0.9488	
oven	y = 0.1464x + 0.4453	0.9620	y- ITS_{wet} x-Cement Content
28 days	y = 0.2708x + 0.0078	0.9892	

Figure 8 ITS of oven curing and 28d curing specimens with different cement content

4.2 Rut Resistance Tests

Figure 9 shows the rut-resistance test results for CR-Foam 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.

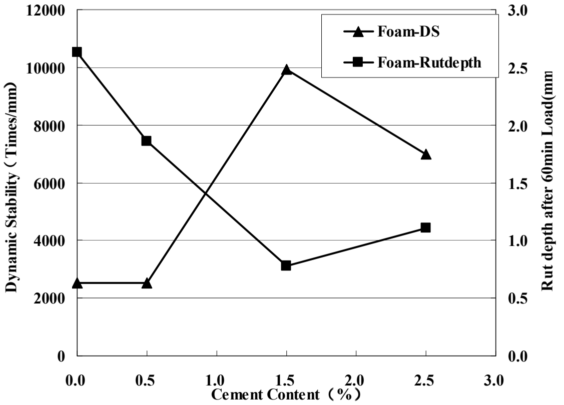


Figure 9 Relationship between DS and cement content

The DS values of all specimens with cement were even higher than China's specifications for HMA used in hot areas (MOT, 2004), implying that the CR-Foam 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-Foam mixtures, and the optimal cement content is around 1.5%.

4.3 Low temperature bending beam tests

Figure 10 shows low temperature (-10℃) bending beam test results for CR-Foam mixtures with varying cement content. The bending strain at failure (ε_B) decreased as the cement content increased from 0.0% to 0.5%; afterwards, adding more cement did not result in further significant change ofε_B. The bending strength at failure (R_B) reached its peak value at 1.5% cement content, too much and too lower cement content leaded to lower R_B. From these low temperature (-10℃) bending beam test results, it can be seen that the optimal cement content is around 1.5%.

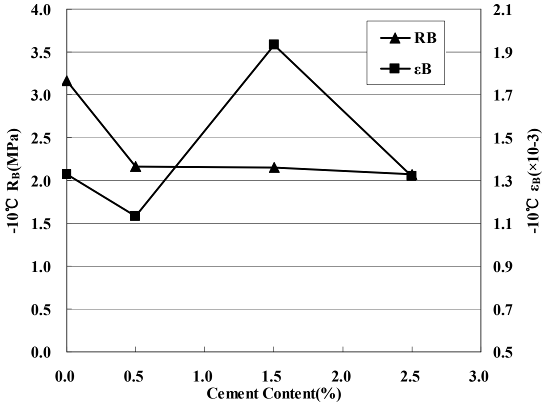


Figure 10 Bending Beam Test Results of Mixtures with Different Cement Content

5. 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-Foam mixtures to improve properties; thus, the curing methods that use an accelerated process did not reflect the real conditions of CR-Foam mixtures.
(4) Adding cement enhances the rut resistant properties of CR-Foam 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.
(5) 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-Foam mixtures have excellent high temperature performance.
(6) The bending strength at failure (R_B) reached its peak value at around 1.5% cement content.
Therefore, Portland cement is absolutely necessary in CR-Foam 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-Foam mixture is around 1.5%.

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KEY WORDS

Foamed asphalt; Cold recycling; Indirect tensile strength; Pavement; Portland cement.