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The Investigation of Cold-mix Asphalt Creep Stiffness Testing Using Multiple Test Apparatuses and Gradations

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by

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ABSTRACT

Many current methods of designing and testing Cold In-Place Recycled (CIR) asphalt are undesirable because they require large amounts of material and significant preparation. In an effort to lessen the cost and time of materials testing, this research utilizes several different methods of small scale testing of creep stiffness. These methods include using a Discovery Hybrid Rheometer (DHR) and a three point bending test to find the creep stiffness of emulsion based CIR. The new testing methods utilized samples on the scale of up to a hundredth the size of what the traditional methods of testing require. The two smaller scale tests were compared to the traditional Indirect Tension Test (IDT) testing. In order to fully evaluate the two reduced sample size test methods, this research observed the effect of gradation, temperature, emulsifier type, and Recycled Asphalt Pavement (RAP) content on creep stiffness. If successful, the use of these new test methods could significantly decrease the damage done to roads, and reduce the cost of material management incurred through the quality control testing methods for pavement. Results showed very good correlation between DHR and IDT testing with a proportional difference between the samples. The standard deviations between the DHR and IDT testing were 18.6% and 19.2% of the mean values respectively, indicating similar accuracies of tests. The tests were also able to distinguish between types of material. The proportional difference between the IDT and DHR is expected and is due to the difference of sample and loading configuration. This research begins the validation of using smaller scale DHR tests for CIR stiffness testing.

ACKNOWLEDGEMENTS

Special thanks are due to MeadWestvaco for financial and technical support. Also, I would like to thank Cory Bramlett, Erica Yeung, Kaisha Plambeck, Ken Rutabana and John Ryan who have provided immense help with lab work. I would also like to thank Dr. Andrew Braham for the time and effort he has invested in me both to help me develop and be successful as a graduate student and to become prepared for the world of professional engineering.

DEDICATION

This thesis is dedicated to my wife Anna, who has been a consistent encouragement and motivation for me throughout my graduate studies. I couldn't ask for a better wife and friend to spend all of my life with.

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I. INTRODUCTION

Frequently, the process of designing and testing roads has a high materials demand. The mass of materials needed for testing can be in the magnitude of tons for a single job. The processes of obtaining, transporting, and storing these materials are often very costly, as many times the laboratory for testing materials is located a significant distance from the job. There is a significant need to move towards mix design and quality control methods which are less material demanding.

Several paving technologies have been developed in order to reduce the energy and resource demands of paving. Two common paving technologies are the use of Recycled Asphalt Pavement (RAP) and asphalt emulsions. Asphalt emulsions are used in a wide variety of road construction and maintenance procedures and are able to be used at much lower temperatures. In 2006, 5-10% of the asphalt used in the United States was in emulsified form (1). Asphalt pavement is the most recycled material in the United States with almost 30 million tons of RAP used annually (2). Both of these technologies are utilized in the process of Cold In-place Recycling (CIR), which uses asphalt emulsion and RAP to create new pavement at ambient temperatures.

Research (3) has compared the life-cycle environmental analysis of CIR construction methods to that of hot-mix asphalt alternatives. Results show that CIR options are much more desirable than traditional hot-mix asphalt from an environmental perspective. There has been a significant amount of research conducted to understand CIR performance. Fairly common mix design practices (4) include testing raveling through wet track abrasion testing, and thermal cracking through the use of IDT creep testing at low temperatures. Superpave shear testing and the use of

an Asphalt Pavement Analyzer are also commonly used in mix design. The IDT creep data can be used to model thermal stress in a material, which can be combined with tensile strength data also obtained from IDT testing to calculate critical cracking temperature. Research which compared emulsion based CIR with a lime slurry and a fly ash based CIR section of road showed that emulsion based CIR performed significantly better (5). This was concluded to be related to material creep compliance which is the inverse of creep stiffness. The compliance was significantly higher for the emulsion based material. This high compliance indicates a resistance to thermal stress and therefore thermal pavement cracking.

Asphalt emulsions have been used since the early 1900's. The technology has been significantly refined and specialized over the last 20 years (6). Emulsions are a desirable alternative to cut-back asphalts (asphalt dissolved in diesel fuel) because they are more environmentally friendly and in many cases, cheaper. Most of the research has allowed the production of emulsions which are more specialized for specific uses. Emulsions are classified by both the pH which they are effective, the reaction speed at which the chemistry will set and break as it contacts new surfaces and the modification of original binder. Emulsions are used in a wide range of pavement applications such as spray seals, tack coats, chip seals, waterproof coatings, slurries, microsurfacing, full mixture paving, cold in-place recycling and patching.

In regions where temperatures frequently drop below freezing, thermal cracking of asphalt pavement is a significant problem. Creep stiffness is one of the inputs required for the prediction of low temperature performance using both the Mechanistic Empirical Pavement Design Guide (MEPDG) and Superpave mix design. There are three current test methods for predicting asphalt thermal stresses at low temperatures. They are Indirect Tensile Test (IDT) conducted according to AASHTO T322-02 (7), the Thermal Stress Restraint Specimen Test (TSRST) conducted

according to AASHTO TP10 (8) and the use of a Bending Beam Rheometer (BBR) described by AASHTO T313 (9). IDT and TSRST testing have been proven to accurately predict low temperature properties, however, both tests are logistically and financially undesirable for use in general quality control because they require large samples, long sample conditioning times, expensive specialized equipment and gauges, complicated analysis and routine calibration. The BBR test dictated by AASHTO T313 is used for finding the creep stiffness of asphalt binder only. There has been a significant amount of research (2, 10-12) which sets the groundwork for a BBR and other types of three point bending tests to be used to find creep stiffness data of Hot Mix Asphalt (HMA) beams. The Dynamic Shear Rheometer (DSR) Creep Test has been developed (13) by Mathy Technology and Engineering Services (MTE). This is a small scale test designed for simple and quick quality control of HMA rutting. These new, smaller scale tests have taken significant strides to reduce the time and resource demand of material testing for HMA testing, however little experimentation has been done in this area with other types of asphalts. Many current methods of designing and testing Cold In-Place Recycled (CIR) asphalt are undesirable because they require large amounts of material and significant preparation. Other testing (12) has shown that the variation of the creep stiffness of samples does not significantly increase or decrease as the gradation is altered. This study compared the variances of creep testing done using 12.5mm, 9.5mm and 4.75mm mixtures, and determined the variances to be equal between the three mixtures. It is also stated that a typical asphalt materials testing has a coefficient of variation of approximately 20%.

Creep stiffness, especially at low temperatures, is largely dictated by the stiffness of the mastic which is formed as the asphalt binder mixes with the fines. Research has shown (14) that the reasonable predictions of creep stiffness can be modeled through finite element reproduction of

real samples. These models used images of full mixture samples to differentiate asphalt mastic and aggregate. The inputs of asphalt mastic viscoelastic properties were entered along with the assumption that aggregate were rigid. The predicted creep stiffness was similar to laboratory tests conducted. Other research (15) measured the linear viscoelastic properties of asphalt mastics using a dynamic shear rheometer (DSR). This research determined that the ratio of mastic to asphalt had a significant effect on the range of the viscoelastic limits, and stiffness of the material. The chemical properties and the gradation of the filler in the mastic also had significant impacts on the viscoelastic properties of the mastic. This is true for CIR material as well as hot mix material. Research conducted by North Carolina State University (16) studied the effects of changing the scales of materials and asphalt material. This work showed the sensitivity material properties to changes in many aspects of asphalt mastics and volumetric properties both in laboratory testing, and through computer modeling. The results showed that asphalt mastics were insensitive to lower end filler volume changes, until a point where mixtures become much more sensitive.

The objective of this experiment was to compare the creep stiffness results from IDT testing of emulsion based CIR asphalt to the results obtained from a three point bend test and a variation of DSR creep testing. This was conducted in an effort to explore more desirable options for low temperature quality control of asphalt. This experiment also observed the effect of gradation, temperature, emulsifier type, and RAP content on creep stiffness.

II. TEST DESCRIPTION

The three tests which were used for evaluation in this experiment are IDT, 3 point bending test and a Discovery Hybrid Rheometer(DHR) test. IDT creep stiffness test was conducted according

to AASHTO T322-07 (1) on a cylindrical specimen 150 mm in diameter by 37-50 mm height. The sample was positioned and loaded vertically across the diameter and the vertical and horizontal strain of each face was measured. The three point bend test was conducted on a rectangular bar with a cross section of 30x 35 mm and a span of 120 mm. A point load was applied to the sample at mid-span and the mid-span deflection was measured from the bottom of the sample. The third test was conducted using a Discovery Hybrid Rheometer (DHR), which is a newer model of a Dynamic Shear Rheometer. One end of the long dimension of a 12.5x 12.5x 50mm bar was loaded in torsion, while the other was held rigidly in place. The rotation of the torqued end was recorded throughout the test. The IDT, three point bend, and DHR tests utilized samples which are approximately 1600, 350 and 16 grams respectively. An image of each of the test configurations is shown in Figure 1. All tests were loaded for a 1000 second period and targeted deflections around 50 to 500 microstrains in order to have measurable deflections above inherent noise and not exceed the linear viscoelastic behavior limit.

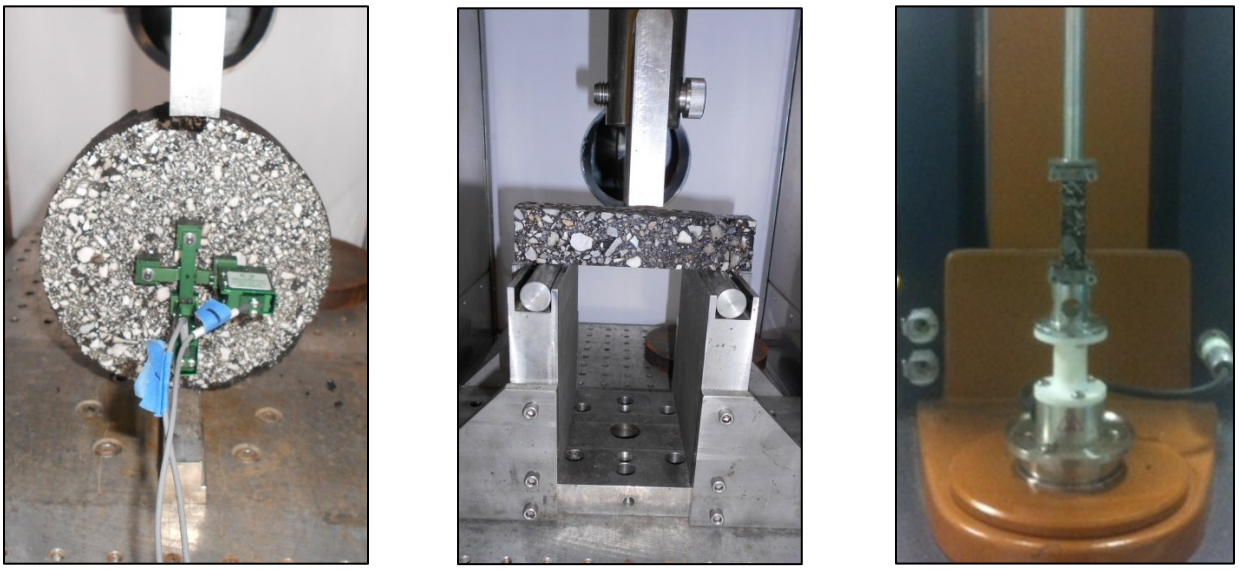

Figure 1: Images of the three testing configurations; IDT (left), three point bend (center) and DHR (right). Photos taken by Author

III. EXPERIMENTAL MATRIX AND MATERIAL

A. EXPERIMENTAL MATRIX

For this experimental plan, 302 tests were run on 108 samples with 9 different mixtures. The variables are listed in Table 1 below and the mix design is described in Table 2 below. The optimum emulsion content was determined through measuring the Marshall Stability at multiple emulsion contents. The emulsion content for reduced gradations was calculated by adjusting the emulsion of full gradation to attempt and maintain similar film thickness between samples. This was based on surface area increase. A partial factorial design of Table 1 was conducted.

Table 1: Experimental Plan

Variable	Number of Options	Options
Testing Apparatus	**3**	**Indirect Tensile Test (IDT)** **Three Point Bend Test** **Discovery Hybrid Rheometer (DHR) Torsion Bar**
Gradation	**3**	**Full (original) Gradation** **Half Gradation** **Quarter Gradation**
Emulsifier	**4**	**Fast Set** **Medium-Fast Set** **Medium-Slow Set** **Slow Set**
Temperature	**3**	**-10°C** **-20°C** **-30°C**
Material	**2**	**Recycled Asphalt Pavement (RAP)** **AHTD Class 7 Virgin Aggregate (Class 7)**

B. MIX DESIGN

Table 2: Mix Design

	Mixture (% passing shown)				
Sieve Size	**Full Class 7**	**Full RAP**	**Half Class 7**	**Half RAP**	**Quarter Class 7**
1”	100	100	100	100	100
3/4”	93.3	93.3	100	100	100
1/2”	86	86	100	100	100
3/8”	76.3	76.3	93.3	93.3	100
#4	51.3	51.3	75	75	93.3
#8	35	35	48	48	75
#16	18.3	18.3	26	26	48
#30	11.5	11.5	16	16	26
#50	5.5	5.5	9.5	9.5	16
#100	3.2	3.2	7	7	9.5
#200	2.4	2.4	4.8	4.8	7
#400	Retained on pan	Retained on pan	3.65	3.65	4.8
#500			Retained on pan	Retained on pan	3.65
#635					3.37
#850					2.88
Water (by mass)	0.02	0.02	.02	.02	.02
Emulsion (by mass)	0.07	0.029	.14	.058	.14
Binder Content	4.55%	1.89%	9.1%	3.77%	9.1%
Binder Grade	PG 64-22				
Design Gyrations	30				
Gmm	2.412	2.447	2.428	2.411	2.428
Air Voids	24%	20%	15%	21%	21.7%

C. SAMPLE GRADATION REDUCTION METHODS

The gradations of the three mixtures are shown in figure below.

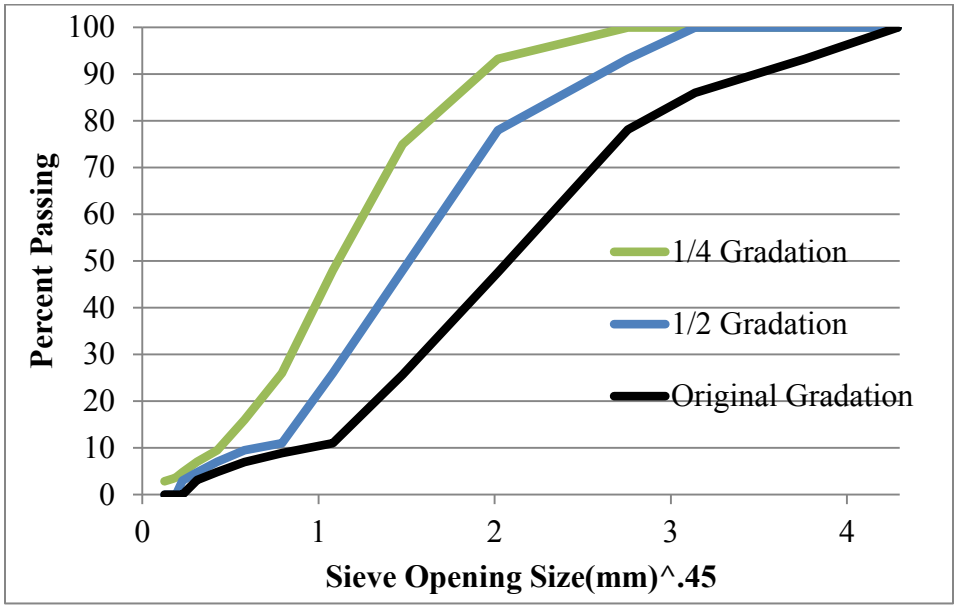

Figure 2: Gradation of Reduced Samples

Film Thickness

In order for the miniaturized samples to behave similarly to the larger samples, there was a question of if the binder film thickness should be similarly reduced, or kept the same. The reduced sample sizes required additional binder in order to maintain a consistent film thickness as surface area increased. The design for reduced gradation materials attempted to increase binder thickness proportionally to the increase in surface area of the finer material. The surface area has been determined using several methods of evaluation, including the Hveem method, the Duriez and Arrambide method (17) and a surface area to volume based calculation made assuming all particles to be spherical.

Because the spherical assumption was the only method with a means to calculate the surface area of coarse aggregate, the surface area was calculated for the coarse aggregate (retained on a number 4 sieve) then weighted with the previous methods. This was used to get an estimate of the full mix specific surface area from each mixture. The equations of the three methods are shown below.

Hveem Method:

$$S_s = \Sigma \; S_{af,\,No.} \times P_{No.} \qquad [1]$$

Where:

$S_{af,\,No.}$ is the surface area factor for sieve number No.

$P_{No.}$ is the percentage passing by weight that sieve.

The sieves No. 4, 8, 16, 30, 50, 100 and 200 have the respective coefficients of .41, .82, 1.64, 2.87, 6.14, 12.29 and 32.77 m^2/kg.

Duriez and Arrambide method:

$$S_s = 135A + 12B + 2.3C \qquad [2]$$

Where:

A=Percentage by weight of the fractions finer than .08mm

B= Percentage by weight of the fractions between .315mm and .08mm

C= Percentage by weight of the fractions between 5mm and .315mm

Spherical Assumption:

$$S_s = \Sigma \; S_{af} \times R_{No.} \qquad [3]$$

Where:

$R_{No.}$ is the percentage of material retained on the sieve which passed the next largest sieve

S_{af} is (d/2)^2*4/((d/2)^3*4/3)/Gs

Where d is the average of the two sieve openings and Gs is the specific gravity of the material

The results of the three evaluations are shown below in Figures 3 and 4.

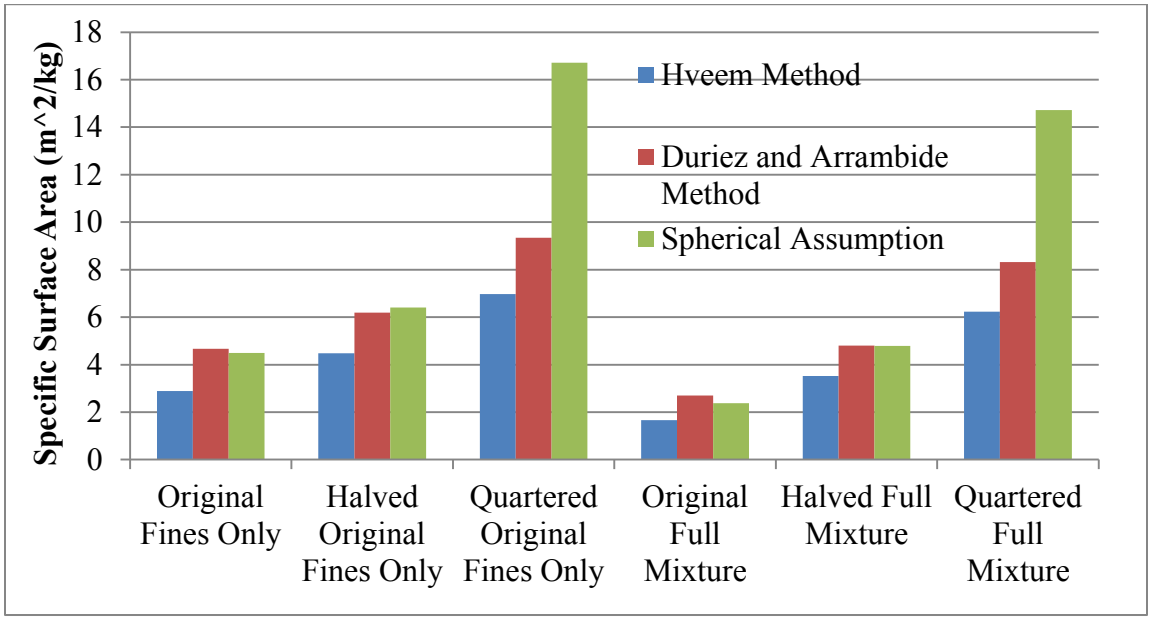

Figure 3 – Surface area prediction from different methods

In order to keep the film thickness consistent for all samples the binder needed to be the increased somewhat proportionally to the surface area. The graph below shows the ratio for each

method between the original and halved gradation (A) and between halved and quartered gradation (B).

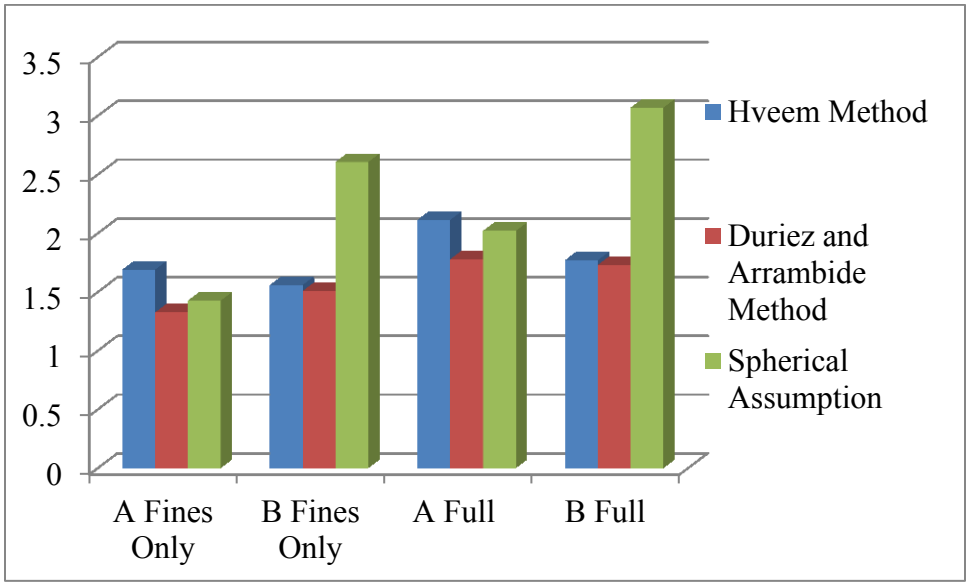

Figure 4 – Specific surface area ratios between:

A-the original and halved gradations and

B-the halved and quartered gradations

As was expected, the ¼ gradation had a significant difference using the spherical assumption. In order to try to compare these samples while taking the fines into account, a formula developed by Craus and Ishai (18) was used to analyze only the P200 material. The Craus and Ishai method is very similar to the Hveem methods, with the exception that it only takes into account P200 material. The sieve openings sizes used are (in microns) 74,60,50,40,30,20,10 and 5 with the respective coefficients 34.72, 41.67, 52.08, 69.44, 104.17, 208.33, 416.67 and 718.39. The coefficients were linearly interpolated to match sieves No. 200, 400, 500, 635 and 850 with

opening sizes (in microns) of 74, 38, 25, 20 and 10. The results were weighted with the R200 material originally predicted by each method. The results are shown below in Figure 5:

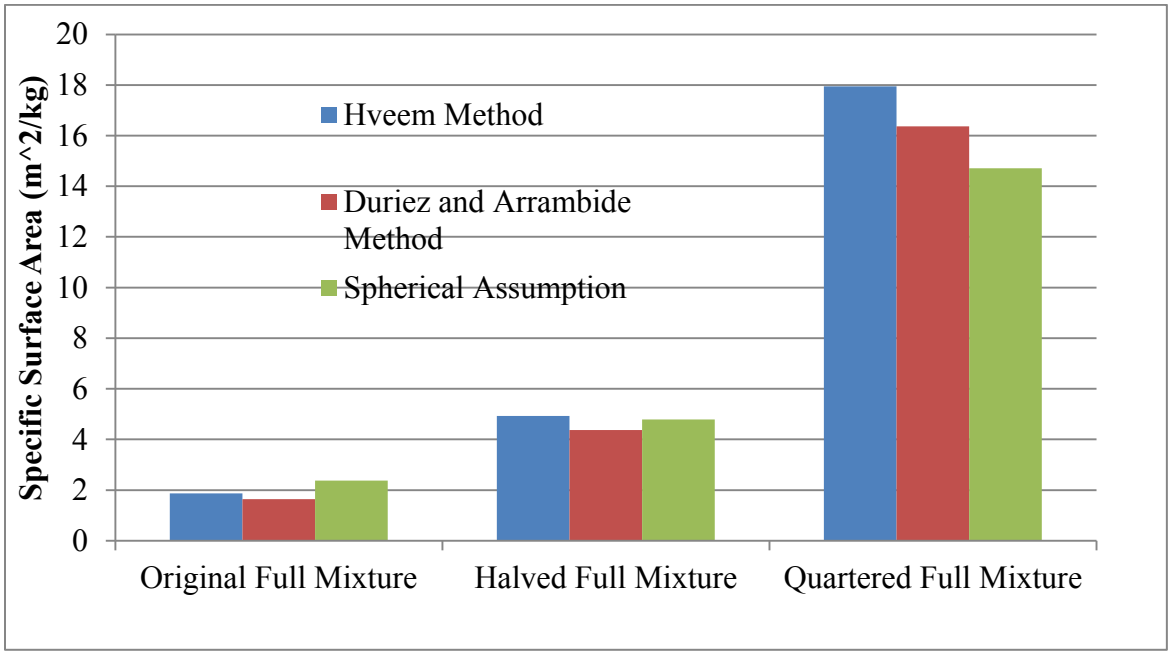

Figure 5: Specific Surface Area predictions with the fines predicted using Craus and Ishai methods

From these numbers, a binder increase of 2 from the original to the halved and for the halved to the quartered gradation was chosen. These numbers are not exact, and will require further testing. This was used to determine the mix design for the reduced samples sizes.

D. SAMPLE PREPARATION

The following procedure was used for sample production:

1. Weigh out appropriate gradation of materials, begin to mix in bucket mixer
2. Add water content slowly as soon as the material begins mixing
3. Allow 1 minute of mixing, add emulsion content slowly, allow 1 more minute of mixing
4. Compact the mixture to 30 gyrations in a 150 mm mold
5. Oven cure for 48 hours at 60°C
6. Freeze sample for at least 2 hours
7. Samples cut for:
    a. IDT
        i. Top 5 mm cut off to ensure a smooth surface
        ii. 150 mm diameter cylinders cut with a height of 37-50 mm
    b. Three Point Bend Samples
        i. Samples cut vertically into 30 mm rectangular slices
        ii. Slices cut into 30 x 35 mm bars
    c. DHR
        i. Top 5 mm cut off to ensure a smooth surface
        ii. 150 mm diameter cylindrical slices cut with a height of 12.5 mm
        iii. Tile saw used to cut the slices into 12.5 mm wide strips (12.5 x 12.5mm cross sections)
        iv. Strips cut to 50 mm length, ensuring a 5 mm clearance from the outside surface to prevent any surface irregularities from altering the sample

Much of this process was similar to HMA fabrication, with a few modifications. The water was added to the mixing to ensure an even coating of emulsion over the aggregate. The curing period was provided in order for the emulsion to have time to break and allow the water in the mix to evaporate. The samples were frozen for two hours after the curing period in order to stiffen the binder so they could be cut into their respective geometries without the samples being damaged.

E. DIMENSIONAL MEASUREMENTS

The dimensions of the DHR and three point bend samples were calculated by averaging four measurements of the width and thickness for each beam. The measurements were taken along the length at end points and two evenly spaced points along the length. This dimensional information was input individually for each sample to calculate the stress and deflection used in calculating the creep stiffness. All measurements were made with digital calipers.

The dimensions for the IDT creep samples were taken according to AASHTO T322-07. The diameter and width of the samples were all measured three times and used in the calculations according to the specifications.

F. CALCULATIONS FOR CREEP STIFFNESS

The IDT creep compliance was calculated according to AASHTO T322-07 (1) according to Equation 4

$$D(t) = \frac{\Delta X \cdot Davg \cdot bavg}{Pavg \cdot GL} \cdot Ccmpl \quad [4]$$

ΔX- the average of the middle 4 of 6 horizontal deflections measured, the high and low values were discarded(mm)

Davg- Average diameter for specimens(mm)

bavg- Average specimen thickness(mm)

Pavg- Average load (kn)

GL- Gauge length (38 mm)

Ccmpl- Parameter for creep compliance which is calculated by

$$Ccmpl = .6354(\frac{X}{Y})^{-1} - .332 \quad [5]$$

X- Horizontal Deflection at t=500s (mm)

Y- Vertical Deflection at t=500s (mm)

The creep stiffness from the three point bend test was calculated through the Bernoulli-Euler law of elementary bending theory. This calculation was also made with the high and low extreme value removed, and the stiffness was taken as the average of the middle values. This requires the assumption that plane sections remain plane, the material is isotropic and vertical deflections and rotations of the beam are very small. With these assumptions creep stiffness can be calculated through the following equation:

$$S(t) = \frac{Pl^3}{48I\delta(t)} \quad [6]$$

S(t)- Creep Stiffness

P- Load on the center of the beam

L- Beam span(120mm)

I- Cross sectional moment of inertia of the beam

δ(t)- Midpoint deflection over time

The DHR Creep stiffness was computed as a function of the given inputs of dimensions, torque load and rotational deflection. The strain was calculated according to Equation 7.

$$S(t) = \frac{\varepsilon_{xy}}{\frac{r}{J_T}\tau} \quad [7]$$

S(t)- Shear creep stiffness

ε_{xy}- Shear strain ($\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$)

r- Distance from centroid to outermost point of cross section

J_t- Torsional constant

τ- Applied torque

Similar to the other two tests, the extreme high and low values were removed in the calculation of the average. It should be noted that the value computed by the DHR is stiffness in shear, whereas the values computed by the other two tests are stiffness values in tension. There will be

an expected proportional shift between the DHR and other data, which will be related to the Poisson's ratio of the material. (19) It should be both temperature and material dependent.

IV. RESULTS AND DISCUSSION

The stiffness values at 16, 60, 120, 240, 500 and 1000s were recorded from each test. The materials themselves also had distinct trends which reflected similarly across the three tests. The results of testing the different materials are shown below in Figure 6. The Full Class 7 material held together poorly and had difficulty being compacted and sawed. It became clearly damaged during the IDT testing, at strains which should have been nondestructive. The Full Class 7 data was inconsistant and is therefore not included on the figures. The results given are from testing at -10°C and represent the typical results.

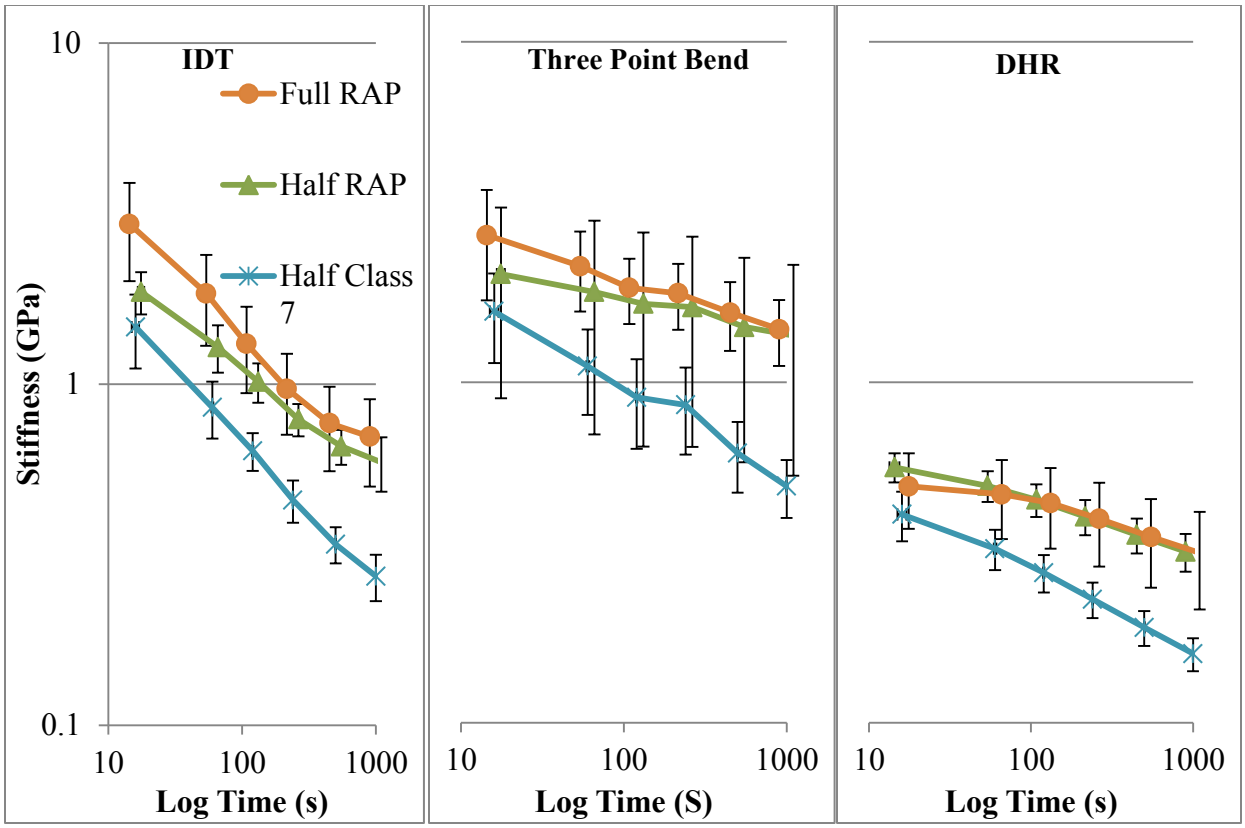

Figure 6: Results of material tests using the slow setting emulsifier at -10°C. The error bars represent the standard deviation of the sample. The graphs have been slightly offset in order to make the error bars more readable.

As can be seen by these graphs, the data collected by these tests had similar shapes with different slopes and magnitudes. The three point bend test, and IDT test have roughly the same magnitude of stiffness values, whereas the DHR test reports values which are significantly less stiff. This is expected because the DHR measures the shear stiffness of the material, whereas the three point bend test and IDT both measure the tensile stiffness of material. The difference is a result of test loading. The IDT creates a tensile force in the samples and measures the strain around the area which is put into indirect tension, whereas the DHR provides a force in torsion for the sample and measures the rotation of the sample. These properties are related to each other in a manner

which should vary with the Poisson's Ratio. Future work obtaining a Poisson's Ratio from each of these samples and using that to relate the IDT and DHR tests could provide useful data to better relate the tests. There was some difficulty with the three point bend test in differentiating the initial creep compliance from the entire sample's slight movement or wiggling as a load was introduced. This is most likely what accounts for the standard deviation being significantly higher on the three point bend test than on the other two tests. The trend of the Half Class 7 material being significantly less stiff than the other materials was reflected in all three test methods. This is possibly due to the higher binder content, which is less stiff than aggregate.

When all three tests were compared for each configuration of testing and temperature, the trend was that the DHR stiffness was significantly lower than the other graphs, whereas the IDT graph started out the highest, but was surpassed by the three point bend data midway through the test. The three point bend and DHR tests are roughly parallell in almost every test. The average coefficient of variation of DHR tests was .186 and the coefficient of variation for IDT averaged .192. The three point bend tests had a coefficient of variation of .448.

Samples with each of the four different emulsifiers were tested using full RAP mixtures in the DHR. The results are shown below in Figure 7. There seemed to be a trend with the emulsifiers that the faster setting emulsifiers resulted in stiffer mixtures. This difference was most likely caused because of the set speed of the emulsifiers. The level which the mixture has "set" will affect how well the material can be compacted. The trend was observed that the two faster setting emulsions had a bulk specific gravity of 4.4% higher than the slower setting emulsions. The binder content and aggregates were identical between the samples. This indicated the faster setting emulsifiers compacted better. However, the standard deviation between the emulsifiers was quite large compared to the difference in range. The standard deviation of the slower

emulsifiers was higher than that of the faster emulsifiers. This is magnified by using a log scale, but is consistent even at a normal scale.

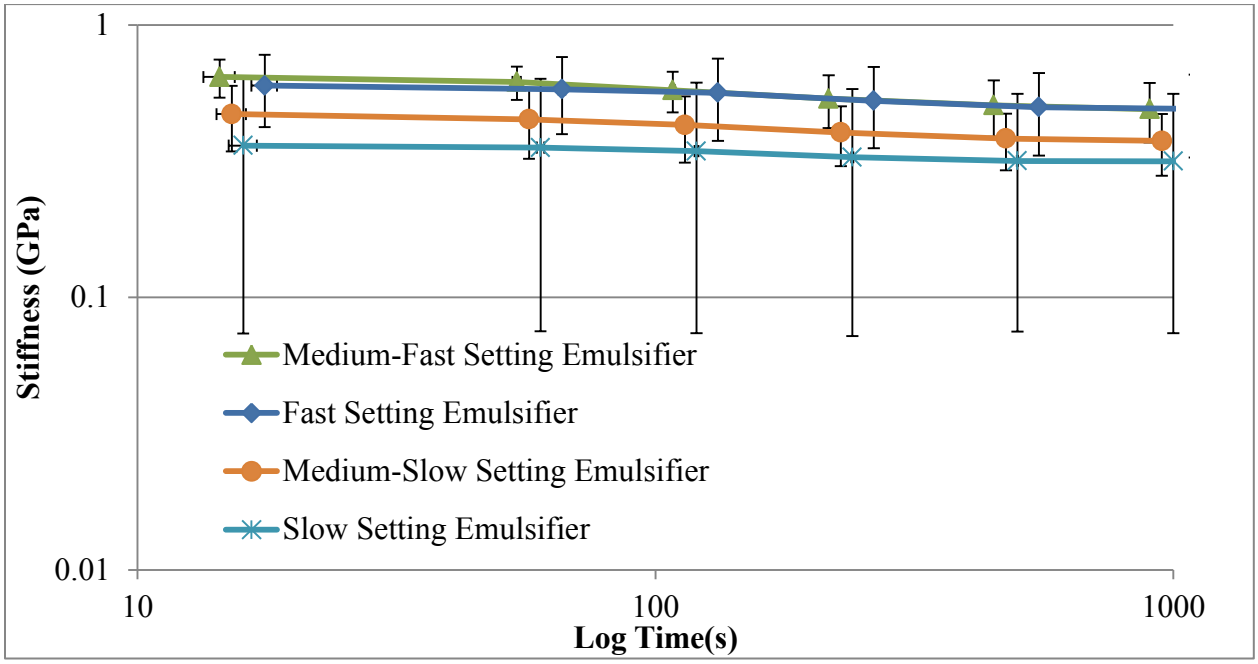

Figure 7: Stiffness results of the four different emulsifiers from DHR testing using Full RAP material at -10°C

The Full, Half, and Quarter gradations were also compared for the Class 7 material. Figure 8 below shows the results of the three materials from the DHR at -10°C. As can be seen by this graph, as the gradation of materials decreases, the stiffness gets lower, and the standard deviation increases. As the mixture became finer, the specific surface area increased. Because of this, the emulsion content was increased between full and half gradation to try and maintain a consistent film thickness for the aggregate. Binder has a much lower stiffness than aggregate, so having a higher binder content in the finer mixtures could be why stiffness was lower for the half mixture than the full mixture. When the emulsion content was increased again between the half and

quarter gradation material, the material became “soupy” and was not able to be compacted or formed into a sample. Even after curing this mixture for two days, it was able to be permanently deformed through being pressed on with a finger. The same amount of binder was therefore used between the half and quarter samples. Because there was more surface area for the emulsion to cover in the finer mixtures, there could be areas of the mixtures which were uncovered, and therefore far less stiff. These materials would have distinct asphalt mastic characteristics, and therefore would be expected to have different properties.

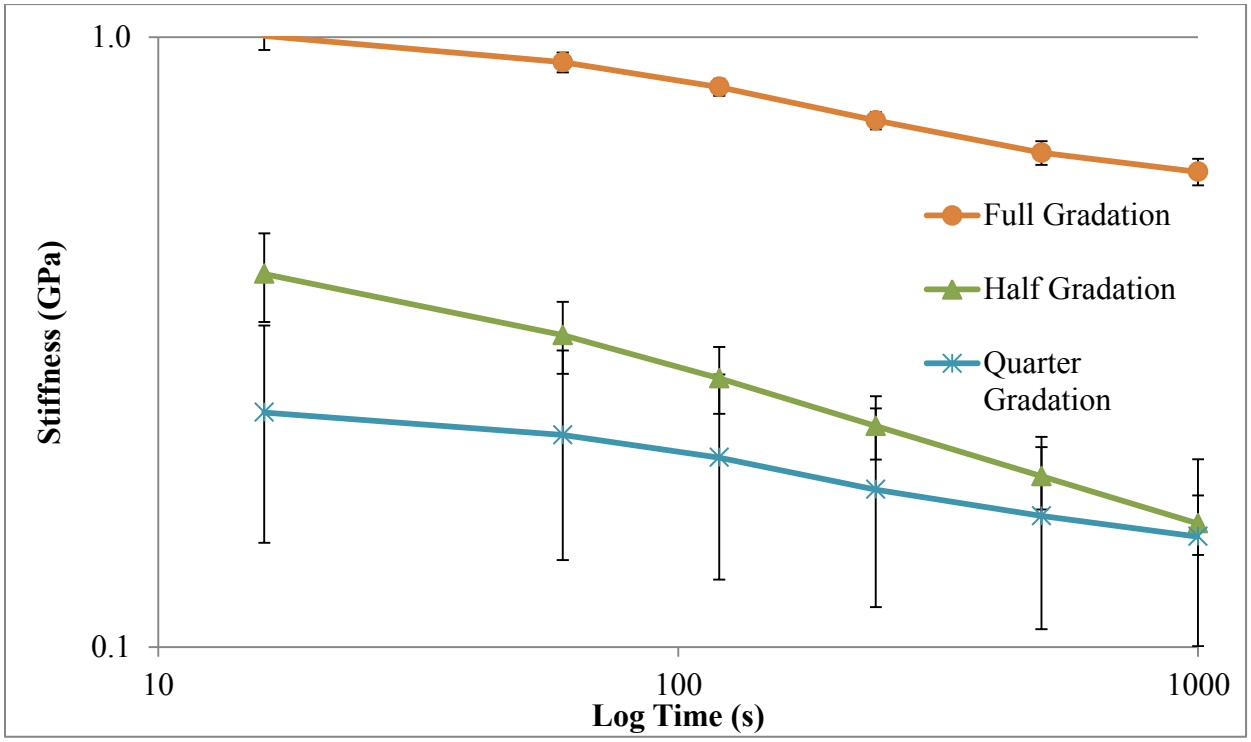

Figure 8: Quarter, Half, and Full Gradations of Class 7 material from the DHR test using the slow setting emulsifier at -10°C

When the results of the DHR and IDT stiffness graphs were plotted against each other, the results could be modeled well by a linear trend line (R^2=.86-.98). The results of the DHR test

were all lower than the IDT results. The three point bending test had results which were similar in magnitude as the IDT results, however the deflections for the three point bend test occurred much faster and peaked sooner than those of the IDT test. The results of three point bend testing and IDT stiffness could also be modeled with a linear trend line for -10°C and -20°C, but most of the results at -30°C had very poor correlation. Figures 9 and 10 show typical results of plotting the three point bend and DHR tests against the IDT test.

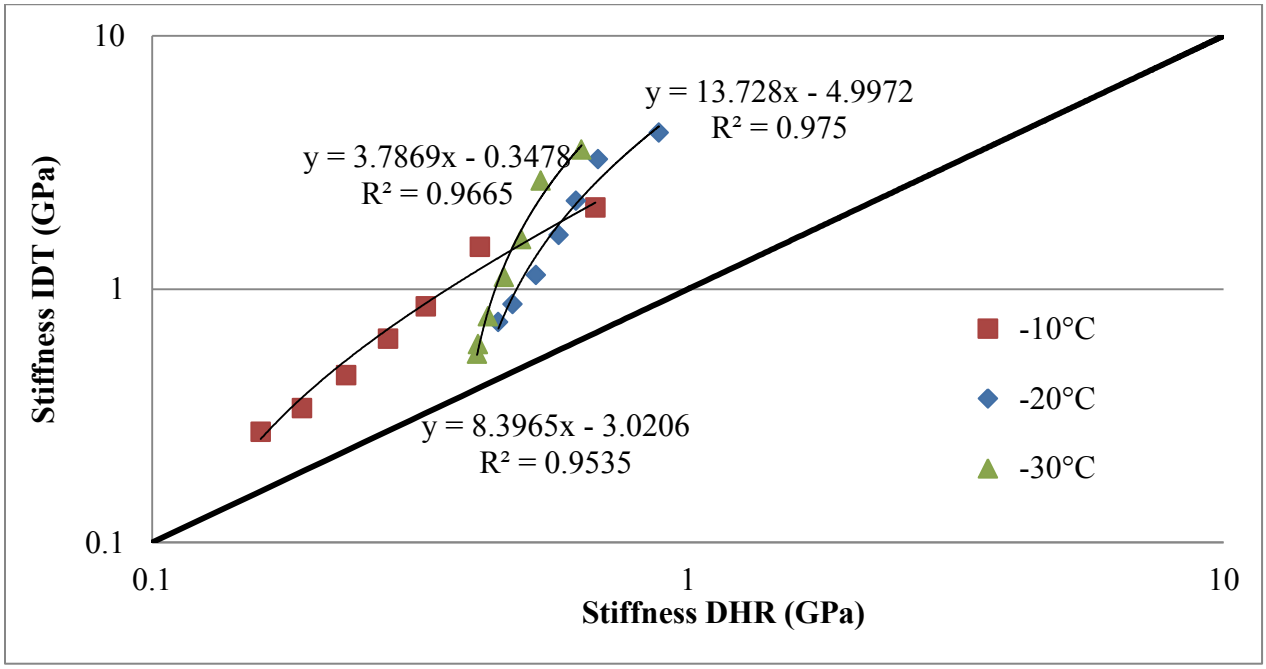

Figure 9: Results from comparing IDT and DHR Testing using slow emulsifier and Half RAP material

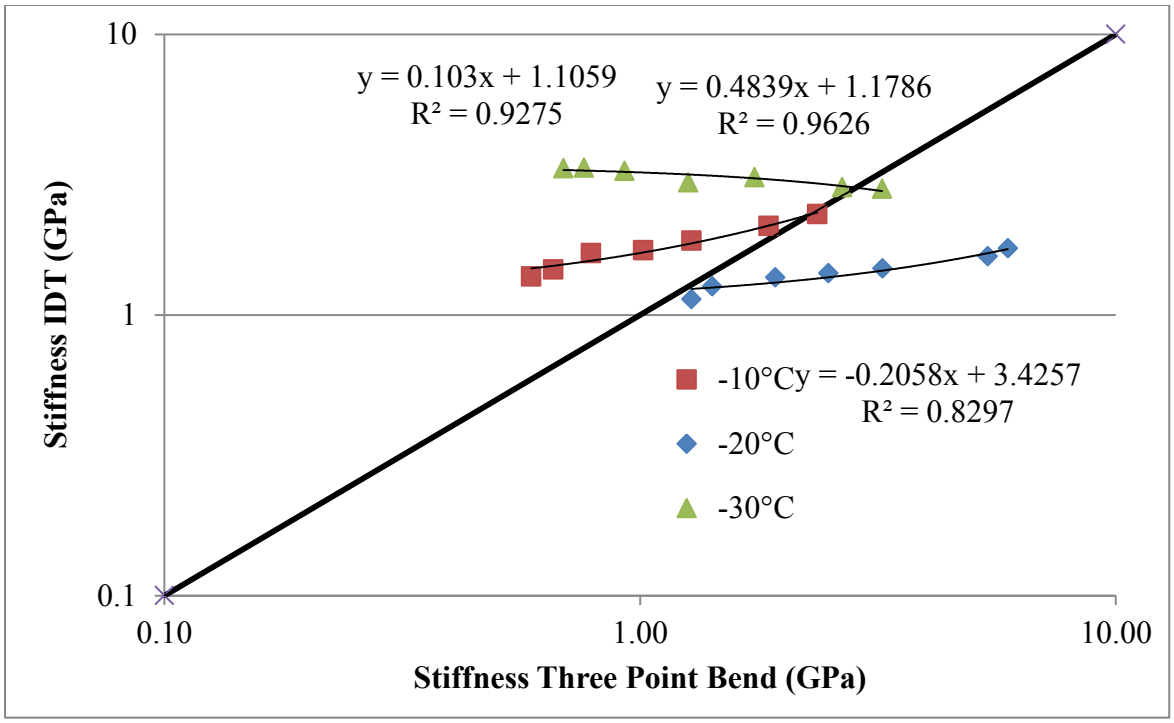

Figure 10: Results from comparing three point bend and DHR testing using slow emulsifier and Half RAP material

Because the DHR is measuring the shear stiffness, a shift factor should be applied to the results before it is compared to testing in tensile stiffness. This shift factor is linked to the Poisson's Ratio and will therefore change with material and temperature. Multiplying the results of DHR testing at -10°C by 2.53 created stiffness data which was very similar to IDT testing. The shifted graph for DHR and IDT testing is shown in Figure 11. The shifted graph for DHR and three point bend testing used a factor of 3.86 and is shown in Figure 12.

The creep stiffness values at 500s measured with through DHR and IDT were compared using a shift factor of 1.85. From this data the difference of means between Half Class 7, Half RAP and Full RAP was respectfully 3.9%, .3% and 15% of the mean value for IDT. The 95% confidence interval range for the expected difference between the DHR results and shifted IDT results was

18%, 11% and 41% of the mean. The 95% confidence interval of the IDT results varies respectively at 20%, 19% and 46%. The effect of this difference was evaluated using the MEPDG. No difference was found in the results between values calculated with the standard creep stiffness values and values 20% greater than standard. The MEPDG analysis is not very sensitive to creep stiffness values. This has also been confirmed through other reports as well (20). This test was conducted using the climate of Indianapolis, IN using a traffic value of 2000 average annual daily truck traffic.

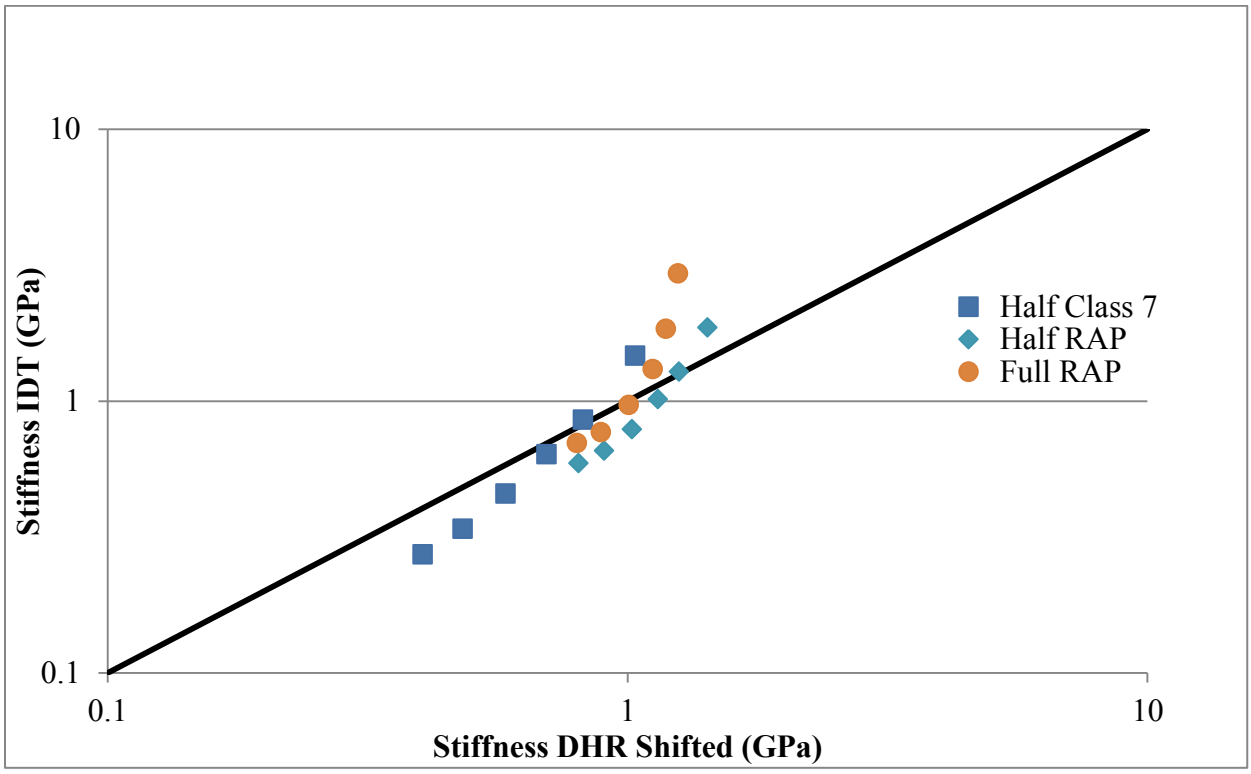

Figure 11: IDT and Shifted DHR results from slow setting emulsifier tested at -10°C

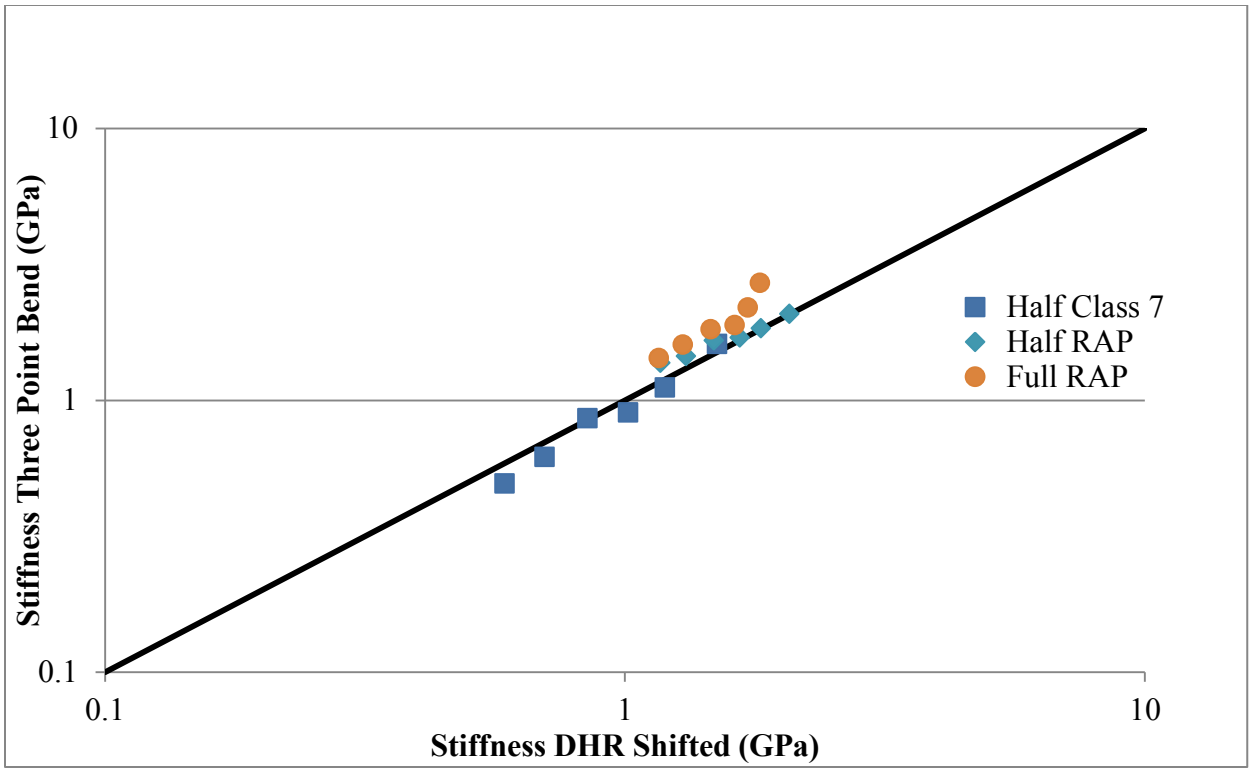

Figure 12: Three point bend and Shifted DHR results from slow setting emulsifier tested at -10°C

V. CONCLUSIONS

The data which was gathered through this experiment showed good trends and correlations between the three tests. The IDT and DHR test both showed similar results for creep stiffness and as was expected, the DHR results were proportionally smaller than the IDT creep results, but showed similar differences in materials. When multiple scales of material were tested, the stiffness decreased as the mixture became finer for Class 7 material. This was most likely a result of having higher binder content and a change in the mastic composition based on the addition of fines, which changes mixture properties. The Half and Full RAP material showed similar

behavior, which indicates the mastic properties, and material properties were similar between the two mixtures. The faster setting emulsifiers produced mixtures which were slightly denser and stiffer. The coefficient of variation and distinguishing between different mixtures makes the DHR is a potential candidate to be used as a replacement test for IDT testing. Further testing specifically with the Poisson's Ratio should be done to explore this option.

Through experimental analysis, the study has the following conclusions:

1) The DHR data is similar in shape, and material differentiation to the IDT and three point bend data. The DHR was able to detect the same differences between materials and temperature using sample sizes at 1% of the scale of the IDT test.
2) The IDT and three point bend results were very similar in magnitude, although the variation of the three point bend test was much higher. This is likely due to the method and instrumentation for the measuring of the sample deflection.
3) Mixtures made with faster setting emulsifiers were slightly stiffer than mixtures made with slower setting emulsifiers. This is likely due to the emulsifiers affecting mixture compaction.
4) As the gradation of Class 7 samples became downsized, the stiffness decreased and the standard deviation increased. RAP materials showed similar properties as their gradations were downsized.
5) The accuracies of IDT and DHR results were very similar and three point bend testing was much less accurate. The respective coefficients of variation are .192, .186, and .448.
6) Providing a shift factor for DHR results made them very similar to the results of IDT and three point bend tests.

7) When IDT tests were compared to shifted DHR results, the coefficient was about the same or smaller than the variability of the IDT test. The expected difference from the tests made no difference when analyzed through the MEPDG.

VI. SOURCES

1) Transportation Research Circular (2006): Asphalt Emulsion Technology, Number E-C102

2) Zofka A., Marasteanu, M., Li X., Clyne T. and McGraw J (2005): Simple method to obtain asphalt binders low temperature properties from asphalt mixtures properties, Journal of the Assocaition of Asphalt Paving Techonologists from the proceedings of the technical sessions, 255-282

3) Cross, S. A., Chesner, W. H., Justus, H. G., Kearney, E. R., (2011): Life-Cycle Environmental Analysis for Evaluation of Pavement Rehabilitation Options, Transportation Research Record: Journal of the Transportation Research Board, 2227, 43-52

4) Forsberg, A., Lukanen, E., Thomas, T., (2002): Engineered Cold In-Place Recycling Project Blue Earth County State Aid Highway 20, Minnesota, Transportation Research Record, 1813, 111-123

5) Thomas, T., Kadrmas, A., and Huffman, J., (2000): Cold In-Place Recycling on US-283 in Kansas, Transportation Research Record, 1723, 53-56

6) James, A., (2006): Overview of Asphalt Emulsion, Transportation Research Circular, Asphalt Emulsion Technology, E-C102, 1-14

7) American Association of State and Highway Transportation Officials (AASHTO) T 322-07 (2011): Standard Method of Test for Determining the Creep Compliance and strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device, 11 pages

8) American Association of State and Highway Transportation Officials (AASHTO) TP10 (1993): Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength (TSRST)

9) American Association of State and Highway Transportation Officials (AASHTO) T 313-12 (2012): Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), 21 pages

10) Velasquez R., Zofka A., Turos M. and Marastenu M. O. (2011): Bending beam rheometer testing of asphalt mixtures, International Journal of Pavement Engineering, 12:5, 461-474

11) Velasquez R., Marasteanu M., Labuz J. and Turos M. (2010): Evaluation of bending beam rheometer for characterization of asphalt mixtures, Asphalt Paving Technology Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions, 79:02702932, 295-324

12) Ho C., Romero P. (2011): Using Asphalt Mixture Beams in the Bending Beam Rheometer, Road Materials and Pavement Design, 12:2, 293-314

13) Reinke R. and Glidden S. (2005): Laboratory Investigation of HMA Performance Using Hamburg Wheel Tracking and DSR Torsional Creep Tests, Journal of ASTM International, 1469, 50-81

14) Dai, Q., and You, Z., (2007): Prediction of Creep Stiffness of Asphalt Mixture with Micromechanical Finite-Element and Discrete-Element Models, Journal of Engineering Mechanics, 133:2, 163-173

15) Liao, M.C., Chen, J. S, and Airey, G, (2013): Characterization of Viscoelastic Properties of Bitumen-Filler Mastics, Proceedings of the Eastern Asia Society for Transportation Studies, 9

16) Underwood, B. S., Kim, R. Y., (2011): Experimental investigation into the Multiscale Behaviour of Asphalt Concrete, International Journal of Pavement Engineering, 12, 4, 357-370

17) Craus, J., and Ishai, I., (1977): A method for the determination of the surface area of fine aggregate in bituminous mixtures. Journal of and Vol. 5(4), pp. 284-291.

18) Duriez, M., and Arrambide, J.,(1962): Nouveau de Tomes 1, 2 and 3, Dunod, Paris.

19) Alger, Mark, S. M. (1989): Polymer Science Dictionary, Chapman and Hall: London, 107

20) Schwartz, C. W., Li, R., (2011): Sensitivity Evaluation of MEPDG Performance Prediction, National Cooperative Highway Research Program, 1-47, 505 pages

VIII.

Appendix A Stiffness values for three tests, four materials and temperatures

DHR	Full C7 -10	SD	-20	SD	-30	SD
5	1.29	0.09	1.05	0.25	0.87	0.16
16	1.00	0.05	0.85	0.22	0.79	0.20
60	0.91	0.03	0.81	0.25	0.76	0.25
120	0.83	0.03	0.76	0.26	0.74	0.28
240	0.73	0.02	0.70	0.21	0.72	0.31
500	0.65	0.03	0.66	0.19	0.72	0.34
1000	0.60	0.03	0.65	0.19	0.73	0.38

DHR	Half C7 -10	SD	-20	SD	-30	SD
5	0.6720949	0.2	0.88	0.25	0.63	0.13
16	0.4090492	0.1	0.68	0.17	0.53	0.09
60	0.3244947	0	0.62	0.15	0.49	0.10
120	0.2758315	0	0.57	0.14	0.45	0.11
240	0.2303744	0	0.52	0.12	0.42	0.11
500	0.1904994	0	0.47	0.11	0.41	0.11
1000	0.16	0.02	0.44	0.10	0.40	0.11

DHR	Half RAP -10	SD	-20	SD	-30	SD
5	0.77	0.09	0.9	0	1.14	0.09
16	0.56	0.05	0.7	0	0.98	0.07
60	0.50	0.03	0.6	0.1	0.93	0.06
120	0.45	0.02	0.6	0.1	0.88	0.06
240	0.40	0.02	0.5	0.1	0.81	0.06
500	0.36	0.02	0.5	0.1	0.75	0.04
1000	0.32	0.02	0.5	0.1	0.73	0.05

Full RAP

DHR	-10	SD	-20	SD	-30	SD
5	0.59	0.18	0.53	0.14	0.90	0.15
16	0.49	0.13	0.47	0.13	0.79	0.12
60	0.47	0.11	0.45	0.13	0.76	0.13
120	0.44	0.09	0.43	0.12	0.74	0.14
240	0.40	0.07	0.40	0.10	0.71	0.16
500	0.35	0.06	0.38	0.09	0.69	0.16
1000	0.32	0.06	0.38	0.10	0.68	0.15

Full C7

IDT	-10	SD	-20	SD	-30	SD
5	2.39	0.51	2.96	0.63	4.06	0.52
16	2.07	0.40	2.29	0.46	3.60	0.59
60	1.53	0.32	1.36	0.33	2.03	0.28
120	1.17	0.19	0.89	0.19	1.52	0.23
240	0.90	0.14	0.60	0.14	1.06	0.16
500	0.71	0.09	0.44	0.11	0.84	0.12
1000	0.61	0.08	0.40	0.10	0.79	0.12

Half C7

IDT	-10	SD	-20	SD	-30	SD
5	2.10	0.78	4.15	0.83	3.56	0.65
16	1.47	0.36	3.26	0.49	2.68	0.64
60	0.85	0.16	2.23	0.31	1.58	0.40
120	0.64	0.08	1.64	0.21	1.12	0.30
240	0.46	0.06	1.14	0.15	0.78	0.22
500	0.34	0.04	0.87	0.13	0.61	0.16
1000	0.27	0.04	0.74	0.10	0.56	0.14

	Half RAP					
IDT	-10	SD	-20	SD	-30	SD
5	2.36	0.27	5.93	1.84	3.23	0.59
16	1.86	0.26	5.39	1.48	2.66	0.48
60	1.28	0.20	3.23	0.87	1.74	0.33
120	1.02	0.13	2.49	0.63	1.26	0.19
240	0.79	0.09	1.92	0.44	0.93	0.14
500	0.66	0.08	1.42	0.33	0.76	0.09
1000	0.59	0.11	1.28	0.45	0.69	0.08

	Full RAP					
IDT	-10	SD	-20	SD	-30	SD
5	3.36	1.12	3.57	0.46	3.47	1.17
16	2.95	0.94	2.99	0.57	2.71	0.71
60	1.84	0.55	2.40	0.36	1.76	0.22
120	1.31	0.37	1.89	0.24	1.21	0.07
240	0.97	0.26	1.33	0.17	0.85	0.07
500	0.77	0.21	1.00	0.17	0.67	0.07
1000	0.70	0.20	0.83	0.18	0.60	0.07

Three Point Bend	Full C7 -10	SD	-20	SD	-30	SD
5	8.41	5.97	1.99	1.00	2.27	0.54
16	5.02	2.29	1.67	0.72	2.22	0.47
60	2.72	1.22	1.25	0.44	2.43	0.54
120	2.11	1.13	1.08	0.34	2.47	0.55
240	2.07	1.10	1.04	0.31	2.53	0.52
500	1.30	0.87	0.75	0.19	2.48	0.26
1000	0.82	0.45	0.59	0.24	2.56	0.59

Three Point Bend	Half C7 -10	SD	-20	SD	-30	SD
5	1.9106451	0.659	1.64	0.49	2.10	0.62
16	1.6126484	0.475	1.63	0.55	2.04	0.57
60	1.114416	0.313	1.41	0.47	1.96	0.82
120	0.9022963	0.265	1.29	0.41	1.95	0.92
240	0.858154	0.245	1.24	0.40	2.11	1.19

500	0.6194602	0.145	1.16	0.37	2.15	1.52
1000	0.49	0.10	1.10	0.39	2.20	1.75

Three Point Bend	Half RAP	-10	SD	-20	SD	-30
5	2.29	1.28	1.7	0.7	2.81	1.62
16	2.08	1.18	1.6	0.7	2.85	1.67
60	1.84	1.14	1.5	0.6	3.09	1.93
120	1.70	1.05	1.4	0.6	2.97	1.79
240	1.66	1.02	1.4	0.6	3.26	2.13
500	1.45	0.87	1.3	0.6	3.34	2.34
1000	1.37	0.84	1.1	0.5	3.33	2.22

Three Point Bend	Full RAP	-10	-20	SD	-30	SD
5	2.95	1.22	3.73	2.69	1.14	0.40
16	2.70	0.96	3.65	2.77	1.07	0.37
60	2.19	0.58	3.40	2.70	1.09	0.42
120	1.89	0.41	3.50	3.01	1.08	0.41
240	1.83	0.40	3.48	3.00	1.07	0.39
500	1.60	0.36	3.17	2.78	1.11	0.46
1000	1.43	0.31	2.51	2.09	1.21	0.59

DHR	Fast Set	SD	-20	SD	-30	SD
5	0.58	0.06	0.62	0.18	0.84	0.10
16	0.55	0.05	0.60	0.18	0.82	0.10
60	0.53	0.05	0.58	0.18	0.82	0.10
120	0.50	0.05	0.56	0.19	0.80	0.08
240	0.46	0.04	0.53	0.17	0.76	0.09
500	0.42	0.04	0.50	0.17	0.74	0.11
1000	0.40	0.04	0.49	0.17	0.75	0.12

DHR	Medium Fast		-20	SD	-30	SD
5	0.309	0.2	0.7	0.1	0.75	0.08
16	0.296	0.2	0.6	0.1	0.73	0.08
60	0.287	0.2	0.6	0.1	0.70	0.11
120	0.282	0.2	0.6	0.1	0.68	0.14
240	0.268	0.2	0.5	0.1	0.64	0.16
500	0.254	0.1	0.5	0.1	0.62	0.16
1000	0.253	0.1	0.5	0.1	0.62	0.16

DHR	Slow Set	SD	-20	SD	-30	SD
5	0.59	0.18	0.53	0.14	0.90	0.15
16	0.49	0.13	0.47	0.13	0.79	0.12
60	0.47	0.11	0.45	0.13	0.76	0.13
120	0.44	0.09	0.43	0.12	0.74	0.14
240	0.40	0.07	0.40	0.10	0.71	0.16
500	0.35	0.06	0.38	0.09	0.69	0.16
1000	0.32	0.06	0.38	0.10	0.68	0.15