emulsion having four cement contents.

MATERIALS

Triplicate test specimens were produced in the laboratory and were prepared using a blend of 85% RAP and 15% #10 screenings that was produced concurrently as a CCPR material for a construction project in Virginia (VDOT, 2018). The gradation for the CCPR material is shown in Figure 1. The CCPR blend was combined with two types of asphalt emulsion, a high float (HF) and a cationic slow set (SS). Specimen sets having four different cement contents were prepared for each emulsion type. The percentage of emulsion for all mixtures was 2.5% and the four cement contents were 0%, 0.5%, 1.0%, and 3.0%. A cement content of 1.0% is a typical value observed by the authors from previous studies. The values of 0.5% and 3.0% were included to observe the performance of a cement content lower than and much higher than typically used, respectively.

TEST METHODS

Six different methods were used to quantify the performance laboratory prepared CR specimens tested using the indirect tensile geometry. These methods included: indirect tensile strength (ITS); Marshall Stability; CT Index, Cracking Resistance Index (CRI), and Fracture Strain Tolerance (FST) using the IDEAL-CT test procedure; and the N_{flex} factor. The ITS and Stability tests are common mixture design tests for CR materials and were used to compare properties of these mixtures with previous work. The CT Index has been used previously to assess the cracking potential of CR mixtures while the CRI, FST, and N_{flex} factor analysis procedures are more typically used for assessing the cracking potential of asphalt mixtures. The IDEAL-CT and N_{flex} tests were selected because they require minimal specimen preparation which is important as CR mixtures tend to ravel with significant handling when unconfined.

All test specimens were fabricated using a gyratory compactor with a 6-inch diameter mold; the compaction level was set at 30 gyrations. Since each test type required a different thickness specimen, the mass of material was adjusted to produce the desired specimen thickness while keeping the number of gyrations constant. The ITS, Stability, and IDEAL-CT test specimens were all produced to the desired thickness (75mm minimum, 95.2±5mm, and 62±2mm, respectively) without trimming the ends of the test specimens. The N_{flex} test specimens were fabricated to a thickness of 115mm and then trimmed using a wet saw to 50±5mm; two test specimens were obtained from each gyratory-prepared sample. Each test specimen was cured in a forced draft oven at 60°C for 72 hours.

The ITS of the specimens prepared in this study was determined in accordance with ASTM D6931, *Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures*. After curing, the ITS specimens were conditioned for two hours at 25°C before testing. The specimens were loaded at a deformation rate of 50 mm/min. The peak load from the load vs. vertical displacement curve of each specimen was recorded (an example is shown in Figure 2), and the ITS was calculated as follows:

$$S = \frac{2000 \times P}{\pi \times t \times D}$$

where:

S = indirect tensile strength, kPa; P = maximum (peak) load, N; t = specimen thickness, mm; and D = specimen diameter, mm.

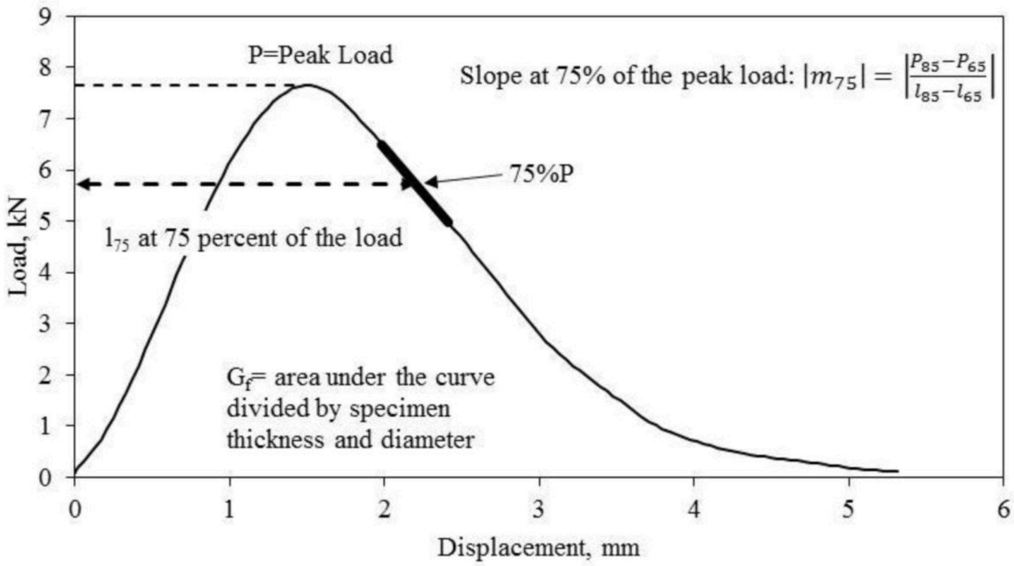

Figure 2. Example load versus displacement curve from the indirect tensile test and analysis parameters

Marshall Stability tests were conducted in accordance with ASTM D5581, *Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus (6 inch-Diameter Specimen)*. Following curing, test specimens were conditioned at 40°C for three hours. Immediately after installing the test specimen in between the upper and lower segments of the breaking head, the constant loading rate of 50 mm/min was applied on each specimen. The stability and flow values of the specimens were determined from the maximum load and the vertical displacement at the maximum load, respectively.

The IDEAL-CT test (Zhou et al., 2017) utilizes the same loading configuration and rate as the ITS test as described above to calculate a CT Index. Additionally, the IDEAL-CT test requires an application of a contact load of 0.1 kN on a test specimen before the test starts at the defined loading rate. Following curing, test specimens were conditioned at 25°C for 2 hours. Once the load versus vertical displacement curve (Figure 2) of each specimen was obtained, then the cracking test index (CT Index) was calculated as follows:

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D}$$

where,

G_f = the fracture energy (kN/mm) which is determined from the ratio of the area under the load vs. displacement curve divided by the product of the thickness (t) and diameter (D); l_{75} = the post-peak displacement rate at 75% of the peak load (mm); m_{75} = the slope of the post peak curve at 75% of the peak load (kN/mm).

The CRI parameter, originally developed for evaluating the cracking potential of asphalt mixtures using the semi-circular bending test (Kaseer et al., 2018), was adopted for use in this study with the IDEAL-CT test procedure. The CRI parameter is calculated by dividing the fracture energy (kN/mm) by the peak load (kN) as follows:

$$CRI = \frac{G_f}{P}$$

The fracture strain tolerance (FST) parameter is another cracking parameter calculated from the load versus displacement curve obtained from the disk-shaped compact tension test, and is used for evaluating the low-temperature cracking potential of asphalt mixtures (Zhu et al., 2017). Similar to the CRI, the FST parameter was included in this study using the IDEAL-CT test procedure to evaluate the cracking potential of the CR mixtures. The FST parameter is defined as the ratio between the fracture energy (kN/mm) and the IDT strength (kPa) as follows:

$$FST = \frac{G_f}{S}$$

The N_{flex} factor (West et al., 2017) is a recently introduced asphalt mixture cracking resistance index calculated from the ITS test data. The N_{flex} test is considered to be more suitable to assess field performance in that the test specimen is compacted to a field density rather than a specified void content. For this study, the N_{flex} test specimens were compacted to 30 gyrations as were all the other test specimens. In this procedure, the load versus vertical displacement curve from the ITS data is first converted into the stress versus estimated-strain curve. The stress levels corresponding to several vertical-displacement points were calculated from the ITS strength equation given above. The corresponding strain level was estimated by multiplying the vertical displacement by an assumed Poisson's ratio of 0.35 and dividing by the specimen diameter. Once the stress versus estimated-strain curve was established, the N_{flex} factor was calculated by dividing the toughness (area under the stress versus estimated-strain curve--kPa) by the post-peak slope of the estimated-strain rate at the first inflection point (m_s--kPa) as follows:

$$N_{flex} = \frac{T_{inf}}{|m_s|}$$

Table 1. Strength properties of CCPR materials

	Cement content, %	Average indirect tensile strength, kPa	Average stability, kN
Slow Set	0	450.5	26.0
	0.5	358.4	24.9
	1	474.8	33.6
	3	706.2	44.6
High Float	0	411.5	23.4
	0.5	329.6	23.7
	1	385.4	29.2
	3	560.1	39.3

Following curing, N_{flex} test specimens were conditioned for 2 hours at 25°C and tested in accordance with 2017 AASHTO draft specification *Standard Method of Test for Determining the Indirect Tensile N_{flex} Factor to Assess the Cracking Resistance of Asphalt Mixtures*.

RESULTS AND DISCUSSION

Table 1 shows the results of strength tests that document the acceptable strength properties of the materials produced in the laboratory. Virginia Department of Transportation specifications require a minimum ITS and Stability of 310 kPa and 11.1 kN, respectively (VDOT, 2015). As expected, adding cement generally increased the strength and stability of the CCPR materials. It is not clear why the strength for both emulsion types and the stability for the slow setting emulsion decreased when 0.5% cement was added. Retained strength and stability tests using saturated test specimens were not conducted.

When considering the values shown in Table 1 alone, the addition of more cement appears to result in a positive performance gain. However, ARRA (2014) recommends a maximum of 1% cement for CR mixtures when an active filler is included citing the possibility of brittle behavior when excessive cement is added. Despite this warning, no test results are provided as supporting evidence. From the results of Table 1, it is clear that additional analysis methods are needed during CR mixture design to quantify the potential for undesirable brittle behavior.

To demonstrate the potential for change in the load versus displacement behavior of CR mixtures having different cement contents, ITS test data was plotted replacing the measured load by a normalized load. The normalized load at each displacement interval was calculated by dividing the measured load by the peak load for that specimen, thus the maximum load value for each mixture is normalized to 1.0. Figure 3 shows an example of the normalized load versus displacement for test specimens using high float emulsion at 0%, 0.5%, 1.0%, and 3.0% cement.

As shown in the Figure 3, increasing cement contents tend to collapse the load versus displacement curve. This reduces the area under the curve (toughness) and increases the post peak slope. The toughness for the example shown was reduced by approximately 16%, 24%, and 43% while the post peak slope (calculated at approximately 75% of peak load) increased by approximately 14%, 55%, and 123% by including 0.5%, 1.0%, and 3.0% cement, respectively. The example shown in Figure 3 illustrates the potential for material behavior change that is undocumented in current CR mixture design procedures.

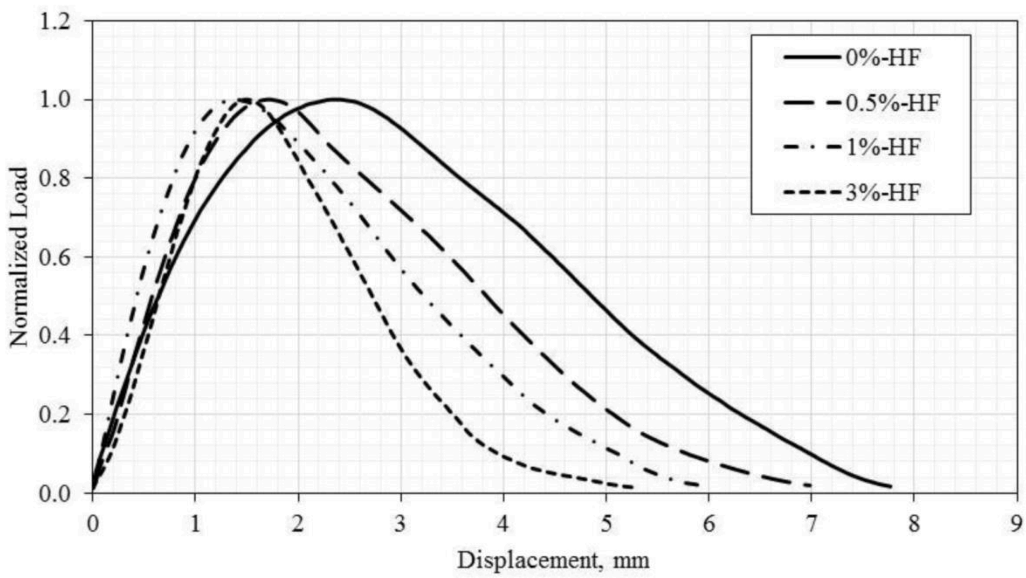

Figure 3. Normalized load versus displacement behavior at different cement contents

The results of the different cracking tests and analysis methods are shown in Table 2. For all tests, a higher value indicates greater resistance to cracking. As expected, the increase in cement content reduced the CCPR materials ability to resist cracking. It is interesting to note that even with a very small amount of cement (0.5%) that the test results show a large change in cracking resistance. What is not shown is if the change in laboratory cracking resistance translates to a detrimental change in field performance.

A Tukey's multiple comparison test with a 95% confidence interval was conducted to assess the ability of the cracking tests and analysis methods to discern differences resulting from the change in cement content. The results of this analysis are shown in Table 3; mixtures that do not share a letter have a statistically significant difference in their mean value. All of the cracking indices were able to statistically discriminate the performance of the CCPR with no cement from those CCPR mixtures including cement, regardless of the emulsion type used. However, with increases in cement content, all four cracking tests and analysis methods failed to distinguish between 0.5% and 3.0% for the slow setting emulsion. The CT-Index and the FST parameter were able to distinguish between 0.5% and 3.0% for the high float emulsion while the N_{flex} factor and the CRI parameter did not.

Table 2. Cracking test and analysis methods results

	Cement content, %	Average CT index	Average Nflex factor	Average Cracking Resistance Index (CRI)	Average Fracture Strain Tolerance (FST)
Slow Set	0	29.8	0.8	369.6	5.4
	0.5	10.3	0.4	248.0	4.1
	1	9.6	0.4	238.7	3.6
	3	6.2	0.2	209.1	3.0
High Float	0	58.5	1.1	473.6	6.9
	0.5	25.8	0.6	337.2	4.9
	1	16.3	0.4	305.5	4.4
	3	9.4	0.4	249.4	3.6

The ability to distinguish between emulsion type used was also mixed. The CT index, FST, and CRI parameters were sensitive to the emulsion type when the mixtures did not incorporate cement while the N_{flex} factor was not. For a given cement content, the FST parameter was the most sensitive index to the emulsion type, followed by CRI, CT-Index, and N_{flex} factor.

Table 3. Tukey pairwise comparisons of the cracking indices.

	Cement content, %	Grouping			
		CT Index	N_{flex} Factor	Cracking Resistance Index (CRI)	Fracture Strain Tolerance (FST)
Slow Set	0	B	A/B	B	B
	0.5	C/D	C/D	D	D/E
	1	D	C/D	D	E
	3	D	D	D	E
High Float	0	A	A	A	A
	0.5	B/C	B/C	B/C	B/C
	1	B/C/D	C/D	C	C/D
	3	D	C/D	D	E

CONCLUSIONS

The results of this study indicate that the cracking potential of a CR mixture may be assessed in a way that is useful for quantifying influence of the constituent materials. From the results shown, the CT index provides greater discrimination than the N_{flex} factor. Differences from typical asphalt mixture specimen preparation include that the specimens were all prepared to the same number of gyrations (compaction effort). When employing the IDEAL-CT test method, the FST parameter was able to better discriminate between CR mixture changes than the CRI parameter.

The authors emphasize that while the test results shown in this study indicate that a reduction in the laboratory cracking resistance of CR mixtures was found with adding cement as an active filler, it does not indicate whether this addition is beneficial or detrimental to field performance. There are many examples in the literature of well performing CR mixtures that include the use of an active filler (typically around 1%).

While this study does not go so far as to identify the cement contents that can lead to higher cracking susceptibility of a CR mixture, these processes described herein can be used to do so. The results of this study should be furthered by similar testing on a wider variety of CR mixtures. For a more complete picture using a performance-based mixture design approach, the rutting susceptibility of CR mixtures should also be studied. In addition, it is unclear if conducting the cracking tests following moisture conditioning will result in any significant improvement in relating laboratory test results to field performance.

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Investigating Simple Brittleness and Cracking Indexes for Cold In-Place Recycling

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ABSTRACT

In recent years, cold in-place recycling (CIR) researchers have been looking more and more to dense graded asphalt (DGA) testing principles, particularly in relation to cracking. More advanced tests like the disk-shaped compact tension (DCT) require modest-to-intensive specimen sawing procedures and instrumentation, which can present challenges for more friable materials like CIR. Simpler DGA cracking tests [e.g. IDEAL cracking test, indirect tensile (IDT) N_{flex} factor] have become a recent focus, and these types of simpler tests should be investigated for CIR. If specimen preparation and testing complexities can be alleviated, simplified tests may have value for CIR. This paper's objective is to investigate simple CIR brittleness and cracking index parameters that can be obtained from non-instrumented IDT testing. Multiple CIR blends encompassing a range of cracking behaviors were tested, and results indicated cracking properties could be sufficiently characterized by energy index (EI), a simplified fracture energy term, and IDT strength.

INTRODUCTION AND BACKGROUND

Cold in-place recycling (CIR) is a flexible pavement rehabilitation technique that has been used for a number of years. A common approach for CIR research has been to adapt traditional dense graded asphalt (DGA) mix design and testing principles to suit CIR purposes. One area where CIR researchers have been increasingly looking to DGA is that of cracking characterization tests such as the semi-circular bend (SCB) or disk-shaped compact tension (DCT) tests.

For DGA, this category of more advanced cracking tests has gained considerable traction for activities such as laboratory mix design. However, these tests often require modest-to-intensive specimen sawing procedures, instrumentation, or advanced testing equipment (e.g. environmental chamber), presenting challenges in other facets of the paving process such as plant production control. For CIR, which is generally a more friable material than DGA, sawing and instrumentation may negatively impact specimen integrity, resulting in a less viable testing approach.

At the same time that more advanced cracking tests are being evaluated for CIR, some researchers are looking to simplify them for DGA. Simplified tests like the indirect tensile asphalt cracking test (IDEAL-CT) (Zhou et al. 2017) and indirect tensile (IDT) N_{flex} Factor (West et al. 2017) have been presented. By alleviating specimen preparation and testing complexities, such tests are more implementable for applications like plant production control. In a similar manner, simplified tests for CIR that provide a measure of cracking potential, even if an index, may have value, especially considering potential specimen integrity issues with more advanced tests.

Table 1. Cracking Tests Utilized for CIR.

Test	Reference	S[a]	I[b]	T (°C)	Rate[c] (mm/min)	Parameter Reported (Values Reported)	COV (%)
DCT	Charmot and Remoro (2010)	Y	Y	-14.1 to -28.9	1.02*	G_f (74 to 270 J/m^2)	0 to 40
	Teshale et al. (2017)	Y	Y	-28	1.02*	G_f (90 to 145 J/m^2)	1 to 9
Low-Temp SCB	Wegman and Sabouri (2016)	Y	Y	-18	0.30*	FIVE (190 to 425 J/m^2)	---
	Charmot et al. (2017a)	Y	Y	0	0.06*	G_f (149 to 432 J/m^2)	6 to 41
	Teshale et al. (2017)	Y	Y	-28	0.03*	G_f (85 to 140 J/m^2)	7 to 39
Intermediate-Temp SCB	Charmot et al. (2017b)	Y	N	25	50.0	FI (0.7 to 11.2) G_f (360 to 1440 J/m^2)	9 to 83 13 to 78
SIDT	Cox and Howard (2016)	N	Y	20 0 to -20	50.0 12.5	FE (0.04 to 0.87 kJ/m^3) T_{crit} (4.9 to -21.6 °C)	9 to 26 ---
TXOT	Ma et al. (2017)	Y	N	25	---[d]	Cycles to Failure (100 to 180)	Up to 79

a) S refers to sawing; a “Y” indicates sawing of specimens is required
b) I refers to instrumentation; a “Y” indicates instrumentation for measuring strains or displacements is required
c) Rate refers to testing displacement rate; an “*” indicates the load rate refers to crack mouth opening displacement (CMOD) rate rather than crosshead displacement rate
d) An 0.1 Hz loading frequency was used in conjunction with a max opening displacement of 0.381 mm
-- G_f = fracture energy; calculated as the area under the load-displacement curve divided by ligament area; CMOD used for DCT testing whereas load line displacement (LLD) used for SCB testing
-- FIVE = Fracture Index Value for Energy; calculated like G_f using CMOD rather than LLD
-- FI = flexibility index; calculated by dividing G_f by absolute value of the post-peak slope
-- FE = SIDT fracture energy; calculated as the area under the stress-strain curve (up to the peak stress)
-- T_{crit} = AASHTO T322 critical cracking temperature

Consequently, the objective of this paper is to evaluate different CIR brittleness and cracking index parameters that can be obtained from IDT data. Both non-instrumented and instrumented IDT tests were performed on multiple CIR blends stabilized with a range of portland cement and asphalt emulsion contents covering a range of brittleness/cracking behaviors. In all, data from 116 tests is presented.

LITERATURE REVIEW

Cracking Tests for Conventional DGA

DGA cracking tests include the intermediate-temperature Louisiana SCB and Illinois SCB (i.e. I-FIT), low-temperature SCB, DCT, Texas overlay (TXOT), and Superpave indirect tension (SIDT), among others. As discussed in Howard et al. (2016), many of these tests have demonstrated sensitivity to basic properties, have been vetted against field data, and have even been implemented into state agency balanced mix design specifications. However, the need to perform sawing, gluing, and/or instrumentation remains an operational challenge when it comes to expanding a test beyond mix design and into production control.

As a result, simplified tests such as the IDEAL-CT (Im and Zhou 2017, Zhou et al. 2017) and the IDT N_{flex} Factor (West et al. 2017) have been developed. Both utilize standard IDT testing without any instrumentation or atypical specimen geometries. The IDEAL-CT test yields CT_{index}, whereas the other yields N_{flex} Factor. Both parameters incorporate a fracture energy parameter and the slope of the post-peak curve. CT_{index} also incorporates a strain/ductility parameter. Both parameters have demonstrated some level of relationship to physical properties and field data.

Cracking Tests for CIR

Several advanced DGA cracking tests have been investigated for CIR as shown in Table 1. In general, these have followed expected trends. For example, Charmot et al. (2010) reported that DCT fracture energy (G_f) corresponded to field transverse cracking. Charmot et al. (2017a, 2017b) tested binder combinations of 2.5, 3.5, and 4.5% asphalt emulsion and 0, 0.75, 1.5, and 2.25% portland cement (12 blends total). G_f and flexibility index (FI) increased with emulsion content for a given cement content or decreased with increasing cement content for a given emulsion content.

While results have been generally reasonable, variability has been a noted limitation, likely aggravated by the need to saw specimens. Except for the Teshale et al. (2017) DCT data, the upper range of coefficient of variation (COV) values reported where sawing was also required spanned from around 40 to 80%. Practically, many Table 1 references also required instrumentation, which the newer, simpler DGA cracking tests have omitted to facilitate more efficient and economical testing.

In contrast to Table 1, Charmot et al. (2018) investigated the IDEAL-CT test (25 °C and 50 mm/min) for the 12 CIR binder blends tested in Charmot et al. (2017a, 2017b). CT_{index} ranged from 58 at 2.5% emulsion plus 2.25% cement (most brittle blend tested) to 410 at 4.5% emulsion with 0% cement (most ductile blend tested). COVs, however, were still high, ranging from 8 to 43%.

COMPANION WORK

The work described in this paper is part of a larger CIR study (Mississippi Department of Transportation (MDOT) State Study 250 (Cox and Howard 2015)) in which there are two key motivations. The first is a universal CIR design framework that accommodates cementitious or bituminous binders either individually (e.g. 4% cement or 3% emulsion) or in combination (e.g. 2.5% emulsion with 2% cement). Therein, mix designs would be performed in a consistent manner independent of the binder (i.e. identical mixing, compacting, curing, and testing protocols).