Optimizing Cold In-Place Recycling (CIR) Applications Through Fracture Energy Performance Testing

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Cold In-place Recycling (CIR) is pulverizing and rebinding existing Hot Mix Asphalt (HMA) pavements with bituminous and/or chemical additives without heating to produce a restored pavement layer. This process has become a desired rehabilitation alternative for cost, environmental, and performance advantages compared to standard practices. The process utilizes a train of equipment with either volumetric or weight control. It also utilizes various stabilization materials including emulsion, cement, combinations of emulsion/cement, and foamed asphalt.

Performance-based laboratory tests to capture fracture energy of materials have shown they can correlate to field performance quite well. These tests offer an excellent opportunity to differentiate between processes and materials used in CIR for characterization and development of a performance-based specification.

In this study, the performance of CIR using four different stabilization (rebinding) materials of Engineering Emulsion, High Float Emulsion (HFMS-2s), Commodity Emulsion (CSS-1) with Cement, and Foamed asphalt are compared using a newly developed testing method called Fracture Index Value for Energy (FIVE). This test is performed on notched Semi-Circular Bending (SCB) specimens by controlling the crack mouth opening displacement (CMOD) rate. The FIVE test is found to be a practical easy to perform test that is able to compare CIR material low temperature characteristics. In this study, the FIVE test first was verified against Disc-shaped Compact Tension (DCT) test results and then was applied on the four study mixtures. Furthermore, the FIVE test results went through a validation process with inter-lab comparisons by three different testing labs of Braun Intertec, American Testing Engineering, and the Minnesota Department of Transportation (MnDOT).

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EXECUTIVE SUMMARY

Cold In-place Recycling (CIR) is the pulverization and rebinding of existing Hot Mix Asphalt (HMA) pavements with bituminous and/or chemical additives without heating to produce a restored pavement layer. This process has become a desired rehabilitation alternative for cost, environmental, and performance advantages compared to standard practices. The process utilizes a train of equipment with either volumetric or weight control. It also utilizes various stabilization materials including emulsion, cement, combinations of emulsion/cement, and foamed asphalt. Agencies have minimal direction as to specifying equipment, process control, and materials for specific projects and situations. A large gap in understanding what should be specified is the lack of material and process characterization as it relates to the performance of the material.

Performance-based laboratory tests to capture fracture energy of materials have shown they can correlate to field performance quite well. These tests offer an excellent opportunity to differentiate between processes and materials used in CIR for characterization and development of a performance-based specification.

In this study, the performance of CIR material using four different stabilization (rebinding) materials of Engineering Emulsion, High-Float Emulsion (HFMS-2s), Commodity Emulsion (CSS-1) with Cement, and Foamed asphalt are compared using a newly developed testing method called Fracture Index Value for Energy (FIVE). This test is performed on notched Semi-Circular Bending (SCB) specimens by controlling the crack mouth opening displacement rate. The FIVE test is found to be a practical, easy-to-perform test, which is able to compare CIR material low temperature characteristics. In this study, the FIVE test first was verified with Disc-shaped Compact Tension (DCT) test results and then was applied on the four study mixtures. Furthermore, the FIVE test results went through a validation process with inter lab comparisons by three different testing labs of Braun Intertec, American Testing Engineering, and the Minnesota Department of Transportation (MnDOT).

CHAPTER 1: INTRODUCTION

Cold In-place Recycling (CIR) has become a desired rehabilitation alternative for cost, environmental and performance advantages compared to standard overlay/inlay construction practices. The process utilizes a train of equipment with either volumetric or weight control. The process also utilizes various stabilization materials including emulsions, cement, combinations of emulsions/cement, and foamed asphalt. Agencies have had minimal direction as to specifying materials for specific projects and situations. A large gap in understanding what should be specified, is the lack of material and process characterization as it relates to performance and constructability.

Performance based laboratory tests to capture fracture energy of materials have shown they can correlate quite well to field performance. These tests offer an excellent opportunity to differentiate between processes and materials used in CIR for characterization and development of a performance based specification.

A collaboratively developed performance specification between agency and industry will provide for advancement and more successful use of the CIR processes.

1.1 Purpose

The purpose of this research was to:

- Characterize the CIR process and materials using new SCB or DCT performance testing.
- Performing a validation process on SCB or DCT performance tests on CIR through inter-lab comparisons of test results.
- Assess the possibility of developing a new performance based specification applicable to all CIR processes and materials.

1.2 Scope of Services

Tasks performed in accordance with our authorized scope of services included:

- Performing a comprehensive literature review to document current fracture energy performance test protocols and procedures for CIR applications.
- Gathering pavement cores from Carver County roadway(s) deemed suitable for this research.
- Delivering the cores to Braun Intertec and American Engineering Testing (AET) labs for processing and mix designs.
- Preparing specimens by Braun Intertec and AET from the cores at the optimum binder content determined from the mix designs.
- Preparing additional specimens using standard binder contents as outlined in the scope (non-design samples).
- Dividing specimens equally between performance testing laboratories at Braun Intertec, AET and MnDOT, then testing to validate consistency through inter-lab comparisons of performance test results.
- Preparing this report including Technical Advisory Panel (TAP) review and revisions.

CHAPTER 2: LITERATURE REVIEW

Asphalt pavements are subject to deterioration under traffic load and environmental conditions; fatigue cracking, low temperature cracking, and rutting are the primary pavement distresses. Water infiltration through the cracks may subsequently cause weakening and deterioration of the base and/or subgrade. Cracking is also the main reason for many distresses, such as stripping, loss of subgrade support, etc. Since the rehabilitation and maintenance of asphalt pavements to overcome such distresses is usually costly, highway agencies often attempt to address this issue by employing mix and pavement designs that delay deterioration and are easily constructed. Recycling in-place materials is also desirable for cost and environmental benefits realized.

Asphalt mixtures are complex materials and their behavior is strongly dependent on temperature, strain rate, and stress conditions, so attention should be paid to a correct modeling of the mixture characteristics such as cracking resistance. There are several test methods to measure cracking, including direct tension testing, four-point bending beam fatigue, and Superpave indirect tension test, but due to the time associated with these test methods and complexity they are not typically included in the mix design processes. Many design methodologies consider volumetric proportions and strength characteristics of the mixtures, which may not provide adequate insight into mixture performance.

Low temperature cracking is the predominant distress in the northern US and Canada. These cracks can occur as a result of a single curve temperature drop (single event) or of multiple cycles of less severe temperature change (thermal fatigue). Thermal cracks will result in the formation of the transverse cracks of various length and width along the pavement and ultimately accelerate the deterioration of the structure. Therefore, the evaluation and identification of the factors significantly affecting low temperature cracking resistance is of interest to owner/agencies seeking better performing pavements in these northern climates.

As a powerful tool, fracture mechanics has been successfully used to study crack initiation and propagation in all types of materials. Fracture properties of asphalt pavement dictate its ability to resist cracking. This approach has been applied to explore the mechanism of fracture in asphalt mixtures as early as in 1960s and has become increasingly popular in the research community after 1990s. This type of analysis requires testing notched specimens and controlling the load based on crack growth. There are many methods of fracture testing, including the Single-Edge Notched Beam (SEB) [1], the Disc-Shaped Compact Tension Test (DCT) [2, 3, and 4], and the Semi-Circular Bend (SCB) [5, 6, 7, 8, 9, 10, and 11]. Figure 2.1 shows these three different fracture testing configurations.

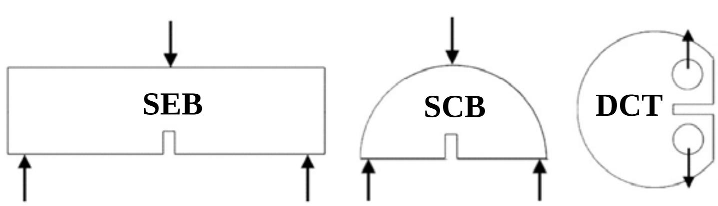

Figure 2.1 Sample geometries for SEB, SCB, and DCT

2.1 Single-Edge Notched Beam (SEB)

Single-Edge Notched Beam (SEB) is consisting of a three-point bending beam configuration with an offset notch. Braham et al. [1] studied the combination of thermal cracking and wheel loads which is believed to create cracking in both Mode I (opening) and Mode II (sliding) direction using SEB configuration. They found it the most useful test based on the equipment.

One of the most critical factors in selecting a suitable fracture test is the specimen geometry. In most of the cases, actual asphalt layer thickness dictates the specimen geometry, thus it cannot be directly controlled or determined. This is the main issue of using SEB, as the beam geometry limits the use of this method on gyratory compacted specimens and field cores.

2.2 Disc-Shaped Compact Tension Test (DCT)

The disc-shaped compact tension geometry is a circular specimen with a single edge notch loaded in tension. Figure 2 presents a DCT specimen. Because of the ease of sample preparation from the gyratory compacted cylinders or field cores samples, DCT is favored over the SEB and has been used by many researchers.

Wagoner et al. [2] tested four mixtures with varied composition and demonstrated that DCT test is able to obtain fracture properties of asphalt concrete specimens obtained from field cores following dynamic modulus and creep compliance tests performed on the same specimen, they concluded that the fracture energy appears to be much better indicator for determining the resistance of the material to fracture than other indirect measures such as tensile strength as the fracture energy approach clearly distinguished between the materials according to differences in binder properties. Kim et al. [3] obtained DCT sample from coring three field projects which resulted in six fundamentally different mixtures. These mixtures were expected to demonstrate significantly different levels of fracture resistance as suggested by visual field crack survey. On the basis of the observations, they reported a reasonable correlation between the lab-measured fracture energy and the field performance of the investigated pavement sections.

It should be noted that DCT testing requires special testing fixture as this test is performed in tension mode. Also it requires more specimen preparation time as it requires extra cut and holes (See Figure 2.2). These holes may cause some stress concentrations which may result in random failures during the test. Also it has been observed that more often crack deviates during DCT test [2]. This violates the assumption of 100% Mode I fracture (opening mode; a tensile stress normal to the plane of the crack) and the fracture mode of test changes from mode I to mixed mode (mode I-II) fracture.

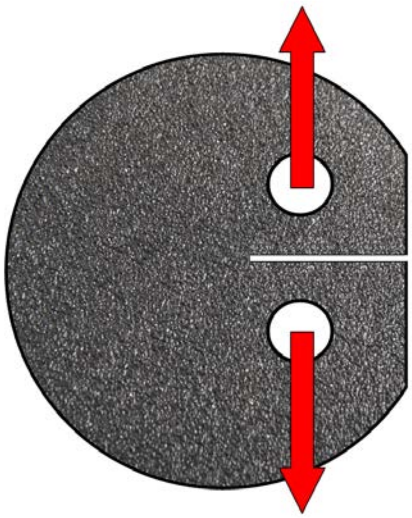

Figure 2.2 DCT test specimen

2.3 Semi-Circular Bending (SCB)

The need of a rapid and simple test that can be performed on easy to prepare specimens led to the semi-circular bending geometry. As Figure 2.3 shows, SCB geometry is consisting of a half disk with a notch of known length. SCB is loaded monotonically until fracture failure. Similar to DCT, because of the ease in sample preparation from the gyratory compacted cylinders or field cores samples, SCB is favored over the SEB and has been used by many researchers.

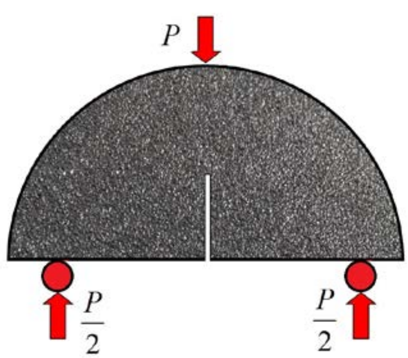

Figure 2.3 SCB test specimen

Compared to DCT, in SCB testing the crack deviation problem is less pronounced as the specimen usually breaks in a more easily characterized way. Molenaar et al. [5] studied the effectiveness of SCB to characterize asphalt mixtures using a finite-element (FE) model that was developed to calculate tensile and compression stresses developing in SCB sample during the test. The analysis showed that the dominant failure mode in the SCB test is cracking due to tension stresses. Figure 2.4 shows the tensile and compressive stresses. The figure shows that indeed large tensile stresses occur at the bottom of the specimen. Therefore, the test gives relevant information on the tensile characteristics of the asphalt mixes tested. It was concluded by the authors that the SCB test can be a very useful tool in mixture design and for quality assurance and quality control (QA/QC) purposes.

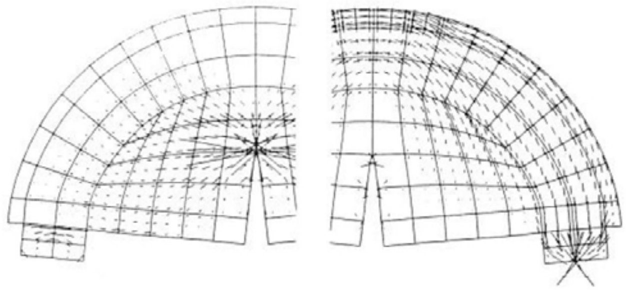

Figure 2.4 Stress field in SCB test; left: tensile stresses, right: compressive stresses [5]

Arabani and Ferdowsi [7] evaluated the SCB test for its suitability to characterize the tensile strength, fracture toughness, and fatigue life of asphalt concrete. Numerical analysis indicated a good agreement between the results of the tensile strength and fracture toughness obtained from SCB test and dynamic modulus of Nottingham Asphalt Tester (NAT). They concluded that the SCB test is very promising test for determination of asphalt concrete characteristics mainly tensile and fracture resistance while it clearly shows the asphalt-aggregate interaction in the mechanical behavior of the asphalt mixtures.

Li and Marasteanu [8] evaluated the ability of the SCB test to evaluate low temperature fracture resistance of HMA. Results indicated strong dependence of low temperature cracking resistance on the test temperature. Six asphalt mixtures were tested representing a combination of factors such as binder type, binder modifier, aggregate type, and air void content. The SCB test was conducted at three low temperatures (-30°C, -18°C, and -6°C). The loading rate and initial notch depth were also varied. Results indicated strong dependence of low temperature cracking resistance on the test temperature. Additionally, significant effects of aggregate type, air void content, binder grade and modifier type were reported. The effect of loading rate and initial notch depth was only observed for the warmest test temperature. The authors also noted the test was conducted with satisfactory repeatability as indicated by the low coefficient of variation.

In a similar study, Elseifi et al. [11] validated a three-dimensional (3D) finite element (FE) model, which was used to interpret and to analyze the failure mechanisms in the SCB test. Results of the experimental program showed that the SCB test results successfully predicted the fracture performance of the evaluated mixes and was able to differentiate between them in terms of cracking resistance. Based on the results of the FE model, damage that propagates in the vicinity of the notch is mainly caused by a combination of vertical and horizontal stresses in the specimen. The effect of shear was negligible in progressing damage in the specimen. Figure 2.5 shows the damage propagation during the test process as predicted by the FE model for the 38.0 mm notch depth specimen. As this graph illustrates, damage gradually progresses upward until total failure is reached.

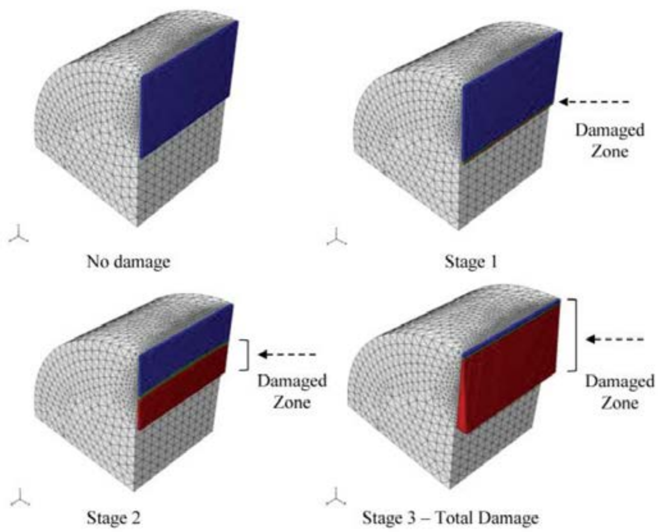

Figure 2.5 Damage evolution in the SCB test [11]

Despite the limitations reported in the literatures, such as the relatively small potential fracture area, it has been indicated that as more knowledge on the SCB characteristics is accumulated, this test shows potential to become a valuable tool for routinely obtaining fracture parameters of asphalt mixtures.

Fracture energy concept was also used to assess Cold In-place Recycling (CIR) mixtures in some studies and was found to be a critical parameter in the performance of CIR measured in the field in terms of resistance to transverse cracking. Charmot and Romero [4] evaluated the ability of SCB test fracture parameters to predict field cracking performance of CIR mixtures on the basis of nine sites in three states consisting of past rehabilitation projects, 2 to 5 years old, that involved CIR and new asphalt concrete overlay mixtures. Testing of field cores showed that the number of transverse cracks increased as mixture fracture energy decreased. The fracture energy of the CIR surface mixtures successfully differentiated projects with satisfactory and poor performance.

2.4 Selected Geometry

Table 2.1 summarizes the advantages and disadvantages of different fracture testing methods among which the SCB test method looks promising as it is simple to conduct (a simple uniaxial load frame can be used to conduct the test), inexpensive, sample preparation is straightforward, simple to analyze, and the mode of failure in SCB samples is due to tensile stress induced by bending. Also, it has been adopted by many pavement material researchers in the asphalt pavement community so far. Therefore, SCB geometry was selected to be used in the current study.

Table 2.1 Advantages and disadvantages of different fracture testing methods

Test Method	Advantages	Disadvantages
SEB	- Pure Mode I loading - Simple loading configuration - Flexibility to investigate other areas (e.g. mix-mode fracture)	- Difficult to obtain field specimens
DCT	- Easily obtained field specimens - Standard ASTM test method for HMA	- Crack path deviation - Special fabrication equipment (tension testing) - Failure around the loading holes - Low fracture surface area
SCB	- Dominant Mode I loading - Simple loading configuration - Easily obtained field specimens	- Low fracture surface area

CHAPTER 3: TEST METHOD

3.1 SCB Trial Testing

One of the primary goals of this research was to validate an implementable performance test for various binders used in the CIR process. Ideally the proposed test method can be used for the mix design and field quality management purposes.

SCB trial testing were performed at Braun's lab to make sure that SCB is a viable test method for CIR material. All trial testing were conducted on dummy CIR specimens and at an arbitrary chosen low temperature of -20°C. At this stage, the primary goal was to be able to run the SCB fracture test under the simplest procedure and with the lowest hardware cost, so the first trials were performed under actuator displacement control. In this mode of loading, the machine starts loading the specimen at a constant actuator displacement rate until the specimen breaks.

Figure 3.1 shows the load versus displacement for a trial test with actuator displacement rate of 0.5 mm/min. As this graph shows, load is increasing up to the peak point and then drops suddenly, probably because of the brittle behavior of CIR materials at low temperatures. This was the case even at very low actuator displacement rates. Therefore, running SCB in actuator displacement control mode is not recommended as it cannot capture the post-peak behavior (crack propagation phase) of the CIR material.

Figure 3.2 presents load vs. actuator displacement curve for the same test. As expected, similar to the load versus time curve, there is a sharp drop in the graph once the load reaches its peak and the tail of the curve is not captured.

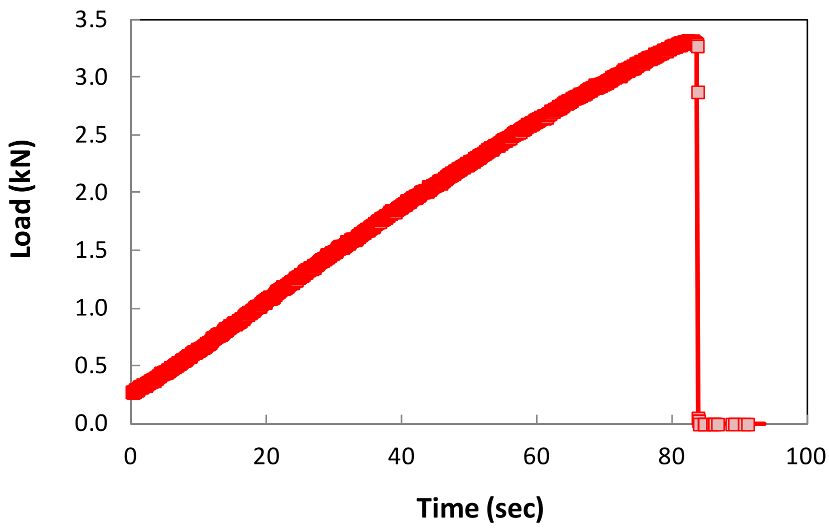

Figure 3.1 Load vs. time in actuator displacement mode

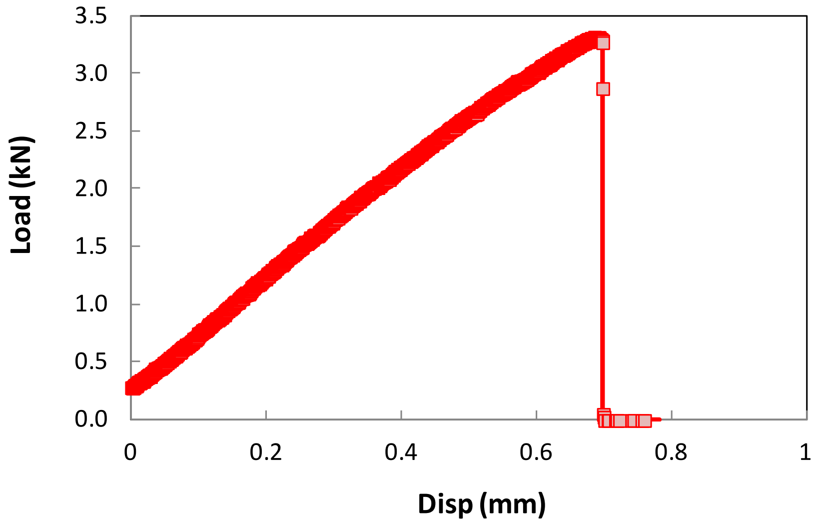

Figure 3.2 Load vs. displacement in actuator displacement mode

To avoid the sudden drop in load, next trials were performed under Control Mouth Opening Displacement (CMOD) mode. These trials were conducted under a CMOD rate of 0.005 mm/sec. Figure 3.3 shows the SCB sample with a CMOD gauge mounted on the notch.

Figure 3.4 shows CMOD versus time. As this graph suggests, the actual CMOD rate (slope of the CMOD vs. time curve in Figure 3.4) is equal to the programmed rate of 0.005 mm/sec and is also constant throughout the test. Figure 3.5 shows the load versus time curve for this test. Unlike the sudden drop of load in actuator displacement control mode, in CMOD control mode the load decreases slowly after it reaches its peak, resulting in a well-defined tail area in load vs. CMOD curve. Also, the pre-specified minimum load level of 0.5 kN was reached during the test.

Figure 3.3 CMOD gauge mounted on SCB sample

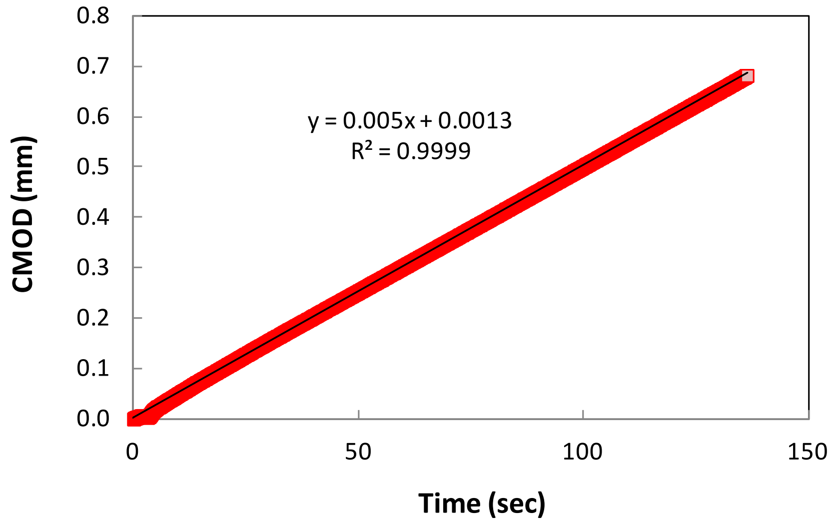

Figure 3.4 CMOD vs. time in CMOD control mode

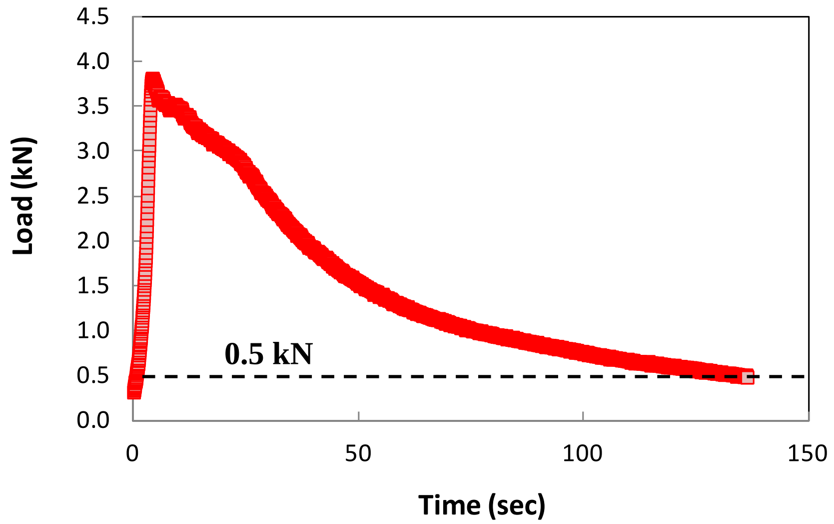

Figure 3.5 Load vs. time in CMOD control mode

It should be noted that to keep the testing requirements simple, no independent load line displacement (LLD) device was installed in the direction of the load during the testing. This led the research team to introduce a new fracture energy index, called Fracture Index Value for Energy (FIVE), in which load vs. CMOD curve is used for the purpose of energy calculation (Figure 3.5).

This is of high importance to note that even though FIVE dimension is energy (Jules), it should not be considered the true fracture energy of the material as the load line displacement is not measured during the test (CMOD measurement is perpendicular to the direction of load). This means that the SCB FIVE values should not be compared against the fracture energy values directly.

3.2 Fracture Index Value for Energy (FIVE) Parameters

Figure 3.6 shows the SCB testing setup. The geometry parameters are as follow:

d : cylindrical sample diameter
b : sample thickness
r : sample radius
a : notch length
l : initial ligament length = w-a
2s : sample loading span

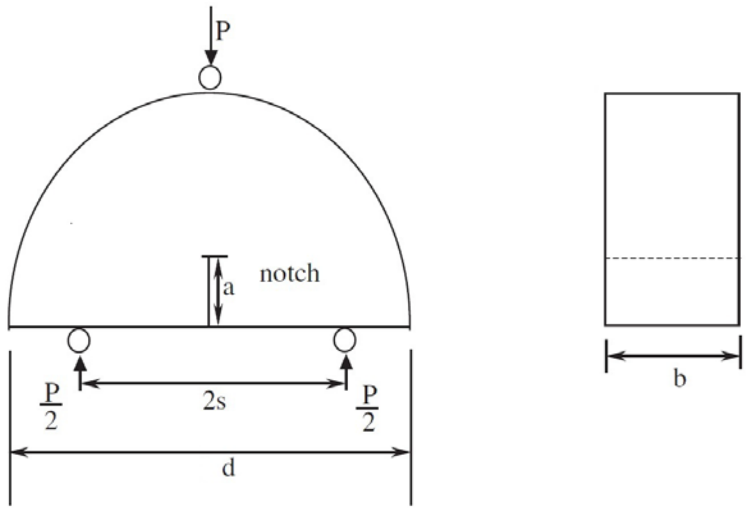

Figure 3.6 SCB sample geometry

As discussed in Section 3.1, the FIVE test should be performed under the CMOD control mode, as shown in Figure 3.3.

The Fracture Index Value for Energy (FIVE) is calculated by dividing the total energy (the area under load vs. CMOD curve) by the ligament area (the product of the ligament length (r-a) and the thickness of the specimen (b)) of the SCB specimen prior to testing:

$$FIVE = \frac{W_f}{A_{lig}}$$

where,

FIVE : fracture index value for energy (J/m^2),
W_f : total energy (J), and
A_{lig} : ligament area.

$$W_f = \int P du$$

where,

P	: applied load (N), and
u	: CMOD displacement (m).

$$A_{lig} = (r - a) \times b$$

where,

r	: specimen radius (m),
a	: notch length (m), and
b	: sample thickness (m).

Total energy is calculated as the area under the load vs. CMOD (P-u) curve as shown in Figure 3.7. The test finishes when the load drops below 0.5 kN (point "u_c" in Figure 3.7). Also, the following parameters can be extracted from the curve:

P_p	: peak force, and
u_p	: CMOD at peak force.

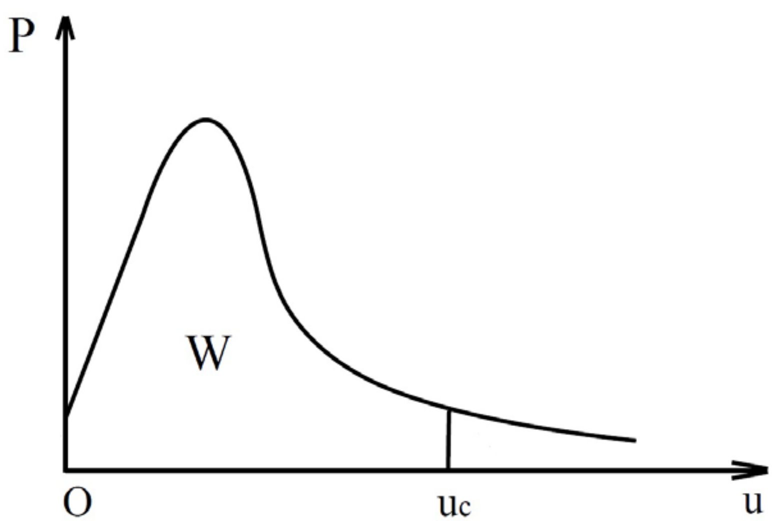

Figure 3.7 Load vs. CMOD (P-u) curve

Total energy (W) under the experimental curve can be computed using a technique called the quadrangle rule:

$$W = AREA = \sum_{i=1}^{n} (u_{i+1} - u_i) \times P_i + \frac{1}{2}(u_{i+1} - u_i) \times (P_{i+1} - P_i)$$

where,

P_i : applied load (N) at the i load application,
P_{i+1} : applied load (N) at the i+1 load application,
u_i : CMOD (m) at the i step, and
u_{i+1} : CMOD (m) at the i+1 step.

3.3 FIVE Test Parameters

FIVE test parameters, testing conditions, and required outputs are summarized in Table 3.1. The testing temperature was defined as 10 degree Celsius above the low binder PG grade of the base binder. As most of the study mixture binders had a low binder PG grade of -28 (except for the foam with a low binder PG grade of -34), a testing temperature of -18°C was used for all the mixtures in this study.

Table 3.1 SCB FIVE testing parameters

Parameters		**Target**	**Measurement Tolerance**
Sample Geometry	d, mm	150±2.5	±0.5
	b, mm	50 to 60	±0.5
	r, mm	75±2.5	±0.5
	a, mm	15±1	±0.5
	2s, mm	127±0.5	±0.5
Testing Condition	CMOD rate, mm/sec	0.005	±0.0001
	Temperature, °C	-18	±0.5
Output	P_p, kN(1)	---	±0.1
	FIVE, J/m^2	---	±1

(1)Peak force

3.4 SCB FIVE Test Verification

In order to verify the applicability of the SCB FIVE test, CIR samples were fabricated at Braun Intertec and AET from three different CIR mixtures. SCB FIVE tests were done at Braun Intertec, while DCT tests were performed at MnDOT (according to MnDOT modified ASTM D 7313). As it was discussed in Section 3.1, the SCB FIVE value cannot be directly compared against fracture energy values from DCT testing, but the trends (mixture rankings) should be the similar.

Table 3 presents the mixtures and number of samples were tested in each case at Braun Intertec and MnDOT.

Table 3.2 SCB testing parameters

Stabilization Material	# of SCB FIVE test at BRAUN	# of DCT test at MnDOT
Engineering Emulsion (EE)	6	6
Cement with Commodity Emulsion (CSS-1 w/ cement)	7	6
High Float Emulsion (HFMS-2s)	7	4[(1)]

[(1)]Two DCT samples broke during the test, while all SCB samples were tested successfully.

Figure 3.8 shows the SCB FIVE test results. As this graph suggests, HFMS-2s appears to have the best performance following by Engineering Emulsion, while CSS-1 with cement shows the worst performance. A t-test was performed to statistically compare HFMS-2s and Engineering Emulsion results. At a significance level (alpha) of 0.01, p-value was found to be 0.1688 (> 0.01) which suggests that the HFMS-2s and Engineering Emulsion results are statistically the same. In other words, HFMS-2s and Engineering Emulsion perform about the same, while CSS-1 with cement shows a worse performance.

Figure 3.9 presents the DCT test results. As this graph suggests, similar to SCB results, HFMS-2s and Engineering Emulsion appears to perform about the same (statistically the same with a p-value of 0.3788), while CSS-1 with cement shows the worst performance. The similar ranking between SCB FIVE and DCT results confirms that SCB FIVE is able to capture the fracture performance of CIR materials.

It should be noted that even though DCT generally showed a better variability (smaller standard deviations), two DCT samples broke during testing, while all SCB testing were successfully completed. This may suggest that the DCT test method is not as practical as SCB when dealing with 100% recycled materials. Also, as it was mentioned earlier, even though SCB FIVE and DCT fracture energy test results have the same dimension of energy (J/m^2), their values cannot be compared directly (i.e. Figure 3.8 and Figure 3.9 values cannot be compared).

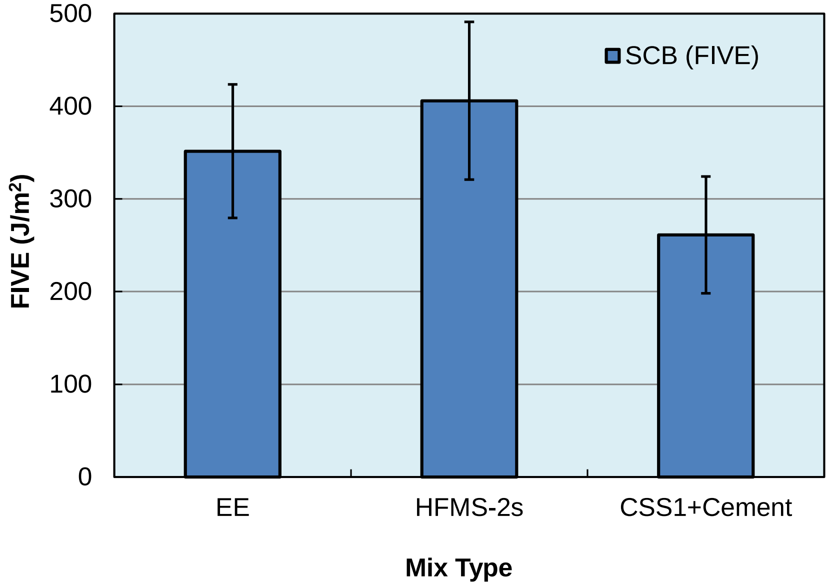

Figure 3.8 Trial SCB FIVE test results

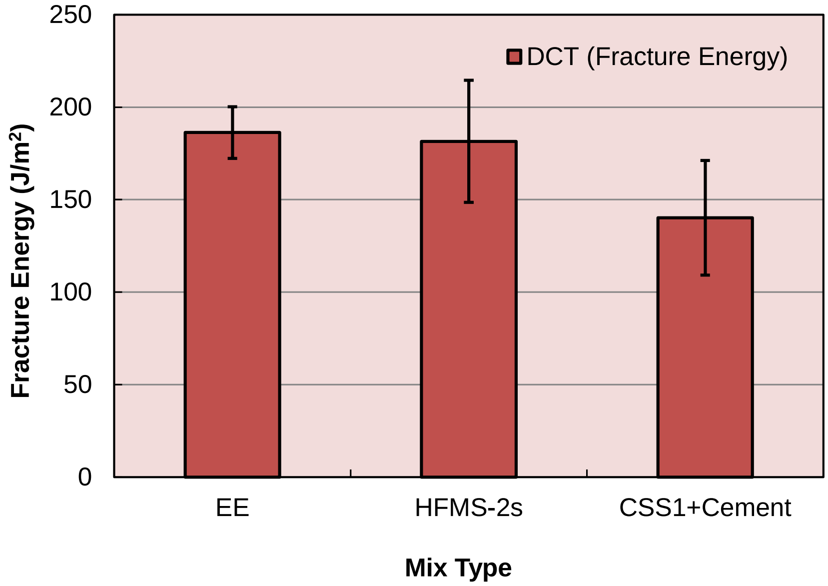

Figure 3.9 Trial DCT test results

CHAPTER 4: EXPERIMENTAL DESIGN

4.1 CIR Mix Designs

A total of four CIR mix designs were performed: Engineering Emulsion (EE) and High-Float Emulsion (HFMS-2s) at Braun Intertec and Cement with Commodity Emulsion (CSS-1) and Foamed Asphalt (Foam) at AET. The suggested three point design and the optimum binder content for each mixture are shown in Table 4.1.

Table 4.1 SCB testing parameters

Stabilization Material	Lab	Three Point Design (%)			Optimum Binder Content
Engineering Emulsion (EE)	BRAUN	2.5	2.8	3.0	2.8%
High Float Emulsion (HFMS-2s)	BRAUN	1.0	2.0	3.0	2.0%
Foamed Asphalt (PG XX-34)	AET	1.8	2.2	2.6	2.2%
Cement with Commodity Emulsion (CSS-1)	AET	2.3	2.7	3.0	2.3% emulsion 1.5% cement

Also, two non-design mixtures were produced to see the effect of not performing the CIR mix designs in the mixture's performances. These mixtures included Foamed Asphalt at 2% (called Non-Foam) and CSS-1 with cement at 2% emulsion and 1.5% cement (called Non-CSS1).

4.2 SCB Sample Preparation

The asphalt cores were taken from different roadways of Carver County, so some variations among them were expected. To minimize specimen-to-specimen variability, the research team decided to crush and blend all the materials together before starting bulk specimen fabrication for testing. Even though this may have created some differences between the materials used for performing the designs with the materials used for sample fabrication, but it was deemed necessary considering the goal of being able to compare lab-to-lab testing results. It should also be noted that Carver County pavements are very consistent as most of the roadways have been constructed by a single contractor.

For consistency, all the testing samples were produced according to the sample preparation procedure below:

1) Batch samples following the medium 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 stabilization material (Table 4.1) 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 CIR samples at 60°C for 48±1 hours and foamed asphalt samples at 40°C for 72±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 (See Figure 4.1).

11) Make a notch of 15±1 mm with a width of less than 1.5 mm on each SCB sample.

12) Allow the samples to dry completely and store them in black plastic bags at room temperature to avoid further aging.

13) Sample Labeling: See Table 4.2 for design samples and Table 4.3 for non-design samples.

    For example: EE-5-T-2 is the second SCB sample from the top puck, from the 5th gyratory compacted specimen made with Engineered Emulsion at Braun's laboratory. Figure 4.2 also presents the sample labeling scheme.

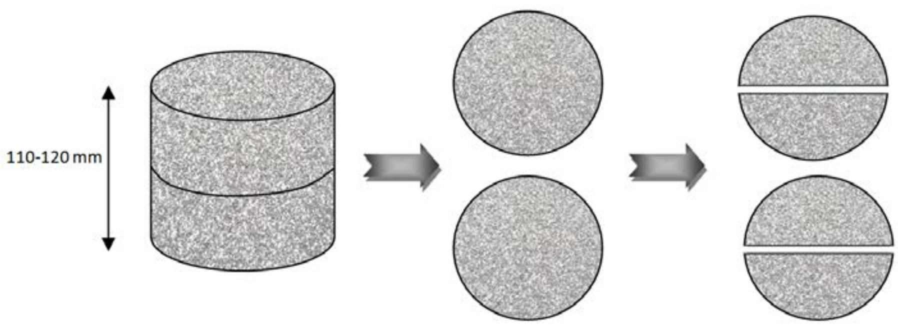

Figure 4.1 Each gyratory compacted specimen results in four SCB samples

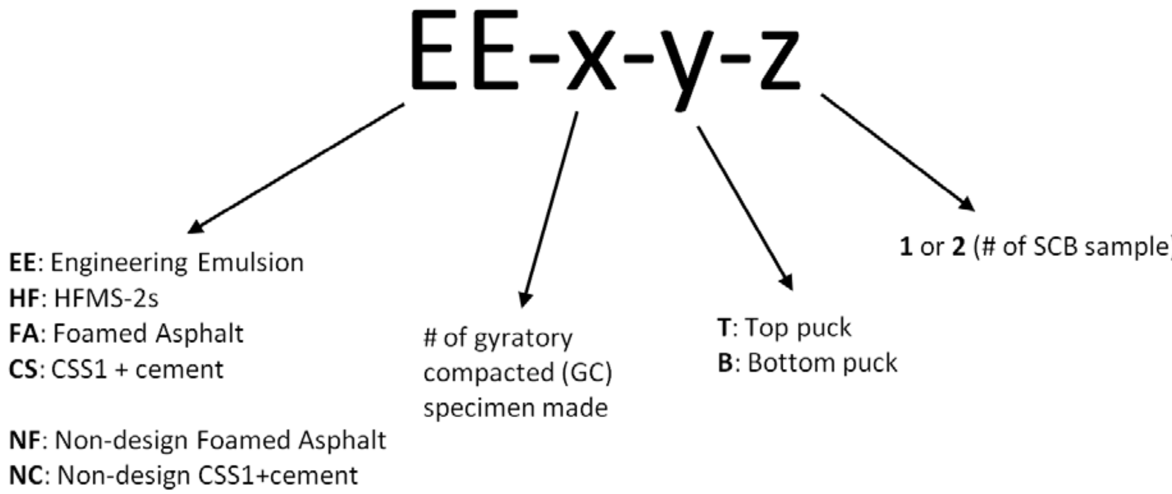

Figure 4.2 Sample labeling scheme

Table 4.2 Sample labeling (Design)

Stabilization Material	Lab	GC[1] Samples	SCB Samples	Binder Type	Specimen Name
Engineering Emulsion (EE)	BRAUN	9	36	CIR-EE	EE-x-y-z[2]
High Float Emulsion (HFMS-2s)	BRAUN	9	36	HFMS-2s	HF-x-y-z[2]
Foamed Asphalt (PG XX-34)	AET	9	36	PG XX-34	FA-x-y-z[2]
Cement with Commodity Emulsion (CSS-1)	AET	9	36	CSS-1	CS-x-y-z[2]

[1]Gyratory Compacted
[2]x=number of the GC specimen made, y=T for the top puck and B for the bottom puck, z= 1 or 2 (number of the SCB sample made from the puck)

Table 4.3 Sample labeling (Non-design)

Stabilization Material	Design	GC[1] Samples	SCB Samples	Binder Type	Specimen Name
Foamed Asphalt (PG XX-34)	2%	9	36	PG XX-34	NF-x-y-z[2]
Cement with Commodity Emulsion (CSS-1)	1.5% cement 2% emulsion	9	36	CSS-1	NC-x-y-z[2]

[1]Gyratory Compacted
[2]x=number of the GC specimen made, y=T for the top puck and B for the bottom puck, z= 1 or 2 (number of the SCB sample made from the puck)

Following the specimen production, specimens were divided according to Table 4.4 between performance testing laboratories at Braun Intertec, AET, and MnDOT, then tested to validate consistency through inter-lab comparisons of performance test results. A total of 162 SCB FIVE testing was conducted in all the three testing labs.

Table 4.4 SCB FIVE testing

Mixture	**Braun Intertec**	**AET**	**MnDOT**	**Total**
Design EE	12	12	12	**36**
Design HF	12	12	12	**36**
Design Foam	12	12	12	**36**
Design CSS-1	12	12	12	**36**
Non-design CSS-1	2	2	5	**9**
Non-design Foam	**---**	**---**	9	**9**
TOTAL	**50**	**50**	**62**	**162**

4.3 FIVE Testing Procedure

4.3.1 Loading Apparatus

The loading apparatus will be capable of maintaining a constant crack mouth opening displacement rate within 2% of the target value (0.0049 – 0.0051 mm/s) throughout the test. Closed-loop servo hydraulic or servo-pneumatic test frames are highly recommended, but not required if the CMOD rate meets the specification listed above. The data acquisition readout for the load cell will display a resolution to 0.001 kN (0.225 lbf).

4.3.2 Bend Test Fixture

Test can be performed in a vertical or horizontal setup and should be composed of steel rollers. The rollers are used to minimize the frictional effects (as suggested by ASTM E 399). In horizontal setup, the bottom plate should be made of aluminum and also covered with polytetrafluoroethylene (PTFE) or Teflon to reduce the friction between the sample and the bottom plate. The rollers should be covered with Teflon to further reduce the friction. Figure 4.3 shows a bend test fixture (horizontal setup).

Figure 4.3 Aluminum bottom plate covered with Teflon strip in horizontal setup

4.3.3 <u>SCB Sample Geometry Measurements</u>

All sample geometries (Table 3.1) should be measured and entered in the specimen testing log (excel spreadsheet) as shown in Figure 4.4. Diameter and thickness of each specimen should be measured in accordance with ASTM D 3549/D 3549M. Individual measurements should be determined to the nearest 0.5 mm. The notch length should be measured on both faces of the specimen and average recorded to the nearest 0.5 mm.

SCB FIVE Testing																						
Specimen ID	Test Date	Test Order	Time Hydraulic Warm-up Ran	Diameter	Thicknesss (50.00 to 60.00)	Ligament Length (57.50 to 62.50)	Desired Test Temp	Time Specimens & TD put into Freezer	Time TD in Freezer Reached Desired Temp	Time (when) removed from freezer	Length of Time in Freezer (min. 2 hrs)	Length of Time at Desired temp in Freezer	TD Temp in Freezer at Specimen Removal	Hold time for Temp Stabilization (min. 15 minutes)	Max Load	Time of Max Load	Defined Slope	Actual Slope	FIVE	Area Under the Curve	Length of Test	Comments
--	--	--	--	mm	mm	mm	°C	--	--	--	Hrs.	Hrs.	ºC	Mins.	kN	Secs.	mm/s	mm/s	J/m^2	Nmm	Secs.	--
EE-1-T-1	7/6/2015	1	1:30 PM	150	55.10	57.90	-18.0	11:30 AM	12:30 PM	1:56 PM	2.43	1.43	-18.0	15	2.807	8.76	0.0170	0.0170	553.68	2298.97	184.36	

Figure 4.4 Testing excel spreadsheet

4.3.4 <u>Temperature Conditioning</u>

For temperature conditioning purposes, two dummy samples are required: (1) Testing Dummy (TD) that stays in the external conditioning chamber, and (2) Monitoring Dummy (MD) which is used for monitoring the temperature during the testing (MD stays in the testing chamber at all times). Figure 4.5 shows the MD sample.

Figure 4.5 Monitoring Dummy (MD)

Verifying test specimens and monitoring dummy (MD) stabilize at similar temperatures should be done at least once per month or maximum 100 tests, whichever occurs first, according to MnDOT Modified ASTM D7313.

Temperature conditioning should be done as follow:

1) Place the testing specimens and the testing dummy (TD) in a temperature controlled chamber at the desired test temperature.

2) The specimens and TD will cool down to the desired test temperature with maximum of 1.5 hours as per monitoring of the TD.

3) Monitor the TD temperature until it falls in ±0.5°C of the desired test temperature at least for 5 minutes.

4) Warm up the servo-hydraulic systems for a minimum of 5 minutes before starting any testing.

5) Set up the first sample in the testing fixture as quick as possible (cut surface should be at the bottom in horizontal setup). Mount the CMOD gauge and ensure the support is centered and level. Start monitoring the monitoring dummy (MD) temperature (MD stays in the testing chamber at all time).

6) Test can be run after a minimum of 10 minutes AND after the MD temperature falls in ±0.5°C of the desired test temperature at least for 5 minutes.

7) If the MD temperature falls out of ±0.5°C of the desired test temperature during the test, finish the test and make a note in the specimen log.

8) No specimen should be kept at the testing temperature for more than 6 hours.

4.3.5 Running the Test

After temperature equilibrium is reached:

1) Apply a seating load of 0.3±0.05 kN in stroke control to ensure the sample is seated properly.

2) Begin to apply load to specimen in CMOD control at a rate of 0.005 mm/sec ensuring that time, load, and displacement are being collected and recorded.

3) During the test have the load versus CMOD visible, paying close attention to the peak load.

4) Terminate the test after the load reached to 0.5 kN.

5) If the CMOD gauge range limit is reached before a load of 0.5 kN, finish the test and make a note in the specimen log.

6) Complete the specimen testing log (excel spreadsheet, Figure 4.4) and setup the next sample.

CHAPTER 5: RESULTS

5.1 Testing Results

SCB FIVE testing was performed on the four study mixtures at the three testing labs. Figure 5.1 through Figure 5.3 present the testing results from Braun Intertec, AET, and MnDOT, respectively. In all the graphs, the bars are showing ±one standard deviation within each tested group.

As Figure 5.1 presents, in the data from Braun Intertec, HFMS-2s showed the best and the CSS-1 showed the worst performances, while EE and Foam were in the middle, with foam performing better. According to AET's results (Figure 5.2), EE and HFMS-2s had the best performances with EE being slightly better, followed by the foam. Similar to Braun Intertec, CSS-1 showed the worst performance among all the mixtures tested at AET. Figure 5.3 shows the testing results from MnDOT; again similar to Braun Intertec, HFMS-2s performs the best and CSS-1 the worst, and EE and Foam are in the middle, with EE performing better.

Figure 5.4 shows all the testing results from the different labs on the same graph. As this graph suggests, all the labs show about the same trend in terms of mixture rankings, but looking at the FIVE values, Braun's values appear to be consistently higher than other two lab results, while MnDOT's values are the lowest. This consistent trend in FIVE values may suggest that an external factor is affecting the testing results. To make sure that this difference is not due to machine-to-machine variability the testing machines went through a validation process. The details of this process and the results is presented in the following section of this report.

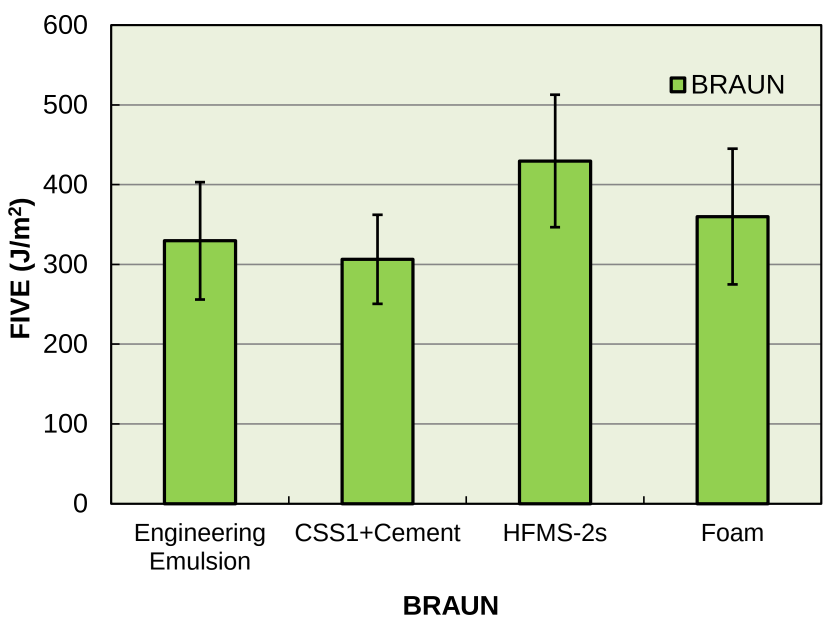

Figure 5.1 Braun SCB FIVE testing results

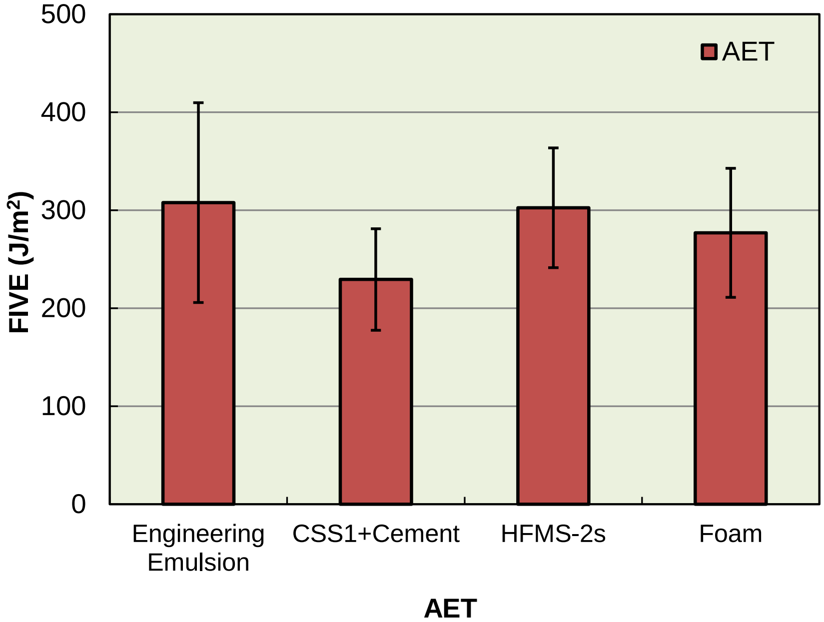

Figure 5.2 AET SCB FIVE testing results

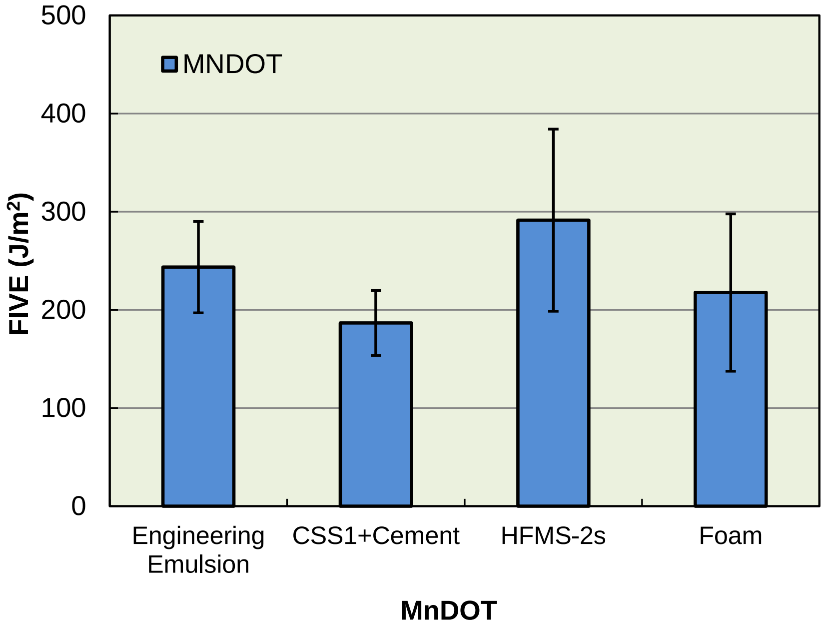

Figure 5.3 MnDOT SCB FIVE testing results

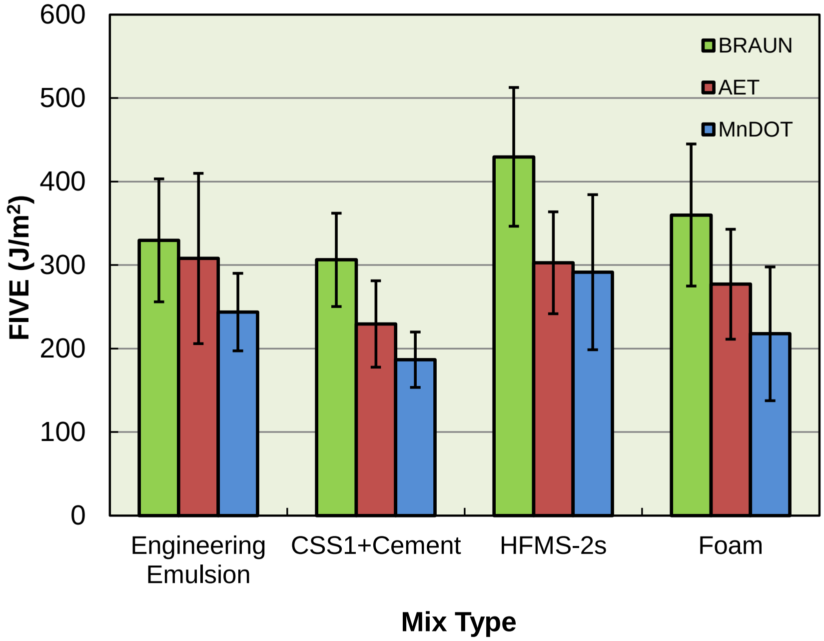

Figure 5.4 SCB FIVE testing results from all testing labs

It would be interesting to see how different the four samples acquired from one gyratory compacted sample are, so the data points are shown in scatterplots with line of equality (LOE). The results can be compared by comparing the result of each half to its companion half (Figure 5.5), or comparing the average of the two bottom samples (bottom disc) to the average the two top samples (top disc) as shown in Figure 5.6. In both graphs, the further the points deviate from the line of equality, the more different the results are.

As some of the points are deviating from the LOE in Figure 5.5, it can be concluded that even the two companion SCB samples (by cutting one disk into two halves) could result in different energy values. As almost everything is about the same during the production of the two companion SCB samples, these differences appears to be due to the variability of the RAP material (100% RAP). It also suggests that when dealing with CIR materials, even trimming the top and bottom of gyratory compacted samples would not result in less variability, so acquiring four SCB samples from each gyro seems to be appropriate to save time and material.

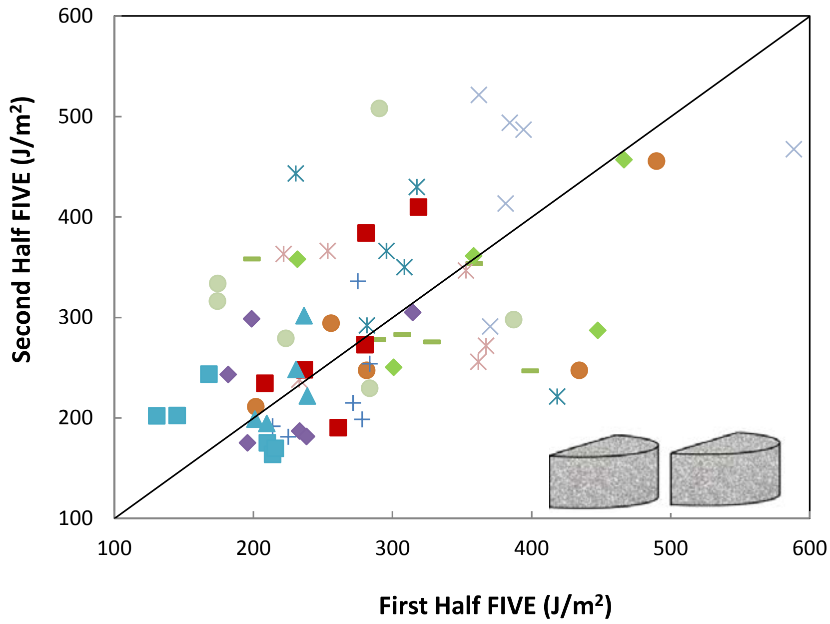

Figure 5.5 Comparing halves (from cutting one disk into two halves)

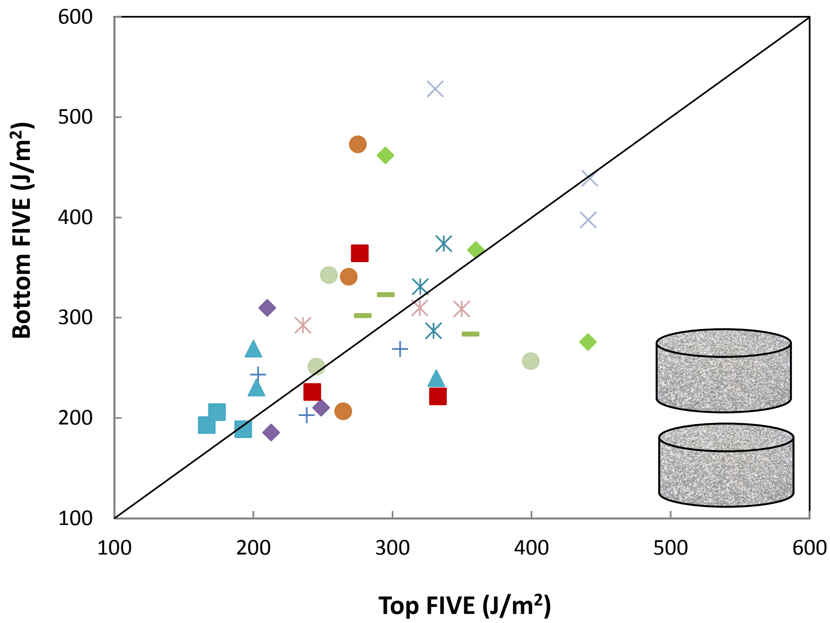

Figure 5.6 Comparing top vs. bottom (from cutting one gyro into two disks)

Also as expected, by going from SCB samples to disks (average of two companion halves), and from disks to gyros (average of two companion disks) data variability decreases. This has been shown in Figure 5.7 (12 SCB's at each lab), Figure 5.8 (6 disks at each lab), and Figure 5.9 (3 gyros at each lab) for Engineering Emulsion (EE) mixture. Other mixtures show about the same trend too.

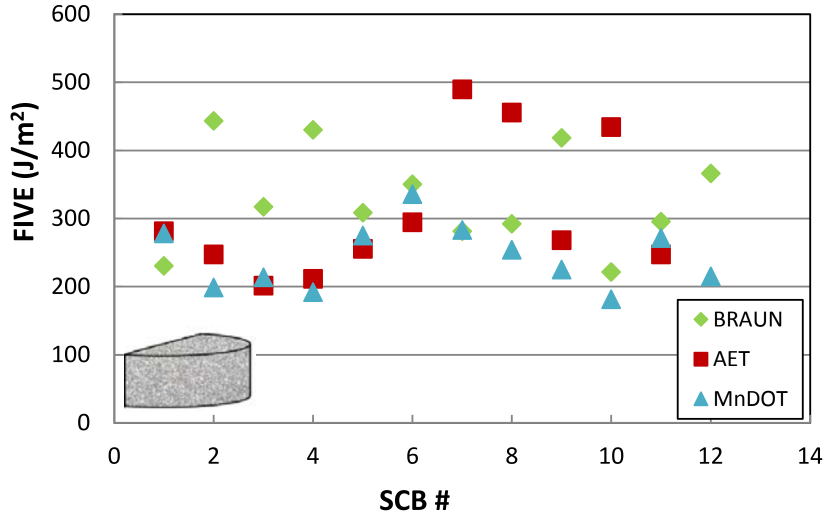

Figure 5.7 SCB FIVE results; all SCB samples

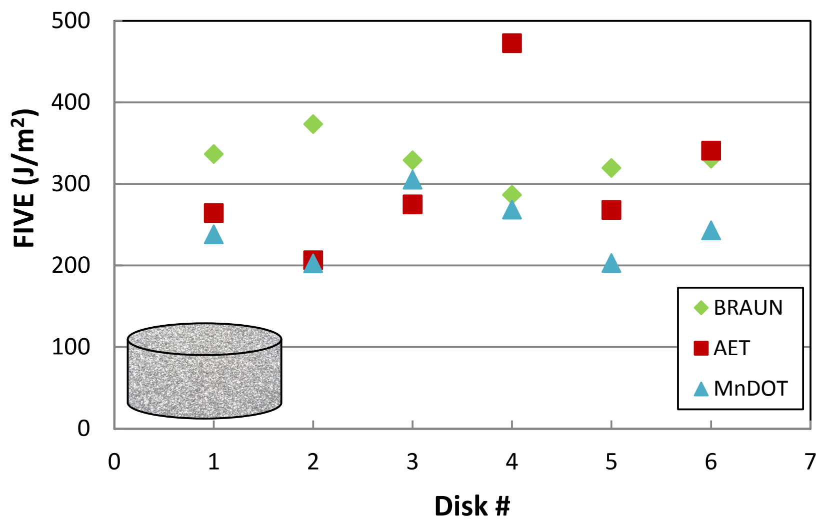

Figure 5.8 SCB FIVE results; disks (average of two companion SCB's)

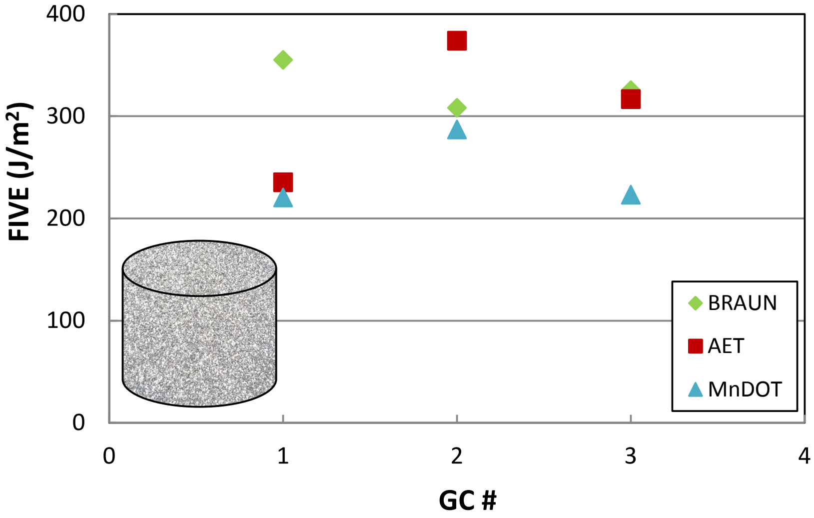

Figure 5.9 SCB FIVE results; gyros (average of four SCB's)

5.2 Machine-to-Machine Variability

As mentioned in the previous section, while all the testing lab results showed about the same trend in terms of mixture rankings, the results from Braun were found to be consistently higher than AET's and MnDOT's values. In order to make sure that the machine-to-machine variability is not affecting the results, the research team decided to run an aluminum validator on all the testing machines. Using a homogenous aluminum validator would diminish the CIR material variability. The validator is expected to result in the same amount of energy once tested in different testing machines.

The validator was designed by the testing machine manufacturer, Testquip LLC, and was fabricated at Braun's machine shop. Figure 5.10 shows the aluminum validator in the testing machine (horizontal setup).

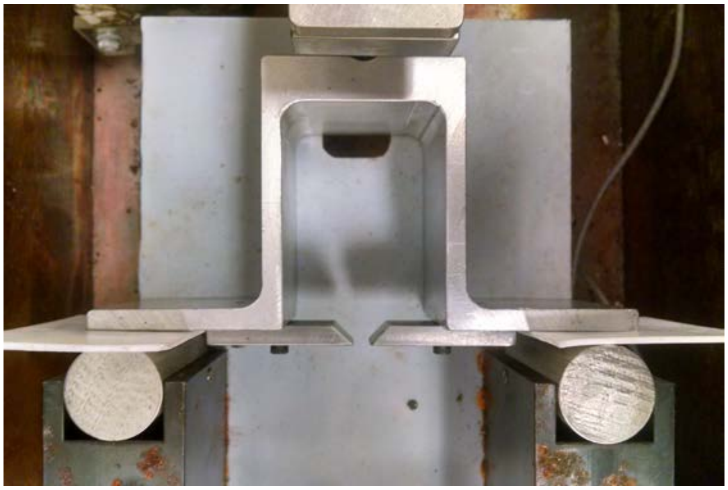

Figure 5.10 Aluminum validator in horizontal setup

Two different Teflon strips (between the sample and the steel rods) were used: 1) the thick Teflon strips which were used for all the testing in this study with a thickness of 1/16 inches, and 2) two back-to-back thin Teflon strips with a thickness of 1/64 inches each.

A total of 11 cycles were performed for each case. The first cycle was discarded and cycle 2 to cycle 11 results were averaged. In each cycle the validator was loaded to a maximum load of 2 kN followed by 1 minute rest. Same procedure was followed on AET's and MnDOT's testing machines.

Figure 5.11 and Figure 5.12 show the validator testing results using thick and thin Teflon strips, respectively. As these graphs show, the data points from an individual machine makes a straight line suggesting that the aluminum validator testing is repeatable and can be used as a validation test. Also, the testing machines have resulted in about the same energy values and, therefore, machine-to-machine variability seems not to be an issue.

It would be interesting to note that the lines seem to collapse better in the case of using thick Teflon strips. The maximum difference between energy values from different machines is less than 1% in the case of thick Teflon and about 3% in case of two back-to-back thin Teflon strips, so it seems that thick Teflon (which was used in this study) is a better option in terms of minimizing the machine-to-machine variabilities.

Comparing the two Teflon setups (thick vs. two thin strips) shows 10-12% higher energy values for the case of two back-to-back Teflon strips. This suggests that employing two thin Teflon strips may be a more efficient way to reduce the friction between the sample and the rods, but as mentioned above, it tends to increase the machine-to-machine variabilities. Figure 5.15 shows Braun's results for both Teflon setups as an example.

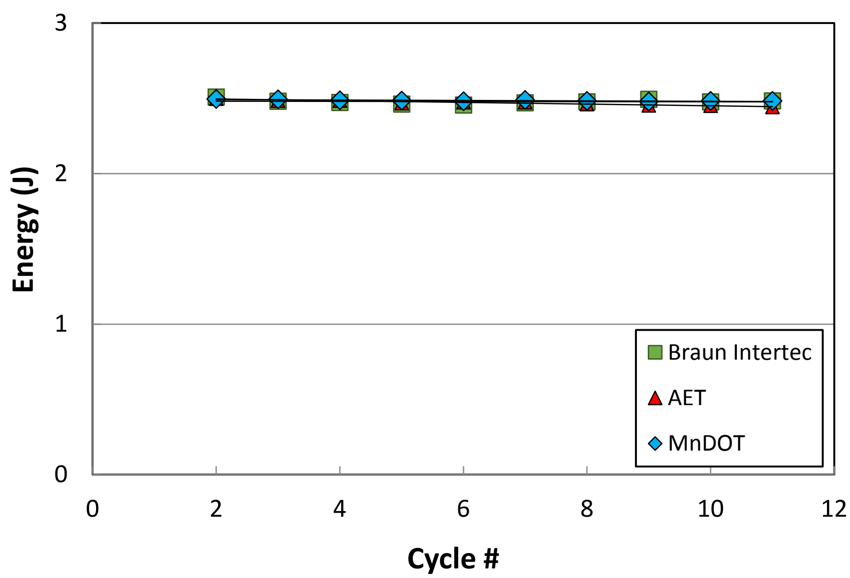

Figure 5.11 Validator results for all three labs with thick Teflon strip

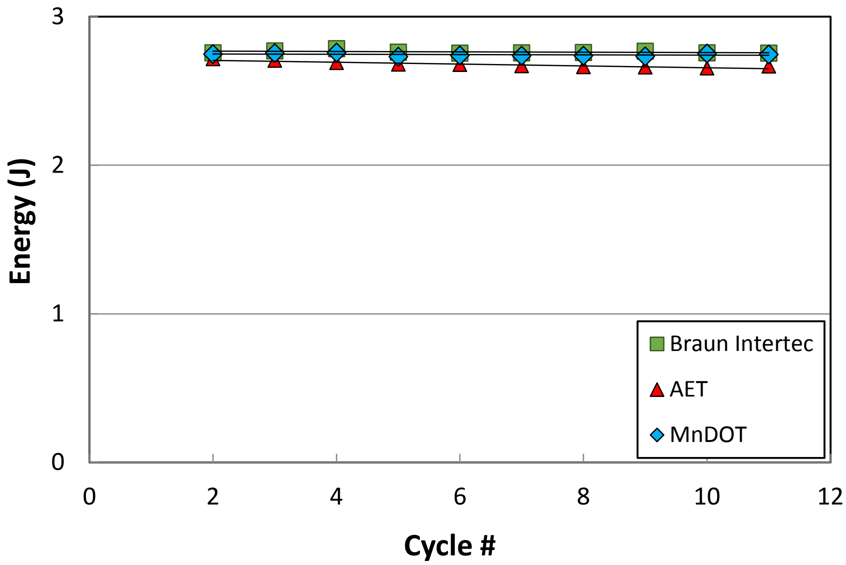

Figure 5.12 Validator results for all three labs with two thin Teflon strips

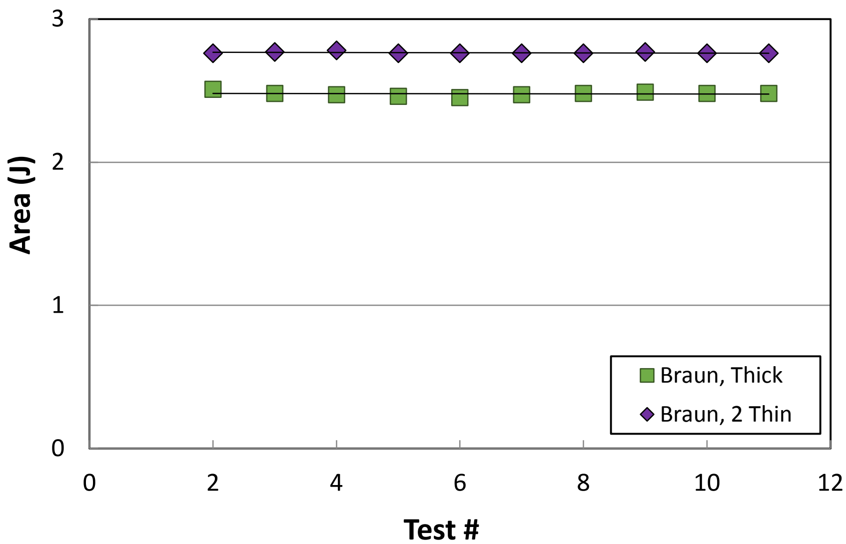

Figure 5.13 Comparing thick and two thin Teflon strips setups at Braun

5.3 Statistical Analysis

Despite all the efforts, the actual reason of Braun's results being consistently higher than MnDOT's and AET's is still unknown at the time of writing this report, so the statistical analysis was performed between the data from AET and MnDOT.

T-test method was utilized for this analysis at the level of significance (alpha) of 0.01. T-test is commonly used to determine if two sets of data are significantly different from each other. Table 5.1 presents the results. As this table shows, p-value is higher than 0.01 for all the four mixtures stating there is not sufficient evidence to conclude that the date sets are different. In other words SCB FIVE testing results are statistically the same between MnDOT and AET testing labs.

Table 5.1 T-test results

Mixture	p-value	Status
Design EE	0.031	Not Significant
CSS1 with Cement	0.012	Not Significant
HFMS-2s	0.366	Not Significant
Foam	0.054	Not Significant

5.4 Suggested Minimum Value for FIVE

It should be noted that specifying a minimum FIVE value as a pass/fail criterion for CIR materials was out of the scope of this research. To better specify a minimum acceptable FIVE value, first test sections using different CIR mixtures should be built and monitored to better relate the FIVE test results to field performances. Also more data points from different CIR mixtures should be gathered.

In order to find an acceptable minimum value for FIVE based on the limited data in this research, the data from AET and MnDOT are shown in Figure 5.14 (Braun's data is excluded). As Figure 5.14 suggest it looks like a minimum FIVE value of 230 J/m^2 could be used as a threshold as a pass/fail criterion of CIR mixture testing. With this definition, CSS-1 with cement mixture fails, while all other three mixtures pass the minimum FIVE of 230 J/m^2, except for the foam mixture tested at MnDOT.

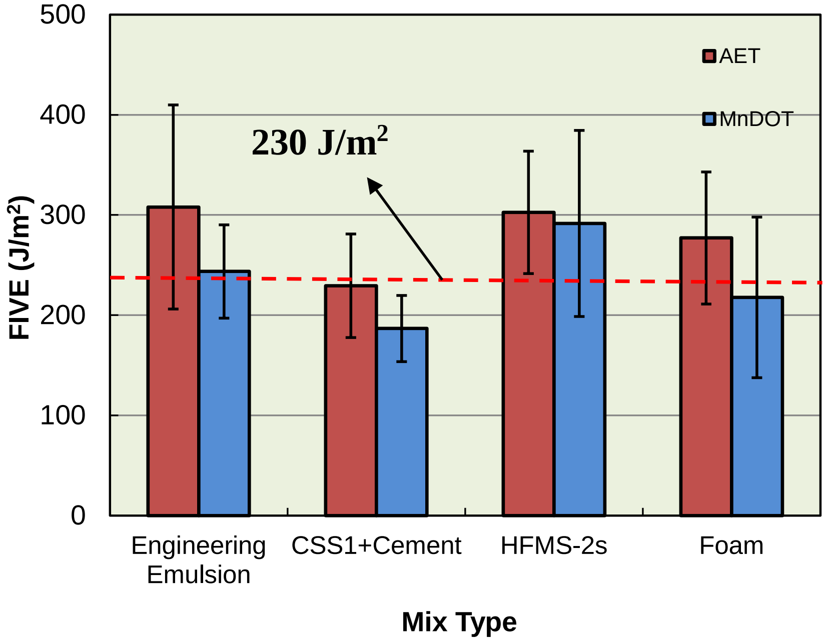

Figure 5.14 FIVE acceptable range

It is also interesting to note that with this definition, even by adding Braun's data we will have:

- Engineering Emulsion: Pass (3/3 labs)
- CSS1+Cement: Fail (2/3 labs)
- HFMS-2s: Pass (3/3 labs)
- Foam: Pass (2/3 labs)

In another words, EE, HFMS-2s, and Foam will pass and CSS-1 with cement will fail in majority of the testing labs.

5.5 Non-Design Mixtures

Two non-design mixtures of: 1) CSS-1 with cement, and 2) foam were made and tested according to Table 4.3 which Figure 5.15 shows the results. The design and non-design mixture performances appear to be statistically the same. It should be noted that these results may be inconclusive because of: 1) a limited number of performance tests were performed on the non-design mixtures (at the same testing laboratory), 2) the selected binder content for non-design mixtures happened to be very close to the optimum binder content of design mixtures, and 3) RAP variability between mix design material and the material that was used for bulk specimen production.

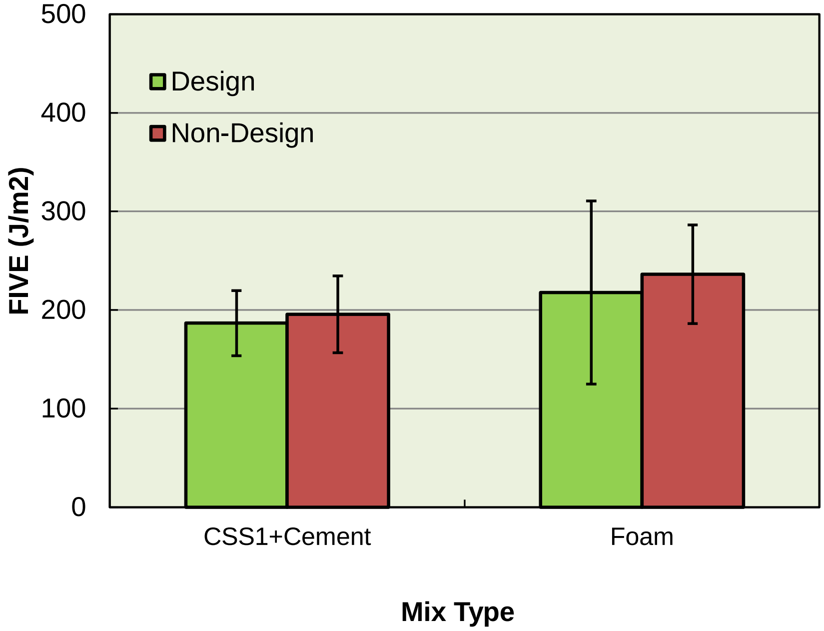

Figure 5.15 Design vs. Non-design results

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In this study, a new performance-based laboratory test, called SCB FIVE, was developed and applied on four different CIR mixtures. Also, FIVE test method lab-to-lab variability was studied through conducting tests at three different testing labs at Braun Intertec, AET, and MnDOT. The findings from this study are as follows:

1) The FIVE concept is a viable option to characterize CIR material behavior.

2) Even though SCB FIVE has not been related to field performance yet, the laboratory test data showed a great potential for SCB FIVE to be used in CIR performance specification.

3) Even though the SCB FIVE test shows more variability than DCT test data, it seems to be a more suitable method, since the data showed that it can provide the same mixture rankings as DCT and also:

    a. It requires less material (one gyratory compacted sample results in 4 SCB samples, while it can only produce two DCT samples)

    b. The sample preparation is easier (it does not require extra cuts and holes)

    c. It provides a better success rate (two DCT samples broke during preliminary testing, while all SCB samples were tested successfully)

    d. It is more practical and can be easily applied in developing QC/QA performance testing to tie field produced mixtures back to project mix designs and thus field validation.

4) Among a total of 162 SCB FIVE tests performed in this study, only three samples failed during testing. This is a success rate of more than 98% which makes the FIVE test even more reliable than DCT testing.

5) Braun's FIVE data were consistently higher than AET's and MnDOT's testing results. Despite all the efforts, the reason is still unknown at the time of writing this report.

6) Statistical analysis suggested AET's and MnDOT's datasets are statistically the same for all four study mixtures (at a level of significance of 0.01).

7) Based on the data of this study, a minimum FIVE value of 230 J/m^2 is suggested. With this definition, CSS-1 with cement will fail and all other three mixtures (EE, HFMS-2s, and foam) will pass the minimum FIVE value of the 230 J/m^2 in majority of the testing labs. A more spread dataset will help achieve a more reliable minimum FIVE value.

8) Test results show that the SCB FIVE test could be a viable quality management test for QC and QA purposes.

Due to the vast potential observed in the SCB FIVE testing method in this study, a wide spread dataset will be required to assure FIVE testing is a viable option for all different types of CIR mixtures on the market. Therefore, the FIVE test is strongly recommended to be considered in all future MnDOT CIR mix design requirements (for information only). The test should also be considered for all future SFDR project mix design requirements (for information only) in order to gather necessary data to determine applicability for mix design and quality management of SFDR projects. The other recommendations are as follows:

1) To better relate the FIVE test results to field performances, we suggest monitoring test sections using different CIR mixtures. We also suggest specifying this test be run for information only on 2016 CIR/SFDR projects in order to gather more data required for performance specification development for 2017 and beyond.

2) Also, to avoid CIR samples from further curing, testing the CIR samples is recommended to be completed during a specific time window once the emulsion is introduced into the mixture.

3) Machine-to-machine variability should be verified periodically as it may bias the testing results. A calibration test on a non-asphalt SCB sample (similar to what was performed in this study on the aluminum validator) is recommended to make sure apparatus measurements are valid.

4) A properly designed CIR mixture along with a proper good quality construction work (including QC/QA procedures) will guarantee a longer service life for CIR applications. A poor construction process (poor compaction, etc.) can waste all the efforts that have taken place in the CIR design stage.

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