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Evaluating Effective Asphalt Content in CIR Mixtures

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Braun Intertec Corporation

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In this study, to evaluate the effect of emulsion reduction during the CIR process in the field, three laboratory CIR mix designs were performed using the same RAP material and emulsion at three different mixing temperatures. The mix design results showed that as the mixing temperature increased, the optimum emulsion content decreased significantly. Also, increasing the mixing temperature improved the mixture compaction. Both the dry and retained stabilities were also higher for the high-temperature mixtures. The critical low temperatures of high-temperature mixtures were higher than the room-temperature mixture (indicative of a worse performance) but still lower than -20°C. From the results of this study, it appears that reducing the emulsion content of the CIR mixtures during the heat of the day, does not necessarily deteriorate the mixture properties. This could result in substantial savings for agencies that use this process without sacrificing long-term performance.

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FINAL REPORT

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EXECUTIVE SUMMARY

Compared to standard practices, cold in-place recycling (CIR) has become a desired rehabilitation alternative based on cost as well as the environmental and performance advantages. For this process, a mix design is performed before production to predetermine the optimal amount of engineered emulsion to use in the remixing component of the process. Several agencies have reported that they have to reduce the predetermined optimum emulsion content from the laboratory mix design during hot weather to assure constructability.

In this study, to evaluate the effect of emulsion reduction during the CIR process in the field, three laboratory CIR mix designs were performed using the same reclaimed asphalt pavement (RAP) material and emulsion at three different mixing temperatures (room temperature, 43°C, and 52°C). The optimum emulsion contents were then determined.

The mix design results showed that as the mixing temperature increased, the optimum emulsion content decreased significantly. This might have been due to the RAP binder becoming more activated at elevated temperatures. Also, increasing the mixing temperature improved the mixture compaction (higher densities and lower air voids). Both the dry and retained stabilities were also higher for the high-temperature mixtures. The critical low temperatures of high-temperature mixtures were higher than the room-temperature mixture (indicative of a worse performance) but still lower than -20°C.

Semicircular bending fracture index value for energy (SCB FIVE) performance-based laboratory testing was also conducted on the study mixtures to capture the fracture energy of the materials. The results showed that the fracture energies of the high-temperature mixtures seem to be slightly lower than the room-temperature mixture, but the statistical analysis showed that all of the study mixtures have statistically similar low-temperature performances.

From the results of this study, it appears that reducing the emulsion content of the CIR mixtures during the heat of the day, does not necessarily deteriorate the mixture properties. This could result in substantial savings for agencies that use this process without sacrificing long-term performance.

CHAPTER 1: INTRODUCTION

Compared to standard practices, cold in-place recycling (CIR) has become a desired rehabilitation alternative based on cost as well as the environmental and performance advantages. The CIR process uses a train of equipment with either volumetric or weight control. The process also uses various stabilization materials including engineered emulsion, cement, combinations of emulsion/cement, and foamed asphalt. The most common process used in Minnesota to date has been milling the road to a depth of 3 or 4 inches, crushing the material and remixing it with an engineered emulsion, then placing and compacting the material on the roadway in a continuous process. In this process, a mix design is performed before production to predetermine the optimal amount of engineered emulsion to be used in the remixing component of the process.

Most agencies have had to reduce the predetermined optimum emulsion content, especially during hot weather, to assure constructability. One explanation for this is that during the heat of the day, the asphalt in the reclaimed asphalt pavement (RAP), and any surface treatment asphalt concrete (AC), becomes activated and more effective as a binder rather than being just an inert black rock. While this seems to be a viable explanation, research is needed to understand long-term performance characteristics when lowering emulsion content from the mix design on CIR projects. Lowering the emulsion content below the optimum mix design percentage has not shown a reduction in short-term performance as it relates to surface raveling or cohesivity.

If it is determined that activation of RAP AC is occurring during the heat of the day, thus allowing a lower emulsion content without sacrificing long-term performance, then there could be substantial savings for agencies that use this process without sacrificing long-term performance.

The intent of this research is to look at long-term performance properties of the CIR material during hot conditions by performing standard CIR laboratory mix designs at elevated temperatures while using performance-based laboratory tests to capture fracture energy of the materials.

CHAPTER 2: CIR MIX DESIGNS

2.1 MATERIALS

The recycling asphalt pavement (RAP) millings used in this study had been collected from a 2017 Brown County CIR project on CSAH 8 by Minnesota Department of Transportation (MnDOT) Office of Materials. Approximately, 850 lbs. of millings were collected from that project. The materials were shipped to Braun Intertec Corporation (Braun Intertec) and American Engineering Testing (AET) laboratories for performing the mix designs. The millings were crushed and proportioned to a CIR "medium" gradation. Table 2.1 shows the gradation used in this study. Figure 2.1 also shows the CIR gradation along with the medium gradation control points. The extracted asphalt content of the RAP was 4.4%.

Table 2.1 CIR gradation used in the study

Sieve Size (US/mm)	% Passing	Control Points (Medium)
1 1/2" (37.5 mm)	100	
1" (25.4 mm)	100	100
3/4" (19 mm)	93	85-96
1/2" (12.5 mm)	70	
3/8" (9.5 mm)	60	
#4 (4.75 mm)	45	40-55
#8 (2.36 mm)	35	
#30 (0.6 mm)	12	4-14
#200 (0.075 mm)	0.6	0.6-3

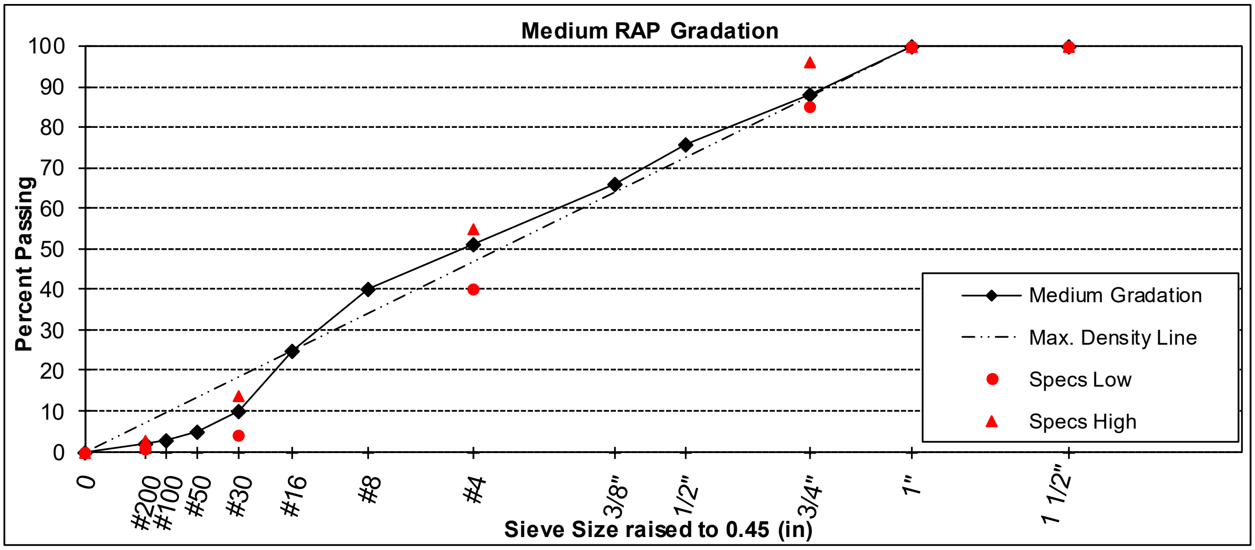

Figure 2.1 CIR gradation used in this study.

The engineered emulsion used in the testing was provided by Flint Hills Resources (FHR) and graded as PG XX-28.

A total of three CIR mix designs were performed in this study using the same materials (RAP and engineered emulsion) and gradation in accordance with the MnDOT Grading and Base Manual [1]. The only variable among these designs was the mixing temperature. The mixing temperatures that were used in this study are as follows:

1) RT: Room temperature (performed by AET)
2) HT1: 43°C (~110°F) (performed by Braun Intertec)
3) HT2: 52°C °F (~125°F) (performed by Braun Intertec)

Testing was performed according to MnDOT's specification for CIR Mix Design in 2018 Grading & Base Manual.

2.2 MIX DESIGN RESULTS

Table 2.2 presents the mix design results, including the dry and retained stabilities, percent air voids, percent raveling, and critical low temperatures for all the mix designs. The optimum emulsion contents are as follows:

1) RT: 3.0%
2) HT1: 1.75%
3) HT2: 1.5%

As it can be seen, there is a significant reduction in the optimum emulsion content at the elevated temperatures.

Table 2.2 CIR mix designs summary

Temperature	**RT (Room Temp.)**			**HT1 (43°C)**			**HT2 (52°C)**			**CIR Spec.**
Emulsion (%)	2.5	3.0*	3.5	1.75*	2.25	2.75	1.5*	2	2.5	--
Bulk Specific Gravity (G_{mb})	2.021	2.031	2.041	2.099	2.111	2.146	2.088	2.087	2.104	--
Density (lbs/ft^3)	126.2	127	127.4	131.0	131.7	133.9	130.3	130.2	131.3	--
Maximum Specific Gravity (G_{mm})	2.381	2.364	2.348	2.389	2.381	2.373	2.381	2.374	2.366	--
Dry Stability (lbs.)	1240	1286	1123	1970	2000	2055	2080	2155	2100	**1250 (min.)**
Vacuum Saturation Level (%)	55	56	56	65	64	60	67	64	59	**55-75**
Retained Stability (lbs.)	865	924	796	1620	1745	1870	1955	2150	1840	--
Retained Stability (%)	70	72	71	82	87	91	94	100	88	**70% (min.)**
Voids (%)	15.1	14	13.1	12.2	11.4	9.9	12.3	12.1	11.3	--
Raveling (%)	--	1	--	1.5	--	--	1.8	--	--	**2% (max.)**
Critical Low Temperature (°C)	--	-30	--	-26	--	--	-20	--	--	**Report**

*optimum emulsion content

Figure 2.2 compares the density of all the study mixtures on the same graph. As this graph shows, HT1 and HT2 have higher densities compared to RT. Figure 2.3 and Figure 2.4 present the dry stabilities and percent of retained stabilities, respectively. As these graphs suggest, RT meets the minimum requirement of both the dry stability (1,250 lbs.) and retained stability (70%) at 3% only, while HT1 and HT2 have significantly higher dry stabilities (in the range 1,950 to 2,150 lbs.) as well as percent retained stabilities (in the range of 80 to 100%).

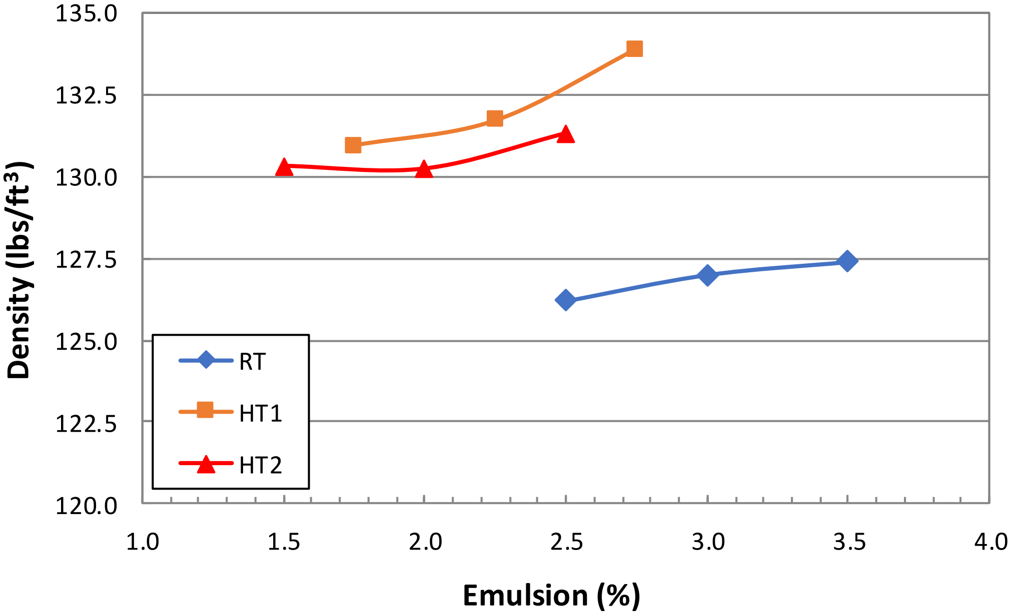

Figure 2.2 Mixture densities.

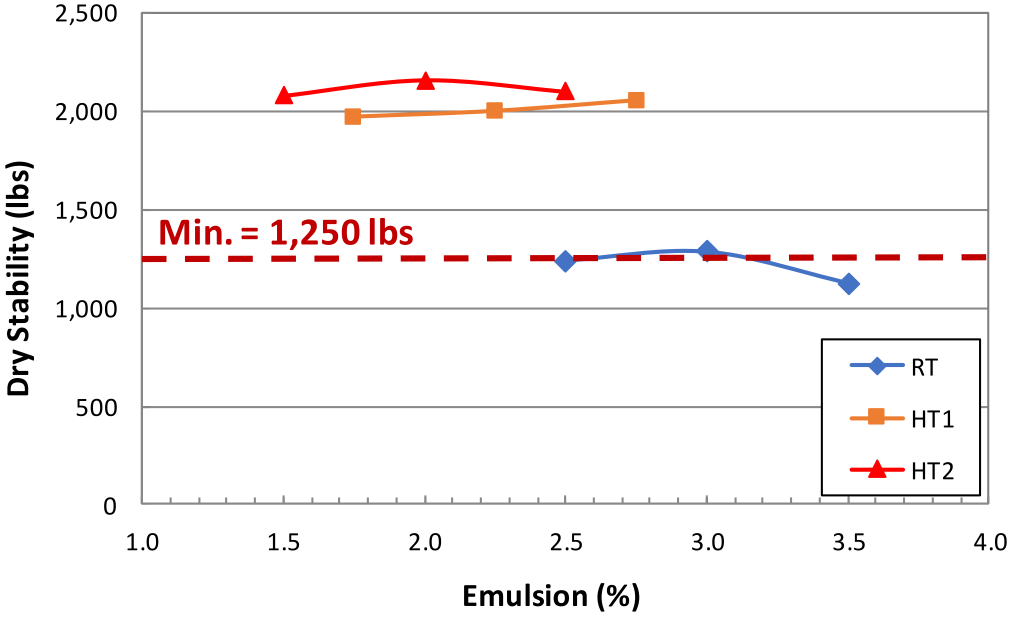

Figure 2.3 Mixture dry stabilities.

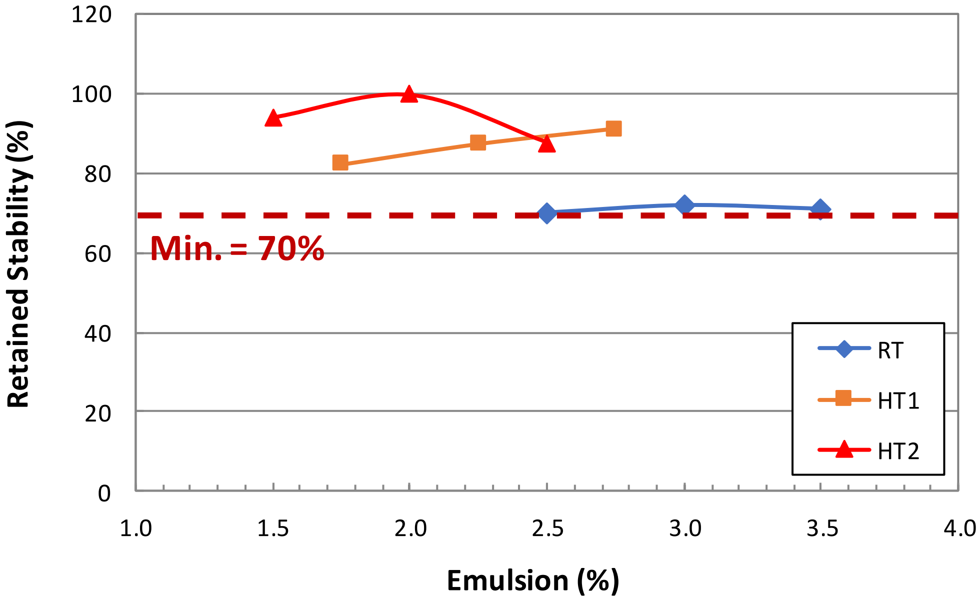

Figure 2.4 Mixture retained stabilities.

Figure 2.5 shows the percent air voids. As it can be seen, the air void of RT mixture at different emulsion contents is in the range of 13 to 15 percent, while it is lower for both the HT1 and HT2 mixtures and changes between 10 to 12 percent.

In Figure 2.2 through Figure 2.5, HT1 and HT2 test results are fairly close; HT1 mixtures have resulted in higher densities and lower air voids, while HT2 mixtures have outperformed HT1 mixtures in regard to both the dry and percent retained stabilities.

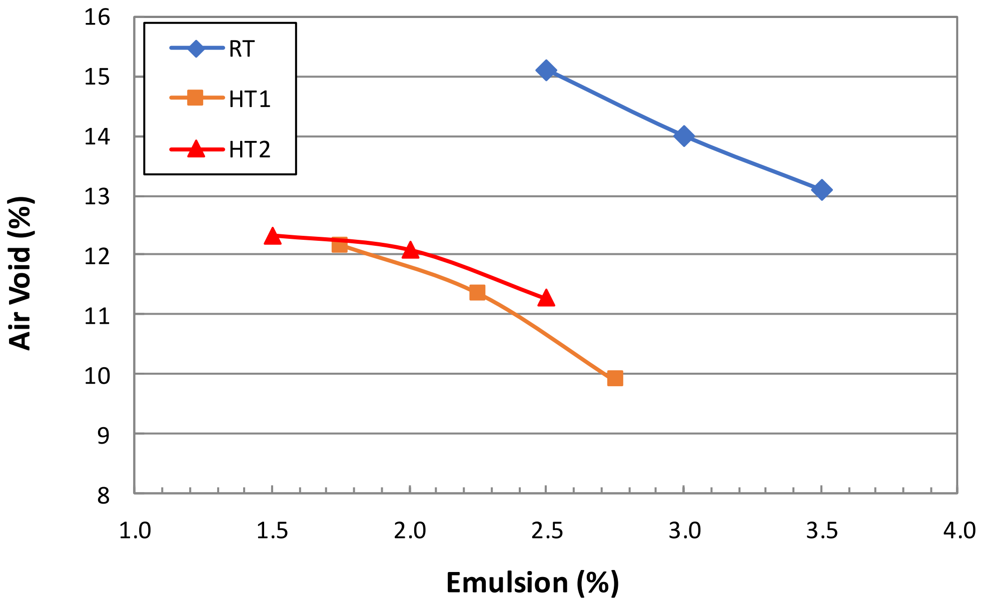

Figure 2.5 Mixture air voids.

In order to confirm that the difference that is seen between RT and HT mixtures is not partly due to lab-to-lab variabilities, a one-point check of the RT mixture was performed at Braun Intertec at the optimum emulsion content from the primary mix design (3%) which Table 2.3 shows the results. As this table suggests, the results are surprisingly close with percent differences in the range of 0 to 3 percent. This suggests that the CIR testing is repeatable quite well and the differences that are seen between RT and HT mixtures are mainly due to the difference in the mixing temperatures.

Table 2.3 One-point check on RT mixture at Braun Intertec.

Property	**AET (RT at 3%)**	**Braun Intertec (RT at 3%)**	**Difference (%)**
Density (lbs/ft^3)	127	125.7	1
Dry Stability (lbs.)	1286	1320	3
Retained Stability (lbs.)	924	945	2
Retained Stability (%)	72	72	0
Voids (%)	14.0	13.9	1

Figure 2.6 shows the percent raveling for the mixtures at their optimum emulsion contents. As this graph shows, percent raveling increases as the mixing temperature increases (and the emulsion content decreases), but percent raveling is still less than the maximum allowable of 2% for all the mixtures. In general, raveling results become more important when the time between placement of the CIR and the overlay increases. If the time between CIR and overlay extends beyond a week, fogseal can be used to reduced raveling due to traffic.

The critical cracking temperature indicates the threshold below which thermal cracking is expected to occur. The critical cracking temperature is defined as the intersection of the calculated pavement thermal stress curve (derived from the low temperature creep data) and the tensile strength line (the line connecting the results of the IDT strength test).

Figure 2.7 presents the critical cracking temperatures of the mixtures at their optimum emulsion contents. As it can be seen, increasing the mixing temperature has increased the critical cracking temperature which is an indication of a poorer low temperature performance. In other words, by increasing the mixing temperature (and reducing the emulsion content), thermal cracking is expected to occur at a higher temperature.

Currently, MnDOT's specification for CIR Mix Design does not specify a maximum for the critical cracking temperature for the CIR mixtures, mainly because there is no widely accepted maximum for this parameter. Also, there are several assumptions involved in low temperature creep data analysis which may affect the results.

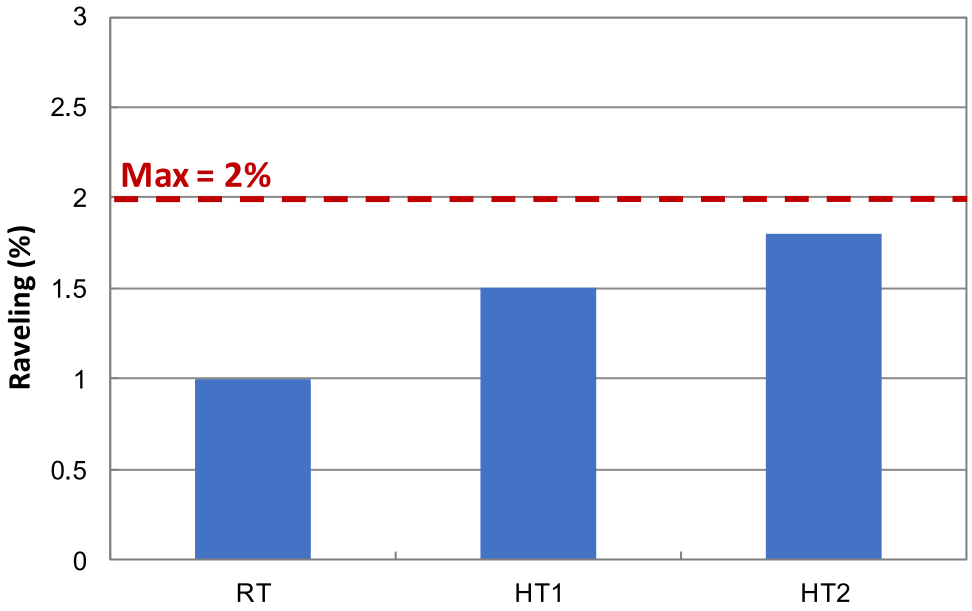

Figure 2.6 Mixture raveling percentages at their optimum emulsion contents.

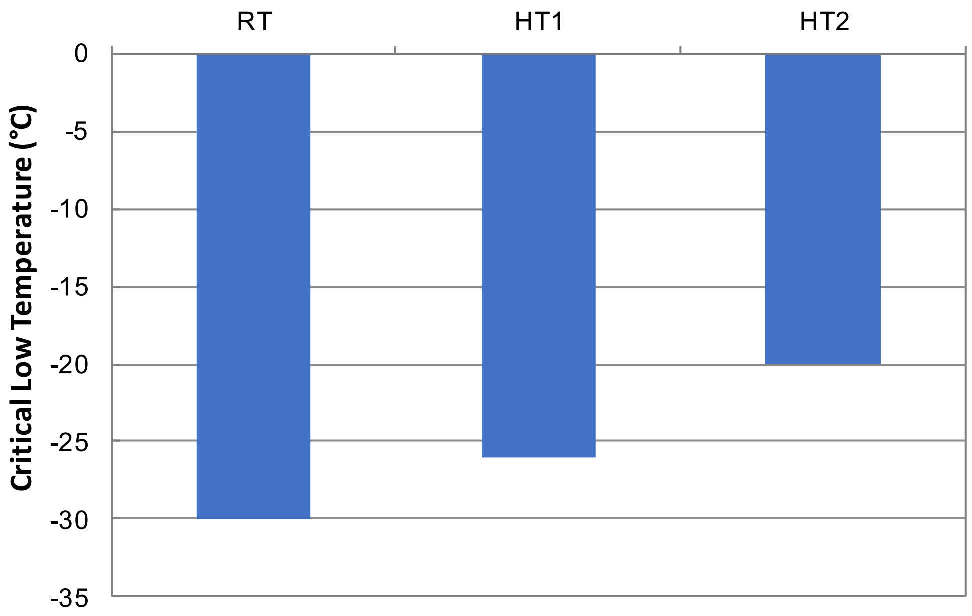

Figure 2.7 Mixture critical low temperatures at their optimum emulsion contents.

Figure 2.8 shows the IDT strength for the mixtures at their optimum emulsion contents. As this graph suggests, HT mixtures have higher strengths at all the testing temperatures of -20°, -30°, and -40°C. Also, HT1 has resulted in relatively higher strengths compared to HT2.

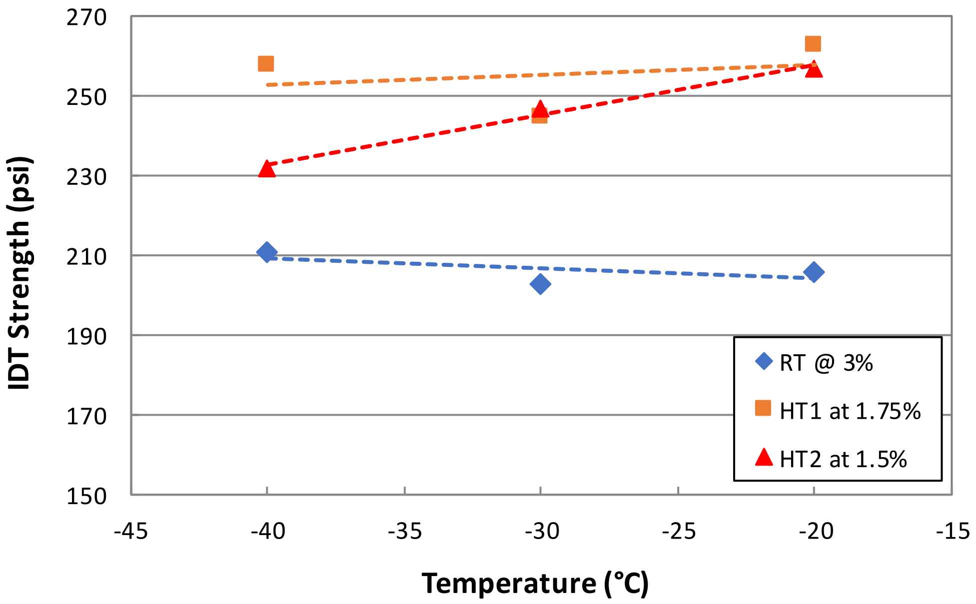

Figure 2.8 Mixture IDT strengths at their optimum emulsion contents.

2.3 CONCLUSIONS

A summary of the findings and the conclusions that can be drawn from this phase of the study are as follows:

- It appears that increasing the mixing temperature activates the RAP binder and therefore, reduces the optimum emulsion content.
- Increasing the mixing temperature to HT1=43°C and HT2=52°C significantly reduced the optimum emulsion content which could result in substantial savings for Agencies utilizing this process. The optimum emulsion content for HT2 (1.5%) was half of the optimum emulsion content of the RT mixture (3%).
- It appears that increasing the mixing temperature has resulted in better compaction of the mixtures; under the same compaction effort, HT mixtures resulted in higher densities and lower air void contents, higher dry stabilities, and higher percent retained stabilities.
- HT mixtures showed higher percent raveling compared to the RT mixture, but were still below the maximum allowable of 2%.
- Critical low temperatures of HT mixtures were higher than RT mixture (indicative of a worse performance), but still were lower than -20°C. There is no widely accepted maximum for this parameter for CIR mixtures.
- The low temperature strengths of HT mixtures were higher than the RT mixture.

CHAPTER 3: PERFORMANCE TESTING

The previously developed performance-based laboratory test, Fracture Index Value for Energy (FIVE), was conducted on the study mixtures to capture fracture energy of the materials at low temperatures. FIVE test is shown to be a practical, easy-to-perform test, which is able to compare CIR material low temperature characteristics [2].

The FIVE test is carried out on Semi-Circular Bending (SCB) samples under Control Mouth Opening Displacement (CMOD) mode. Figure 3.1 shows the SCB sample in the horizontal setup.

Figure 3.1 SCB setup for FIVE testing.

Figure 3.2 shows a typical load versus CMOD curve during the test. As this graph illustrates, the load shows a sudden jump at the beginning of the test. It then gradually decreases to reach a pre-determined load level. The FIVE value is calculated by dividing the total energy (the area under load vs. CMOD curve) by the ligament area of the SCB specimen prior to testing.

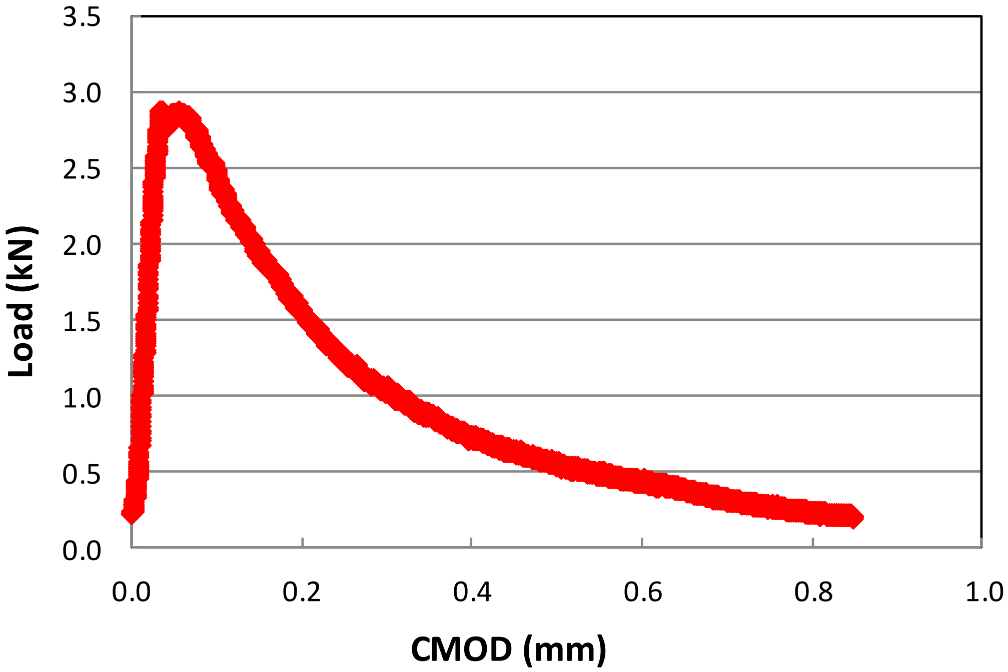

Figure 3.2 Load vs. CMOD during SCB FIVE test.

3.1 TESTING PARAMETERS

SCB FIVE test parameters and testing conditions are summarized in Table 3.1. The testing temperature was defined as 10 degree Celsius above the low PG of the base binder. As the study mixture binders had a low PG of -28, a testing temperature of -18°C was selected.

Table 3.1 SCB FIVE testing parameters

Parameters		**Target**	**Measurement Tolerance**
Sample Geometry	Diameter (mm)	150±2.5	±0.5
	Thickness (mm)	50 to 60	±0.5
	Notch length (mm)	15±1	±0.5
Testing Condition	CMOD rate, mm/sec	0.005	±0.0001
	Temperature, °C	-18	±0.5

3.2 SAMPLE PREPARATION

The millings were crushed and proportioned to the CIR gradation shown in Table 2.1. For consistency, all the testing samples were produced according to the procedure below:

1) Batch samples following the CIR gradation to a quantity of 4,300 grams each, adjust quantity, if needed, to obtain specimen heights of 115±5 mm (a height in the range of 110 to 120 mm is acceptable)
2) Once the proper quantity was found, keep the weight constant during the bulk specimen production in order to minimize sample to sample variation.
3) After the preliminary mixing, add emulsion and further mix for 60 seconds using a mechanical mixer.
4) Immediately dump the sample in an unheated gyratory mold (dump the sample quickly into the mold, rather than pour, to reduce segregation).
5) Compact the specimen at room temperature using the gyratory compactor for 30 gyrations in 150 mm diameter mold, at 600 kPa pressure and 1.16 degree internal angle.
6) Remove the compacted specimens from the mold.
7) Cure the samples at 60°C for 48±1 hours.
8) Allow the specimens to cool down overnight before any further processing is taken.
9) Cut the samples at mid height to get two pucks.
10) Cut each puck in half in order to obtain two semicircular samples.

Following this procedure, each gyratory compacted specimen results in four SCB samples as shown in Figure 3.3.

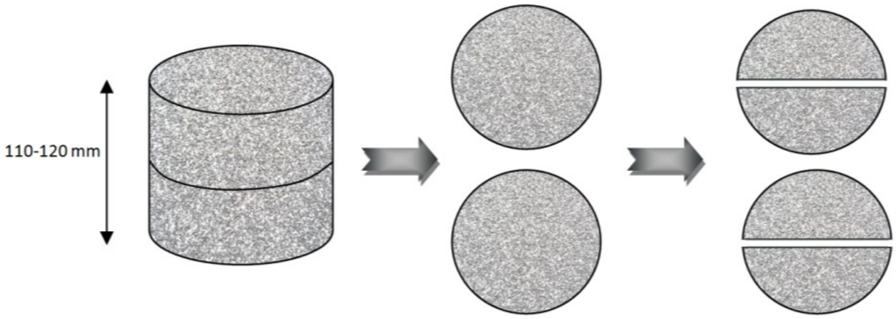

Figure 3.3 SCB sample preparation.

3.3 TEST RESULTS

Eight SCB FIVE tests were carried out on each of the study mixtures for a total of 24 tests. Table 3.2 through Table 3.4 show the testing results for RT, HT1, and HT2 mixtures, respectively.

To reduce the variations in the test results that are commonly seen in any kind of fracture testing, reduced sets of data are developed by eliminating the maximum and minimum FIVE values from the original sets. As Table 3.2 through Table 3.4 suggest, the average FIVE values of the reduced sets are very close to the average FIVE values of the original sets (with less than 3% difference) while the variability of the reduced sets have been reduced significantly, especially in the case of RT mixture.

Table 3.2 SCB FIVE Testing Results for RT mixture.

Mixture	**Specimen ID**	**FIVE (J/m^2)**
RT **(Room Temperature)**	RT1	273
	RT2	368
	RT3	277
	RT4	244
	RT5	303
	RT6	302
	RT7	180
	RT8	185
	Average FIVE (J/m^2)	**279**
	Standard Deviation	**50**
	Reduced Set Statistics	
	Average FIVE (J/m^2)	**281**
	Standard Deviation	**20**

Table 3.3 SCB FIVE Testing Results for HT1 mixture.

Mixture	**Specimen ID**	**FIVE (J/m²)**
HT1 **(43°C)**	HT11	241
	HT12	326
	HT13	267
	HT14	252
	HT15	268
	HT16	269
	HT17	300
	HT18	236
	Average FIVE (J/m²)	**270**
	Standard Deviation	**28**
	Reduced Set Statistics	
	Average FIVE (J/m²)	**266**
	Standard Deviation	**18**

Table 3.4 SCB FIVE Testing Results for HT2 mixture.

Mixture	**Specimen ID**	**FIVE (J/m^2)**
HT2 **(52°C)**	HT21	301
	HT22	289
	HT23	221
	HT24	244
	HT25	283
	HT26	219
	HT27	281
	HT28	371
	Average FIVE (J/m^2)	276
	Standard Deviation	46
	Reduced Set Statistics	
	Average FIVE (J/m^2)	269
	Standard Deviation	29

Figure 3.4 shows a comparison of the SCB FIVE testing results for all the tested mixtures. The error bars show standard deviations (SD). As this graph suggests, all the mixes have resulted in about the same average FIVE value. The FIVE value seems to be slightly lower for HT mixes compared with the RT mixture.

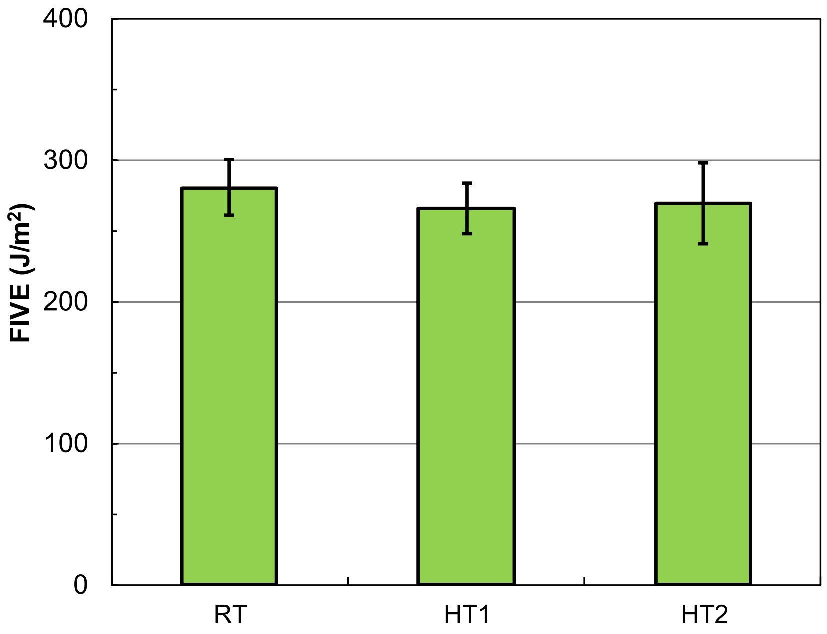

Figure 3.4 SCB FIVE testing results.

In order to determine whether there are any statistically significant differences between the average FIVE values of RT, HT1, and HT2 mixtures, one-way analysis of variance (ANOVA) test was conducted on the SCB FIVE test results. A one-way ANOVA is used to test the null hypothesis that the means of several populations are all equal. Usually, a significance level (alpha) of 0.05 is selected. If F is greater than $F_{critical}$, the null hypothesis is rejected, meaning that the populations are not all equal and at least one of the means is different. Table 3.5 shows the ANOVA test results. As this table shows, F (=0.74) is smaller than $F_{critical}$ (=3.68) and therefore, there is not enough evidence to reject the null hypothesis that the population means are all equal.

Table 3.5 One-way ANOVA test results.

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**$F_{critical}$**
Between Groups	948.638	2	474.319	0.73842	0.49446	3.68232
Within Groups	9635.17	15	642.344			
Total	10583.8	17				

From the ANOVE test results, it can be concluded that RT, HT1, and HT2 have statistically similar low temperature performances despite their different optimum emulsion contents. In other words, the result suggests that at high temperatures, the emulsion content can be lowered, to assure constructability, without jeopardizing the low temperature performance of the CIR mixture.

CHAPTER 4: SUMMARY AND CONCLUSIONS

Several agencies have reported that they have to reduce the predetermined optimum emulsion content from the primary mix design during hot weather to assure constructability. In this study, three CIR mix designs were performed using the same RAP material and emulsion at three different mixing temperatures (room temperature, 43°C, and 52°F). The optimum emulsion contents were then determined. Also, the low-temperature performance of the mixtures was evaluated using the previously developed SCB FIVE testing. A summary of the findings follows:

- The optimum emulsion content decreases as the mixing temperature increases. This may suggest that RAP binder becomes activated at elevated temperatures.
- Increasing the mixing temperature can reduce the optimum emulsion content significantly. This could result in substantial savings for agencies using this process. The optimum emulsion content for HT2 (1.5%) was half of the optimum emulsion content of the RT mixture (3%).
- It appears that increasing the mixing temperature led to better compaction of the mixtures; under the same compaction effort, HT mixtures had higher densities and lower air void contents, higher dry stabilities, and higher percent retained stabilities.
- HT mixtures had higher percent raveling compared to the RT mixture but were still below the maximum allowable of 2%.
- Critical low temperatures of HT mixtures were higher than RT mixture (indicative of a worse performance) but still lower than -20°C. There is no widely accepted threshold for this parameter for CIR mixtures.
- The low-temperature strengths of HT mixtures were higher than the RT mixture.
- SCB FIVE testing results showed that fracture energy of the HT mixtures seemed to be slightly lower than the RT mixture, but statistical analysis showed that the study mixtures have statistically similar low-temperature performances despite their different optimum emulsion contents.
- The results of this study suggested that reducing the emulsion content of the CIR mixtures during the heat of the day does not necessarily deteriorate the mixture properties.

Recommendations for future work follow:

- A similar study may be needed on CIR mixtures with softer emulsion base binders (e.g., PG XX-34), as they are expected to be more prone to high-temperature conditions.
- The effect of a mineral stabilizing agent (e.g., cement) on high-temperature performance needs to be evaluated.
- The effect of a chip seal needs to be assessed. Roadways with chip seal surfacing may have more binder content to become active, so further study is required to properly differentiate roadways with and without chip seal before a standard procedure can be developed for addressing binder reduction for higher-temperature pavements.
- More research is required to develop a standard field protocol for emulsion content reductions from the mix design based on pavement temperature and effective binder content assessment.

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