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LABORATORY PERFORMANCE EVALUATION OF CIR-EMULSION AND ITS COMPARISON AGAINST CIR-FOAM TEST RESULTS FROM PHASE 2

Final Report TR-474
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16. Abstract

Currently, no standard mix design procedure is available for CIR-emulsion in Iowa. The CIR-foam mix design process developed during the previous phase is applied for CIR-emulsion mixtures with varying emulsified asphalt contents. Dynamic modulus test, dynamic creep test, static creep test and raveling test were conducted to evaluate the short- and long-term performance of CIR-emulsion mixtures at various testing temperatures and loading conditions. A potential benefit of this research is a better understanding of CIR-emulsion material properties in comparison with those of CIR-foam material that would allow for the selection of the most appropriate CIR technology and the type and amount of the optimum stabilization material. Dynamic modulus, flow number and flow time of CIR-emulsion mixtures using CSS-1h were generally higher than those of HFMS-2p. Flow number and flow time of CIR-emulsion using RAP materials from Story County was higher than those from Clayton County. Flow number and flow time of CIR-emulsion with 0.5% emulsified asphalt was higher than CIR-emulsion with 1.0% or 1.5%. Raveling loss of CIR-emulsion with 1.5% emulsified was significantly less than those with 0.5% and 1.0%. Test results in terms of dynamic modulus, flow number, flow time and raveling loss of CIR-foam mixtures are generally better than those of CIR-emulsion mixtures. Given the limited RAP sources used for this study, it is recommended that the CIR-emulsion mix design procedure should be validated against several RAP sources and emulsion types.

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Laboratory Performance Evaluation of CIR-emulsion and Its Comparison against CIR-foam Test Results from Phase 2

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1. INTRODUCTION

The previous research developed and validated the mix design procedure for cold in-place recycling using foamed asphalt (CIR-foam). The main purpose of this research is to apply the CIR-foam mix design process developed during the previous phase to the CIR-emulsion mixtures. A potential benefit of this study is a better understanding of CIR-emulsion material properties in comparison with CIR-foam that would allow for the selection of the most appropriate CIR technology and the type and amount of the stabilization material. The simple performance testing (SPT) equipment was used to predict a field performance of various CIR-emulsion mixtures.

Chapter 1 introduces study objective, the scope, and benefits and Chapter 2 summarizes the findings, conclusions, and recommendations obtained from the previous phase. Chapter 3 compiles the most current CIR-emulsion mix design procedures and their implementation results using CSS-1h and HFMS-2p, which are the most commonly used emulsion types in Iowa. Chapter 4 presents the efforts to collect reclaimed asphalt pavement (RAP) materials from two different sources and Chapter 5 evaluates the fundamental characteristics of collected RAP materials such as residual asphalt content and stiffness, RAP gradation, elongation and flatness ratio. Chapter 6 investigates the compaction characteristics of CIR-emulsion mixtures using both a gyratory compactor and a Marshall hammer. Chapter 7 evaluates the application of CIR-foam mix design process to the CIR-emulsion mixtures with varying emulsified asphalt contents. Chapter 8 presents the short- and long-term performance tests of CIR-emulsion mixtures based on the laboratory tests, which include dynamic modulus, dynamic creep, static creep and raveling tests at various testing temperatures and loading conditions. Chapter 9 provides findings, conclusions, and recommendations.

1.1 Objective

During the previous study, the mix design procedure was developed and validated for cold in-place recycling using foamed asphalt (CIR-foam). The current CIR using engineered emulsion (CIR-EE) mix design procedure is complex and requires special equipment that is not commonly available. Currently, no standard mix design is available for CIR using emulsified asphalt (CIR-emulsion) in Iowa. The main purpose of the study is to determine if the CIR-foam mix design process can be applied to CIR-emulsion with some minor adjustments. This project will lead to a better understanding of CIR-emulsion material properties by applying CIR-foam mix design procedure for designing CIR-emulsion mixtures.

1.2 Benefits of the Study

This research examined the existing CIR-foam mix design process with commonly available equipment that may give similar results for the CIR-emulsion mixtures. The performance of the CIR-emulsion mixtures can be directly compared against CIR-foam based on laboratory performance test results. One of the most significant benefits is to provide pavement engineers with a rational mix design procedure that helps them select the most appropriate CIR technology, types and amount of the stabilization material for the existing pavement conditions.

2. SUMMARY FROM PREVIOUS STUDY

During the phase 1 study, strengths and weaknesses of the mix design parameters were identified and the laboratory test procedure was modified to improve the consistency of the mix design process of CIR using foamed asphalt (CIR-foam). Both Marshall and indirect tensile strength test procedures were evaluated as a foamed asphalt mix design procedure using reclaimed asphalt pavement (RAP) materials collected from U.S. 20 Highway in Iowa. Based upon the critical mixture parameters identified, a new mix design process was developed for CIR-foam, which would provide a pavement engineer with a step-by-step method for determining the proper material properties (Lee and Kim, 2003). Upon completion of phase 1 study, the following conclusions were derived:

- Based upon the milled RAP materials throughout the day, time of milling and temperature of pavement during the milling process did not affect gradation.
- For PG 52-34, an optimum foaming water content of 1.3% at 170˚C was selected for use in the laboratory mix design.
- Optimum moisture content was selected at 4.0% for field gradation.
- Most wet specimens lost their strength values significantly – up to 50%, which indicates that CIR-foam mixtures may be susceptible to water damage.
- Indirect tensile strength was more sensitive to foamed asphalt content, with clear peak, than Marshall Stability.
- It was recommended that the indirect tensile strength test should be performed on the wet specimens

During phase 2 study, the developed CIR-foam mix design process was validated against various reclaimed asphalt pavement (RAP) materials to determine its consistency over a wide range of RAP materials available throughout Iowa (Lee and Kim, 2007). Upon completion of phase 2 study, the following conclusions were derived:

- Gyratory compactor produces the more consistent CIR-foam laboratory specimen than Marshall hammer.
- Indirect tensile strength of gyratory compacted specimens is higher than that of Marshall hammer compacted specimens.
- Indirect tensile strength of the mixtures cured in the oven at 60˚C for 2 days is significantly higher than that of mixtures cured in the oven at 40˚C for 3 days.
- Dynamic modulus of CIR-foam is affected by a combination of the RAP sources and foamed asphalt contents.
- CIR-foam is not as sensitive to temperature or loading frequency as HMA.
- Based on the dynamic creep tests performed at 40˚C, CIR-foam mixtures with 1.0% foamed asphalt are more resistant to rutting than CIR-foam with 2.0% or 3.0%.

- Based on the dynamic creep tests performed at 40˚C, the RAP aggregate gradation has a predominant impact on its resistant to rutting.
- Based on the dynamic creep test results performed at 40˚C and dynamic modulus test performed at 37.8˚C, the finer RAP materials with the more and harder residual asphalt were more resistant to rutting.
- CIR-foam specimens with 2.5% foamed asphalt content are more resistant to raveling than the ones with 1.5%.

Based on the extensive laboratory experiments and the field evaluations, the following specific recommendations were made:

- Twenty-five gyrations is recommended for producing the equivalent laboratory specimens produced by 75-blow Marshall hammer.
- Laboratory specimens should be cured in the oven at 40°C for 3 days.
- To determine the optimum foamed asphalt content, indirect tensile strength test should be performed on the vacuum saturated specimens.
- Gyratory compacted specimens should be placed in 25˚C water for 30 minutes, vacuumed saturated at 20 mmHg for 30 minutes and left under water for additional 30 minutes without vacuum.
- The optimum foamed asphalt content should be increased from 1.5% to 2.5% if the penetration index of the residual asphalt from RAP materials decreases from 28 to 15.
- The proposed mix design procedure should be implemented to assure the optimum performance of CIR-foam pavements in the field.

3. LITERATURE REVIEW ON VARIOUS CIR-EMULSION MIX DESIGN PROCEDURES

This chapter compiles the most current CIR-mix design procedures and their implementation results with an emphasis on CSS-1h and HFMS-2p, which are the most common used emulsion types in Iowa. Iowa DOT (2006) states, "CSS-1 emulsion may be used in place of HFMS-2s when the traffic permitted on the CIR layer is less than 500 ADT."

CIR-emulsion is a recycling process that evolved during the late 1980s. The need for a CIR-emulsion mixture with specific engineering properties calls for the use of a mix design. Typical asphalt emulsion, cement, or lime contents range from 1.0% to 3.0% by weight of the reclaimed asphalt pavement (RAP). But, there is currently no nationally accepted method for CIR-emulsion mix design process (ARRA, 2001). Based on a survey of twenty-four states, Lee et al. (2002) reported that eleven states use the Marshall mix design, three states use Hveem, four states use a gyratory compactor, seven states use "other" processes, and four states use none.

Reihe and Apilo (1995) developed a CIR-emulsion design method in Finland suitable for softer emulsion with a viscosity of 1000 to 3000 mm^2/sec at 60˚C. Khosla and Bienvenu (1996) developed a CIR-emulsion mix design process that uses cationic medium setting (CMS) and high float rejuvenating agent (HFRA) emulsions as recycling agents. A recent survey by the Rocky Mountain User Producer Group of thirty-eight states reported some consistency problems due to the lack of standard design and testing methods, which had resulted in raveling, minor segregation, isolated rutting, extended curing time, compaction problems, thermal cracking, and disintegration under traffic (RMAUPG, 1999).

AASHTO-AGC-ARTBA Joint Committee Task Force 38 (1999) published a CIR-emulsion mix design procedure for both Marshall and Hveem equipment, which has been adopted or modified by some state agencies. To improve the modified Marshall method, Lee et al. (2002) developed a new volumetric design for CIR-emulsion utilizing the Superpave gyratory compactor. However, the design variability associated with different types of emulsion (HFMS-2t, CSS-1h, HF150p, Cyclogen ME, and HFE 150-p) was not addressed.

Cationic slow setting (CSS) emulsion typically contains about 65% of asphalt and 35% of water - although some emulsions can hold up to 75% asphalt. Salomon and Newcomb (2001) evaluated three emulsions, CSS-1h (cationic slow setting emulsion), HFMS-2s (high-float medium-setting emulsion with a residue of relatively low viscosity), and HFMS-2p (high-float medium-setting emulsion modified with a polymer). They found that the HFMS-2p emulsion gave the lowest overall air voids, and recommended that the Minnesota DOT should use it until more precise PG binder information could be collected on the aged asphalt from RAP.

Lee et al. (2002) reported that most states use high-float type emulsion; a few exceptions prefer slow- or medium-setting cationic emulsions. Several states include lime, fly ash and Portland cement as an additive. Before 1988, the Oregon DOT used CMS-2s (now called CMS-2RA). Since 1988, they have employed HFE-150. The province of Ontario, Canada also uses HFE-150 (Murphy and Emery, 1996). The Pennsylvania DOT uses CMS-2 emulsion with an asphalt residue of 100 to 120 penetration. When the penetration of the recovered asphalt is in the range of 15–20, CSS-1h emulsion with an asphalt residue of 40~90 penetration is used to achieve softer recovered asphalt (Epps, 1990). To address the problem of rutting, reflective cracking and moisture damage, the New Mexico DOT has elected to use high-float polymer-modified emulsion instead of SS-1 (slow setting) emulsion and CMS-2s (McKeen et al., 1997). The asphalt institute (AI, 1979) recommends using the heaviest asphalt that can be worked, while advocating the use of low-viscosity asphalt for fine aggregates and high-viscosity asphalt for coarse aggregates.

Salomon and Newcomb (2000) recommended that CIR mixtures be compacted with gyratory compactors that produce consistent air voids. They reported that density became constant after about 60 gyrations. At 10 gyrations, relative densities were in the range of 85% to 90% of the maximum density, and at 60 gyrations, they were between 90% and 95% of maximum density. To achieve a desired density of 130 pcf for a laboratory test specimen, Lee et al. (2003) recommended 37 gyrations. Thomas and Kadrmas (2003) suggested 30 gyrations.

Issa et al. (2001) conducted a study to examine the behavior of RAP when rejuvenated with high-float emulsion and Portland cement to produce a cement-emulsion mix. They reported that 2.0% emulsion produced the highest gain in soaked stability because of the addition of the cement. Some CIR-emulsion projects exhibited rutting and asphalt stripping problems. As a result, the Kansas DOT specified Class C fly ash as the only approved recycling additive for CIR-emulsion (Thomas et al., 2000). It was observed, however, that the fly ash section had nearly twice the amount of cracking as a section emulsified with lime slurry. Wu (1999) reported that pavement sections with the fly-ash-stabilized RAP base showed very uniform distribution of shear strains within pavement layers, and had the smallest rut depths among all sections studied in Kansas. Valkonen and Nieminen (1995) found that a small amount of Portland cement-but not lime or gypsum-improved early strength and water resistance.

CIR-emulsion mixture was used as a surface layer in Israel, and when subjected to low-volume traffic for one year it performed well without any kind of distortion (Cohen et al., 1989). In another study, Castedo (1987) concluded that a stable and sound pavement could generally be obtained using CIR-emulsion techniques. Mamlouk and Ayoub (1983) evaluated the long-term behavior of artificially aged CIR-emulsion mixtures and concluded that the emulsion did not have a long-term softening effect on the aged asphalt in RAP materials. To improve the field performance of CIR-emulsion, Thomas and Kadrmas (2003) proposed performance-related tests and specifications for CIR-emulsion including a raveling test, an indirect tensile test at a low temperature for thermal cracking, and Marshall testing of gyratory compacted specimens.

4. COLLECTION OF RECLAIMED ASPHALT PAVEMENT (RAP) MATERIALS FROM TWO COLD IN-PLACE RECYCLING PROJECT SITES

During the summer of 2007, in order to prepare the test specimens for CIR-emulsion mixtures, milled reclaimed asphalt pavement (RAP) materials were collected from two different CIR project sites: County Road 13 in Clayton County and County Road R 38 in Story County. The locations of two CIR project sites are shown in Figure 4-1.

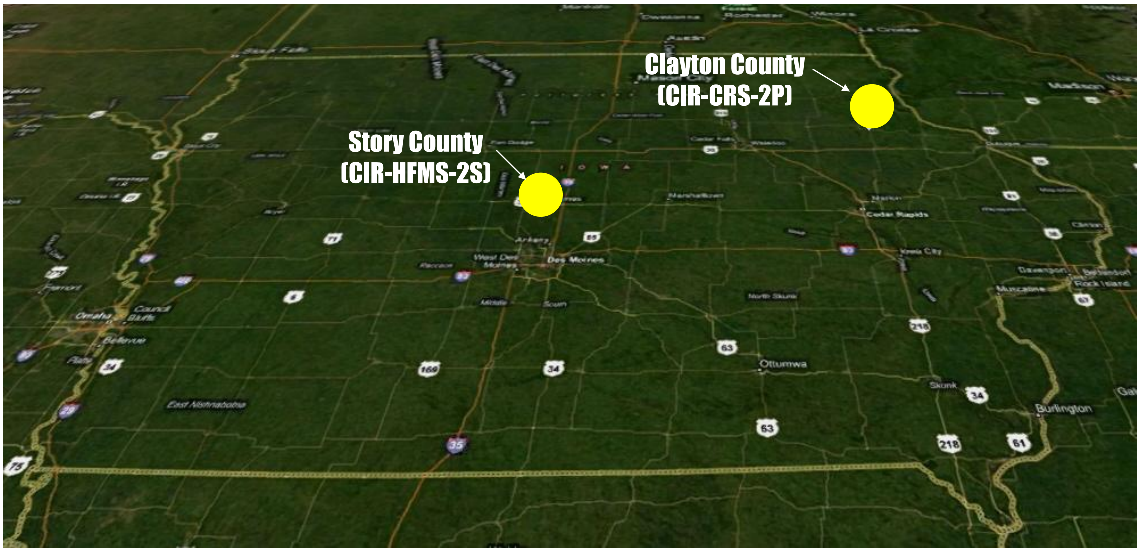


Figure 4-1. Locations of CIR project sites where RAP materials were collected

4.1. Description of Project Sites

As summarized in Table 4-1, 2000 lbs of RAP materials were collected from Clayton County on August 21st, 2007 and 4000 lbs of RAP materials were collected from Story County on September 20th, 2007.

Table 4-1. Basic information of two CIR project sites

Item	RAP Source	
	Clayton County	Story County
CIR Project Site	County Road 13	County Road R 38
Collection Date	August 21, 2007	September 20, 2007
RAP Sampling Time	2:30 p.m.-5:30 p.m.	1:00 p.m.-3:30 p.m.
CIR Method	CIR-CRS-2p	CIR-HFMS-2s
Quantity	4,000 lbs	2,000 lbs
Construction Company	Mathy Construction	WK Construction

4.1.1 Clayton County (County Road 13)

RAP materials were collected from the stockpiles from County Road 13 in Clayton County. As shown Figure 4-2, the job site is located about 2.0 miles away from the city of Edgewood and the stockpile is about 1 mile away from the job site. The RAP materials were collected between 2:30 p.m. and 5:30 p.m. on August 21st, 2007. Figure 4-3 shows the RAP stockpile and the RAP material collection process.

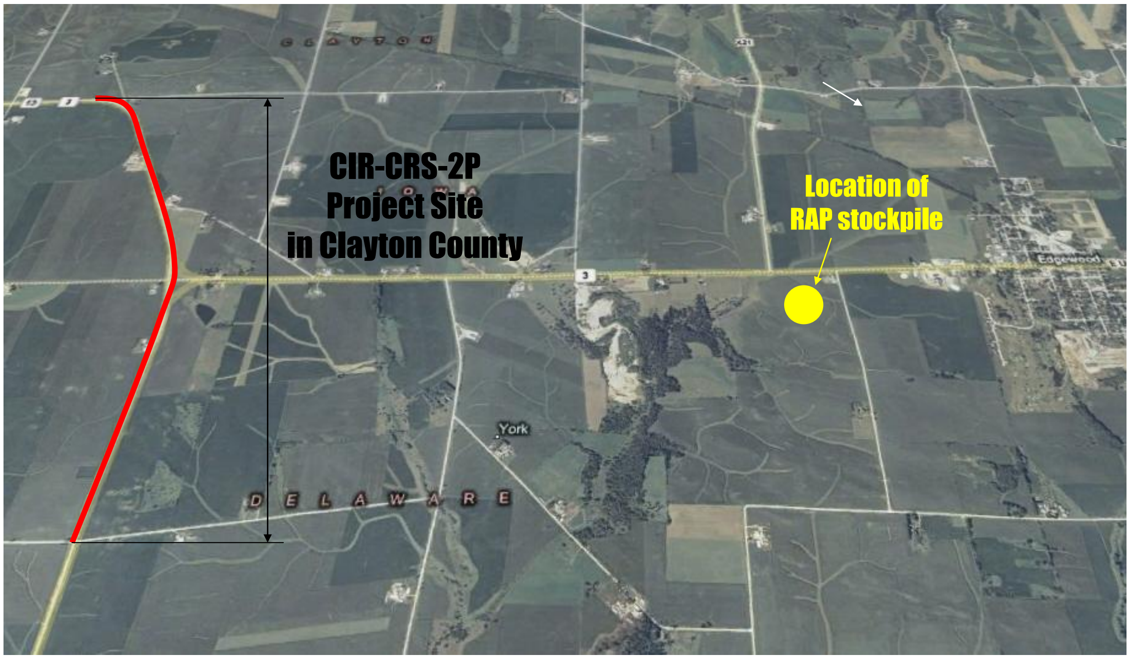


Figure 4-2. Locations of CIR-CRS-2p project site and RAP stockpile in Clayton County

(a) RAP stockpile

(b) Collection of RAP materials

Figure 4-3. Pictures of RAP stockpiles and RAP material collection from Clayton County

4.1.2. Story County (County Road R 38)

The milled RAP materials were collected from the CIR-HFMS-2s project site in County Road R 38. As shown in Figure 4-4, the project site is located near city of Slater. RAP materials were collected between 1:30 p.m. and 3:30 p.m. on September 20th, 2007. Figure 4-5 shows the CIR-HFMS-2s construction process and the RAP material collection process.

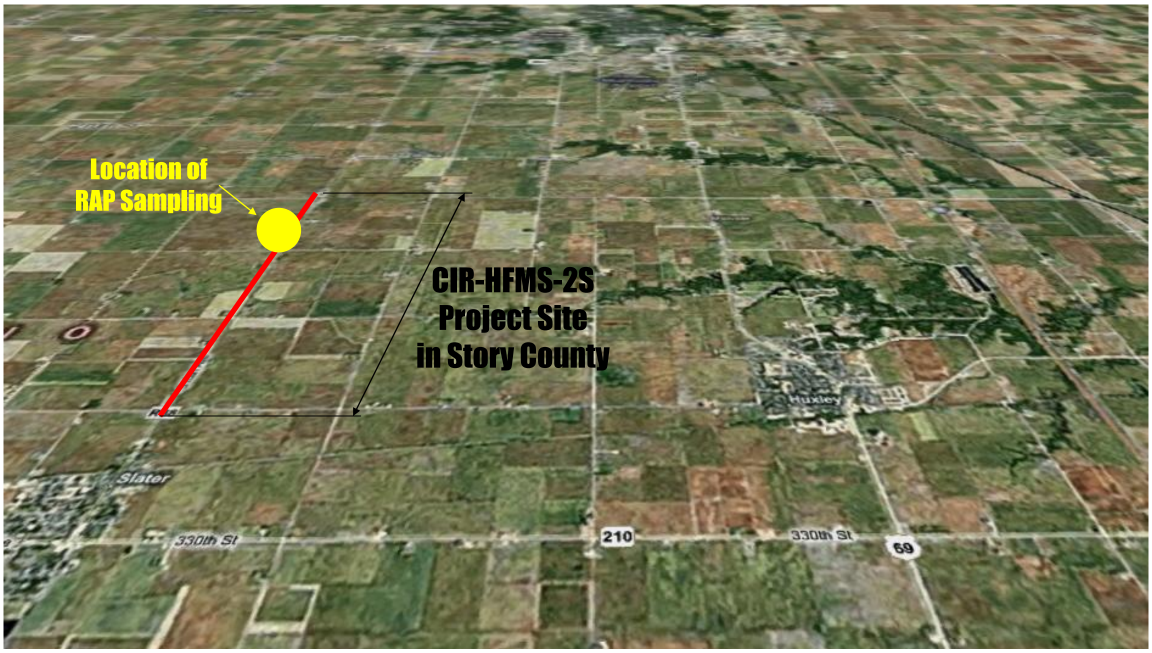


Figure 4-4. Location of CIR-HFMS-2s project site on County Road R 38 in Story County

(a) CIR-HFMS-2s process

(b) Collection of RAP materials

Figure 4-5. Pictures of CIR-HFMS-2s process on County Road R 38 in Story County

5. EVALUATION OF RECLAIMED ASPHALT PAVEMENT (RAP) MATERIALS

The collected RAP materials were evaluated with respect to RAP gradation, extracted aggregate gradation, elongation and flatness ratio, residual asphalt content, penetration index, and G*/sin δ. In the previous study, it was reported that RAP materials with different asphalt contents and penetration indexes had a significant effect on the mix design and performance of CIR-foam mixtures. The RAP materials were brought to the laboratory and dried in the air (25°C~27°C) for 2 to 3 days. Figure 5-1 shows the process of drying RAP materials in the laboratory.

Figure 5-1. Drying process of RAP materials in the laboratory

5.1 RAP Gradation

First, dried RAP materials were divided into six stockpiles which were retained on the following sieves: 25mm, 19mm, 9.5mm, 4.75mm, 1.18mm and passing 1.18mm. As shown in Figure 5-2, sorted RAP materials were stored in 5-gallon buckets holding about 40 lbs of RAP materials. After discarding RAP materials bigger than 25mm, the sorted RAP materials were weighed and their relative proportions are computed as shown in Table 5-1. Design gradations for the laboratory tests are plotted on a 0.45 power chart as shown in Figure 5-3. To allow the comparison of two RAP sources size by size, their relative proportions are graphed in Figure 5-4.

Figure 5-2. Sorted RAP materials in 5-gallon buckets

Table 5-1. Proportions of sorted two RAP materials passing 25mm sieve

RAP Sizes	RAP Source	
	Clayton County	Story County
25 mm - 19 mm	6.7%	6.6%
19 mm - 9.5 mm	27.0%	26.7%
9.5 mm - 4.75 mm	27.4%	22.2%
4.75 mm - 1.18 mm	27.4%	26.7%
Passing 1.18 mm	11.5%	17.8%
Total	100.0%	100.0%

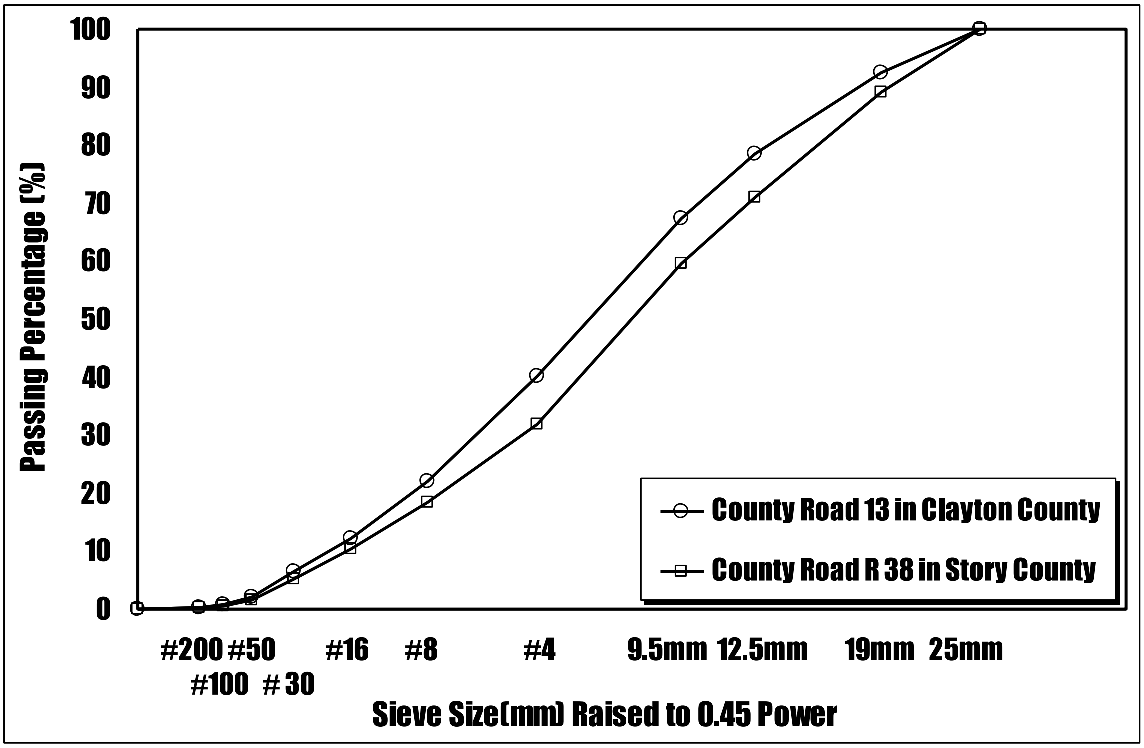


Figure 5-3. Gradation plots of two RAP materials passing 25mm sieve

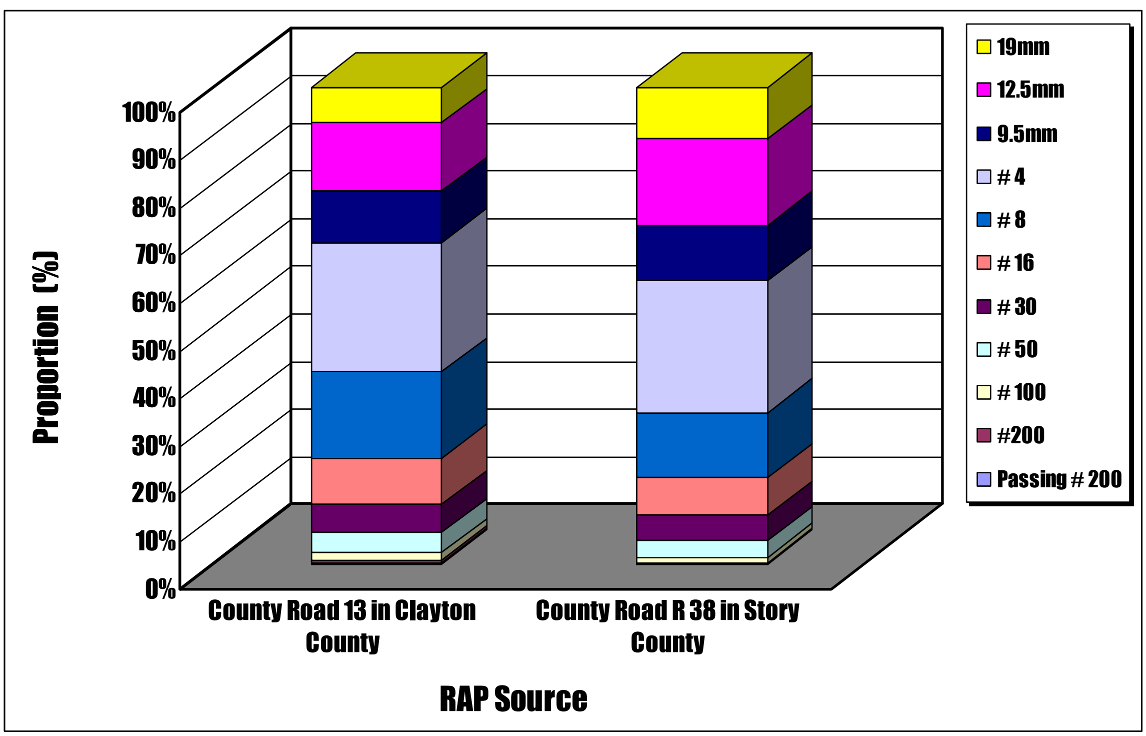


Figure 5-4. Cumulated gradation bar charts of seven different RAP materials passing 25mm sieve

5.2. Characteristics of Extracted RAP Materials

The extracted asphalt content, penetration, dynamic shear modulus, phase angle and extracted aggregate gradation were measured from RAP Materials from two different sources. As summarized in Table 5-2, the extracted asphalt contents are 5.80% for RAP materials collected from Clayton County and 5.81% for RAP materials collected from Story County. The Dynamic Shear Rheometer (DSR) test was performed at three different temperatures, 76°C, 82°C, and 88°C. As shown in Table 5-2, the RAP materials from Clayton County exhibited higher G*/sin δ values than the one from Story County consistently at all three testing temperatures. The extracted asphalt of RAP material from Clayton County exhibited the penetration of 14 while that of Story County exhibited the value of 18. Finally, the aggregate gradation of RAP materials from Clayton County was finer than one from Story County as shown in Table 5-2.

Table 5-2. Properties of extracted asphalts and extracted aggregates

	RAP Source	
	Clayton County	Story County
Extracted AC Content (%)	5.80	5.81
Penetration at 25°C	14	18
G*/sin δ (kPa)	4.26 at 76°C	1.94 at 76°C
	2.07 at 82°C	0.88 at 82°C
	1.04 at 88°C	0.44 at 88°C
Gradation of Extracted Aggregates		
25.0 mm	100.0	100.0
19.0 mm	100.0	100.0
12.5 mm	97.3	96.7
9.5 mm	92.9	90.2
No. 4	74.0	72.6
No. 8	59.4	58.5
No. 16	45.5	46.1
No. 30	34.6	32.5
No. 50	23.0	14.6
No. 100	12.5	5.5
No. 200	4.4	1.7

5.3 Flatness and Elongation of RAP

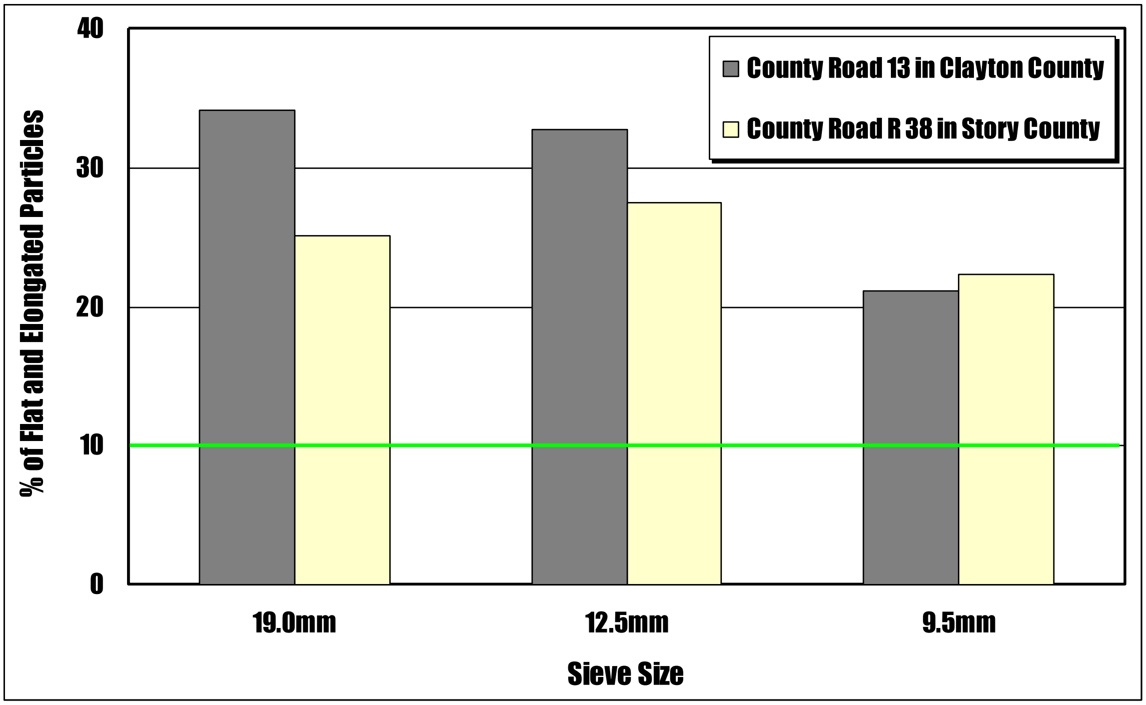
To evaluate the morphological characteristic of RAP materials, the flat and elongation test was performed in accordance with ASTM D 4791 (2005). RAP materials retained on the sieve size of 9.5mm and larger were tested for flatness and elongation. RAP materials of each sieve were weighted to determine a percentage of flat and elongated RAP materials.

Currently, SuperPave specification requires that hot mix asphalt mixtures should have less than 10 % of the aggregates that exceed 5:1 ratio.

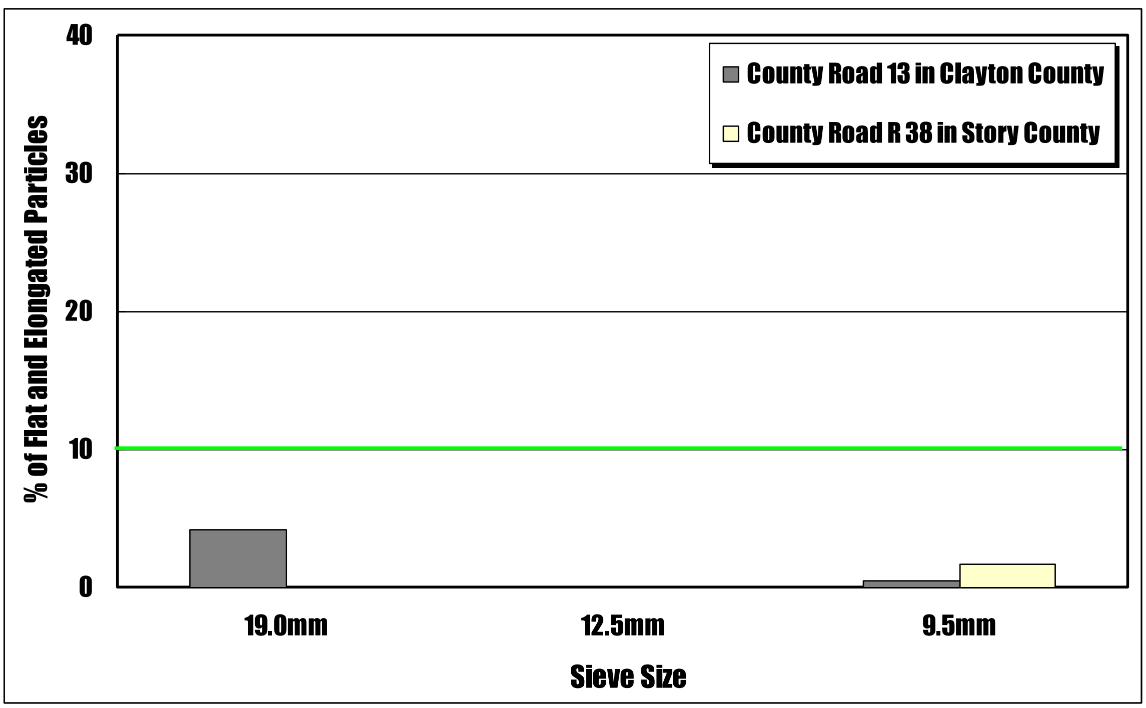
RAP materials retained on each of the following three sieves were analyzed individually: 9.5 mm, 12.5 mm, and 19.0 mm. Percentages of RAP materials which exceed 3:1 or 5:1 ratios were determined to identify the flat and elongated RAP materials. The flat and elongation test results are summarized in Table 5-3 and plotted against different RAP material sizes in Figure 5-5. As can be seen from Figure 5-5 (a), all RAP materials exceeded the 10 % limit of 3:1 ratio. However, as can be seen from Figure 5-5 (b), small amounts of RAP materials were elongated higher than the 5:1 ratio.

Table 5-3. Test results of flat and elongated RAP particles at 3:1 and 5:1 ratios

		Weight (g)			
3:1 ratio					
	Sieve Size	Total Weight of 100 Particles	Flat and Elongated Particles	%	Pass or Fail (>10%)
Clayton County	19.0mm	1341.4	457.6	34.1	Fail
	12.5mm	554.3	181.3	32.7	Fail
	9.5mm	187.1	39.5	21.1	Fail
	Sieve Size	Total Weight of 100 Particles	Flat and Elongated Particles	%	Pass or Fail (>10%)
Story County	19.0mm	1317.7	330.5	25.1	Fail
	12.5mm	458.1	126	27.5	Fail
	9.5mm	180.1	40.3	22.4	Fail
5:1 ratio					
	Sieve Size	Total Weight of 100 Particles	Flat and Elongated Particles	%	Pass or Fail (>10%)
Clayton County	19.0mm	1341.4	55.9	4.2	Pass
	12.5mm	554.3	0.0	0.0	Pass
	9.5mm	187.1	1.0	0.5	Pass
	Sieve Size	Total Weight of 100 Particles	Flat and Elongated Particles	%	Pass or Fail (>10%)
Story County	19.0mm	1317.7	0.0	0.0	Pass
	12.5mm	458.1	0.0	0.0	Pass
	9.5mm	180.1	3.0	1.7	Pass



(a) 3:1 ratio



(b) 5:1 ratio

Figure 5-5. Comparison of % flat and elongated particles at two different RAP sources for 3:1 and 5:1 ratios

6. COMPACTION CHARACTERISTICS OF CIR-EMULSION MIXTURES

The previous study reported that the gyratory compacted specimens produced the consistently higher strength at all foamed asphalt contents than Marshall hammer compacted specimens. It was also noticed that the specimens produced by Marshall hammer were not as consistent as the ones compacted by gyratory compactor. In the previous study, about 25 gyrations have produced the equivalent density of CIR-foam as 75-blow Marshall. A relationship between the densities of CIR-emulsion mixtures compacted by Marshall hammer and gyratory compactor was developed. The design parameters and the number of specimens used for compaction study are summarized in Table 6-1 and Table 6-2, respectively.

Table 6-1. Mix design parameters for the compaction study of CIR-emulsion mixtures

Emulsion Type	CSS-1h
Water Content (%)	4.0%
Emulsion Content (%)	2.0%
RAP Source	County Road R 38 in Story County
Cuing Condition	Oven at 40°C for 3 days
No. of Gyration	20, 30, and 50
No. of Marshall Blow	75

Table 6-2. Number of CIR-CSS-1h-emulsion specimens prepared under various compaction conditions

	Compaction Level			
	20 Gyrations	30 Gyrations	50 Gyrations	75 Blows
No. of Specimen	3	3	3	3

6.1 Bulk Specific Gravities and Air Voids

The theoretical maximum specific gravity (G_{mm}) of CIR-CSS-1h mixtures at 2.0% of emulsified asphalt content (EAC) was measured as 2.394 using the Corelok device. Bulk specific gravities and air voids at three different levels of gyration and 75 blows of Marshall hammer are summarized in Table 6-3 and Table 6-4, and plotted against number of gyrations in Figure 6-1 and Figure 6-2. As can be seen from these figures, the number of gyrations equivalent to 75 blows of Marshall hammer range between 20 gyrations and 30 gyrations.

Table 6-3. Results of bulk specific gravities at four different compaction levels

No. of Specimen	Compaction Level			
	20 gyrations	30 gyrations	50 gyrations	75 blows
1	2.100	2.181	2.207	2.115
2	2.079	2.160	2.198	2.086
3	2.071	2.136	2.181	2.120
Average	2.083	2.159	2.195	2.107

Table 6-4. Results of air voids at four different compaction levels

No. of Specimen	Compaction Level			
	20 gyrations	30 gyrations	50 gyrations	75 blows
1	12.3%	8.9%	7.8%	11.7%
2	13.2%	9.8%	8.2%	12.9%
3	13.5%	10.8%	8.9%	11.4%
Average	13.0%	9.8%	8.3%	12.0%

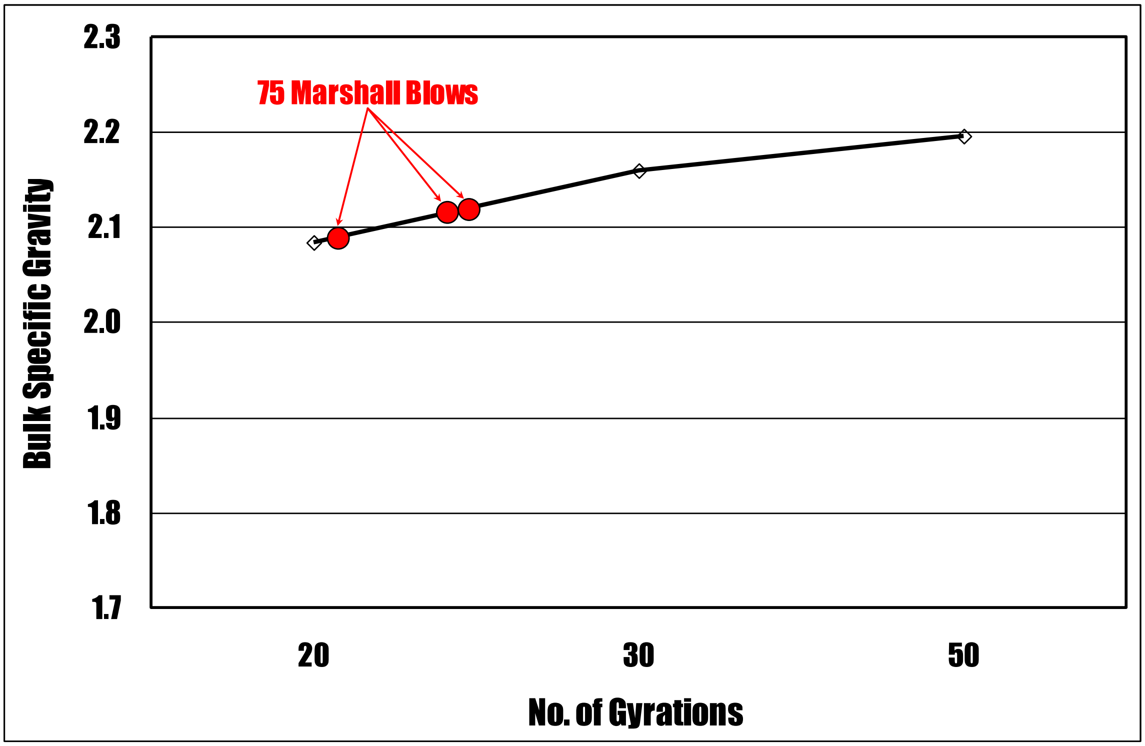


Figure 6-1. Plots of average bulk specific gravities against different number of gyrations

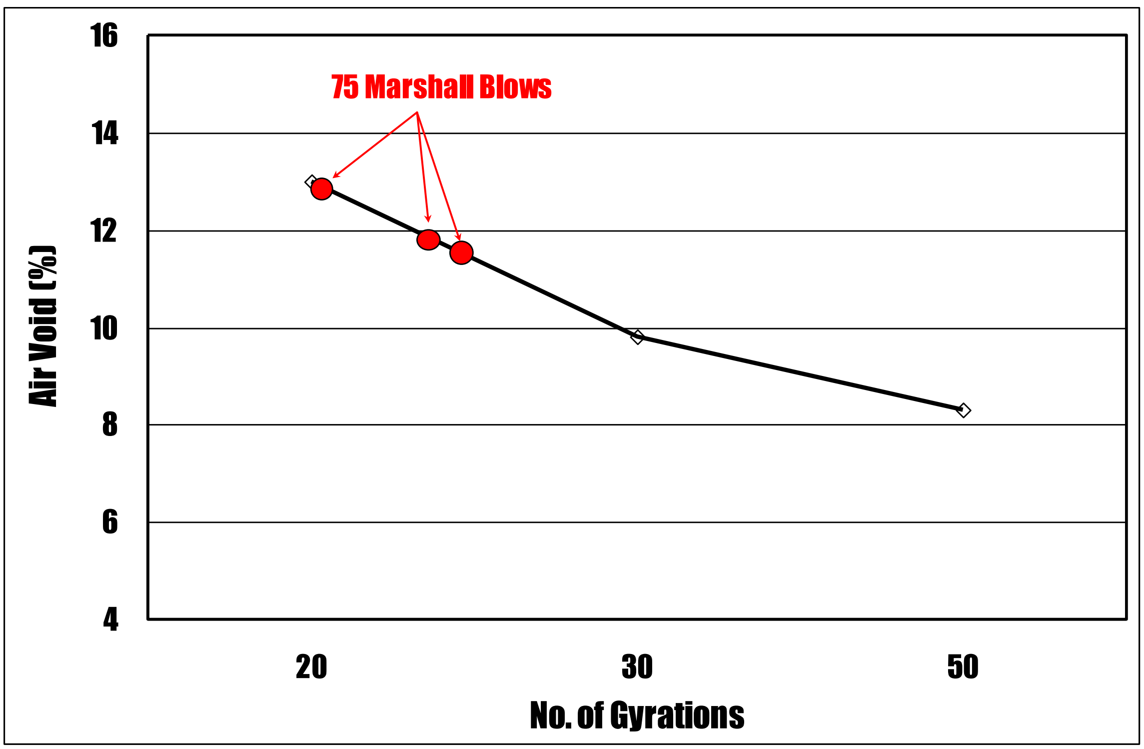


Figure 6-2. Plots of average air voids against different number of gyrations

6.2 Wet Indirect Tensile Strength

CIR-CSS-1h mixtures were compacted at room temperature (25˚C) and cured in the oven at 40˚C for 72 hours. After oven curing, the specimens were allowed to cool down to a room temperature, which normally takes about 2 hours but were reduced to 15 minutes when a fan was used. The cured CIR-CSS-1h specimens for testing at wet condition were placed in 25˚C water bath for 30 minutes, and vacuumed saturated at 20 mmHg for 30 minutes. The saturated wet specimens were left under the water bath at 25˚C for additional 30 minutes. The indirect tensile strength test was performed on wet CIR-CSS-1h specimens.

The indirect tensile strengths of CIR-CSS-1h specimens under three levels of gyration and 75 blows of Marshall hammer are summarized in Table 6-5 and plotted in Figure 6-3. As can be seen from Figure 6-3, the indirect tensile strength steadily increased as the number of gyrations increased. It should be also noted that the indirect tensile strength of the 75-blow Marshall compacted CIR-CSS-1h specimens is similar to the specimen compacted with 20 gyrations to 30 gyrations.

Table 6-5. Results of indirect tensile strength at four different compaction levels

No. of Specimen	Compaction Level			
	20 gyrations	30 gyrations	50 gyrations	75 blows
1	32.2 psi	48.1 psi	48.8 psi	33.4 psi
2	27.1 psi	36.1 psi	45.6 psi	34.7 psi
3	35.6 psi	35.1 psi	38.7 psi	38.1 psi
Average	31.6 psi	39.8 psi	44.4 psi	35.4 psi

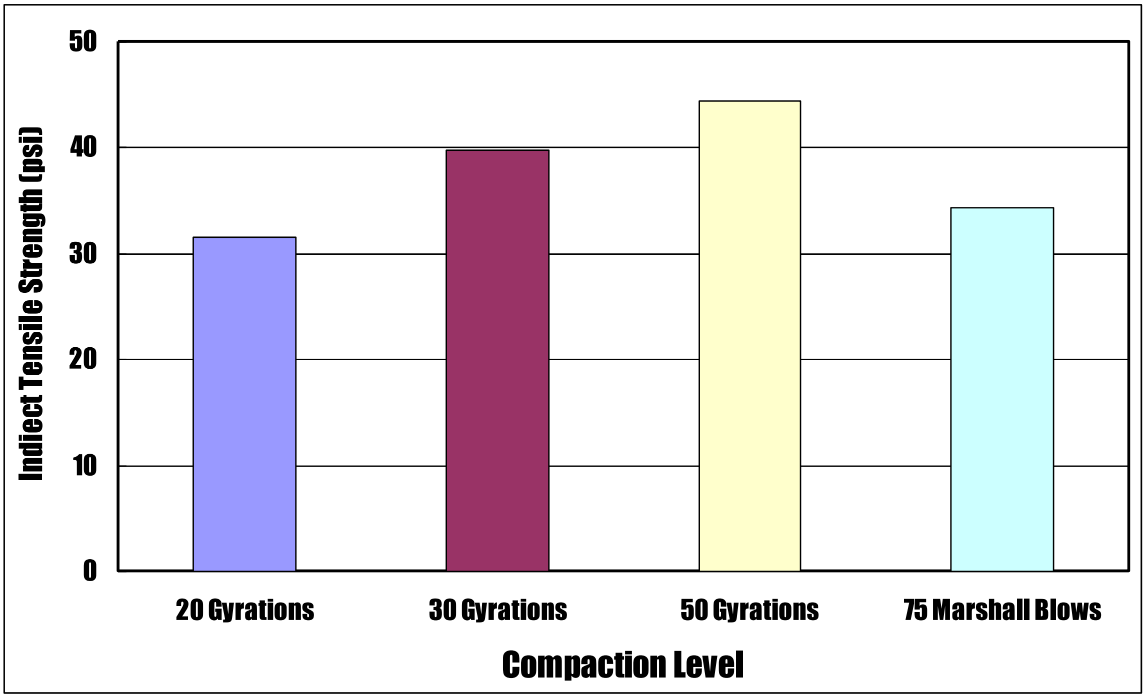
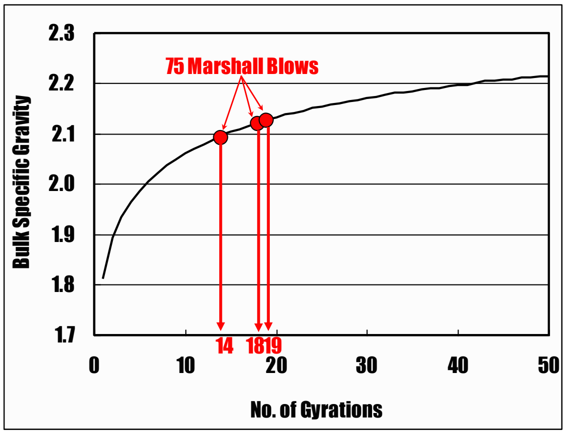


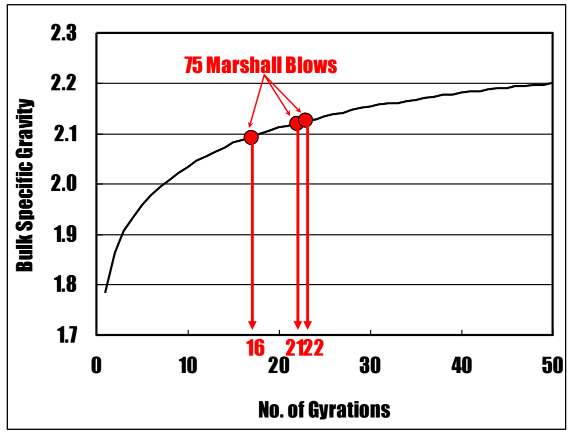
Figure 6-3. Comparison of average indirect tensile strength at four different compaction levels

6.3 Bulk Specific Gravities by Gyratory versus Marshall Compaction

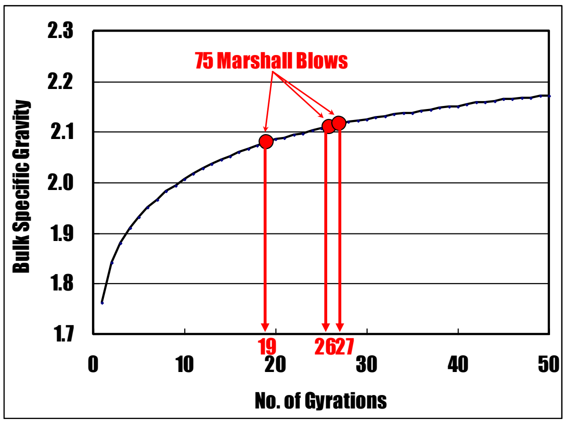
Bulk specific gravities of the 75-blow Marshall compacted CIR-CSS-1h specimens were compared against those of the gyratory compacted CIR-CSS-1h specimens up to 50 gyrations. Figure 6-4 shows bulk plots of specific gravities by gyratory compactor and Marshall hammer against the number of gyrations. As shown in Figure 6-4 (a), (b), and (c)**,** the bulk specific gravities of three CIR-CSS-1h specimens compacted with 75-blow Marshall hammer are plotted to identify the equivalent numbers of gyrations that are in the ranges of 14-19, 16-22, and 19-27, respectively. The average equivalent number of gyrations corresponding 75 blows ranged from 16-23 as shown in Figure 6-4 (d). Based on the limited test results, 25 gyration is selected as the gyration level that would achieve the similar density as the one with 75-blow Marshall hammer. It is interesting to note that the same gyration level was obtained for CIR-foam mixtures.



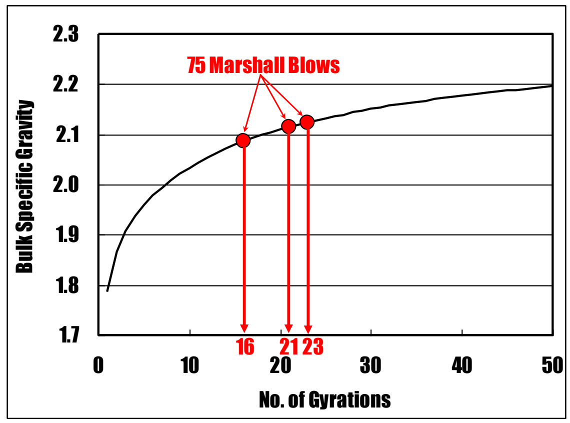
(a) Specimen # 1



(b) Specimen # 2



(c) Specimen # 3



(d) Average

Figure 6-4. Correlation of bulk specific gravity between gyratory and Marshall compacted CIR-CSS-1h specimens

7. APPLICATION OF CIR-FOAM MIX DESIGN PROCESS FOR CIR-EMULSION MIXTURES

In order to determine if the developed CIR-foam mix design process is applicable to CIR-emulsion mixtures, as summarized in Table 7-1, the indirect tensile strength was measured from the wet conditioned gyratory-compacted specimens using two different RAP sources at six different emulsion contents, 0.0%, 0.5%, 1.0%, 1.5%, 2.0% and 2.5% of both standard emulsion (CSS-1h) and engineered emulsion (HFMS-2p). The indirect tensile strength was measured from the wet conditioned Marshall-compacted specimens at four different emulsion contents, 0.5%, 1.0%, 1.5%, and 2.0%. As summarized in Table 7-2, the CIR-emulsion specimens were prepared using both gyratory compactor and Marshall hammer for a combination of six emulsion contents and two different RAP sources.

Table 7-1. Design parameters selected for mix design process for CIR-emulsion

Item	Compaction Method	
	Gyratory Compactor	Marshall Compactor
Type of Emulsion	CSS-1h and HFMS-2p	
Water Content (%)	3.0	
Emulsion Content (%)	0.0, 0.5, 1.0, 1.5, 2.0, and 2.5	0.5, 1.0, 1.5, and 2.0
Curing Condition	oven at 40°C for 3 days	

Table 7-2. Number of specimens prepared for each type of emulsion

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
No. of Specimen	3	3	3	3	3	3	3	3	3	3

7.1 Volumetric Characteristics

7.1.1 Bulk Specific Gravities

Table 7-3 and Table 7-4 summarize the bulk specific gravities (G_{mb}) of CIR-CSS-1h and CIR-HFMS-2p specimens compacted by the gyratory compactor and the Marshall hammer. The bulk specific gravities of CIR-CSS-1h specimens (gyratory and Marshall compacted) and CIR-HFMS-2p specimens (gyratory and Marshall compacted) are plotted against emulsified asphalt contents in Figure 7-1, Figure 7-2, Figure 7-3 and Figure 7-4, respectively. Overall, the bulk specific gravities tend to increase as the emulsified asphalt content increases.

Table 7-3. Bulk specific gravities (G_{mb}) of CIR-CSS-1h specimens compacted by Gyratory compactor and Marshall hammer

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
Clayton County	2.023	2.011	2.059	2.145	2.193	2.207	2.089	2.106	2.117	2.121
Story County	2.029	2.030	2.102	2.102	2.125	2.141	2.115	2.112	2.099	2.147

Table 7-4. Bulk specific gravities (G_{mb}) of CIR-HFMS-2p specimens compacted by Gyratory compactor and Marshall hammer

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
Clayton County	2.023	2.096	2.078	2.130	2.150	2.191	2.145	2.193	2.207	2.205
Story County	2.029	2.118	2.086	2.124	2.117	2.144	2.102	2.125	2.141	2.134

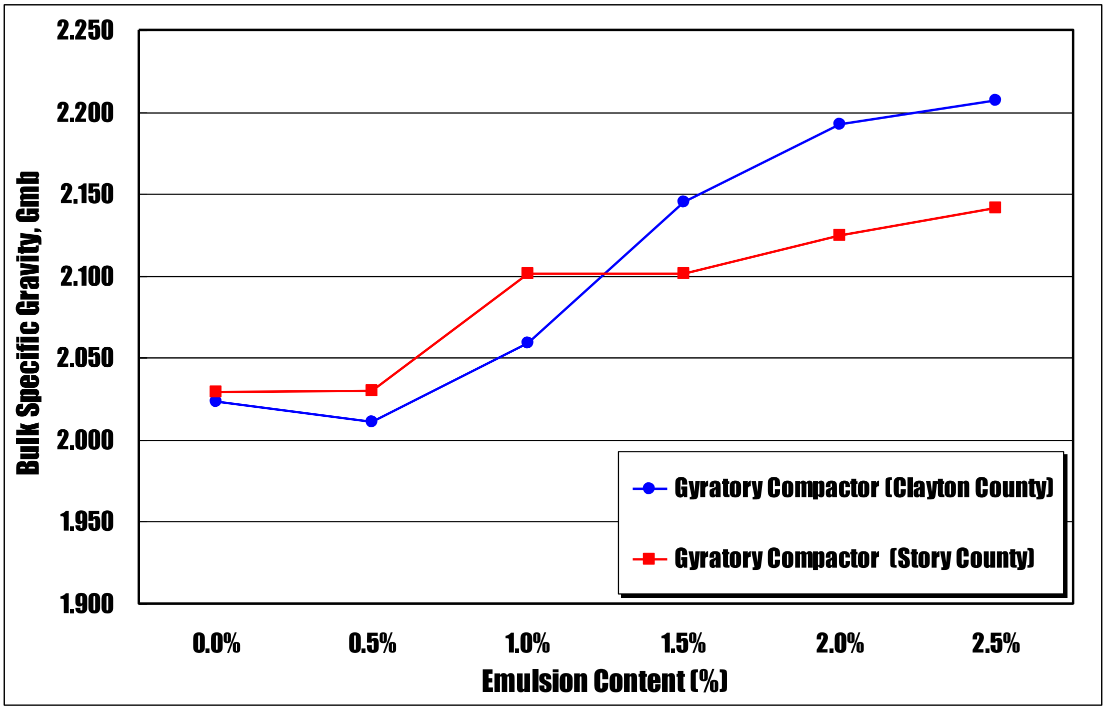


Figure 7-1. Plots of bulk specific gravity against emulsified asphalt content for gyratory compacted CIR-CSS-1h specimens using different RAP materials

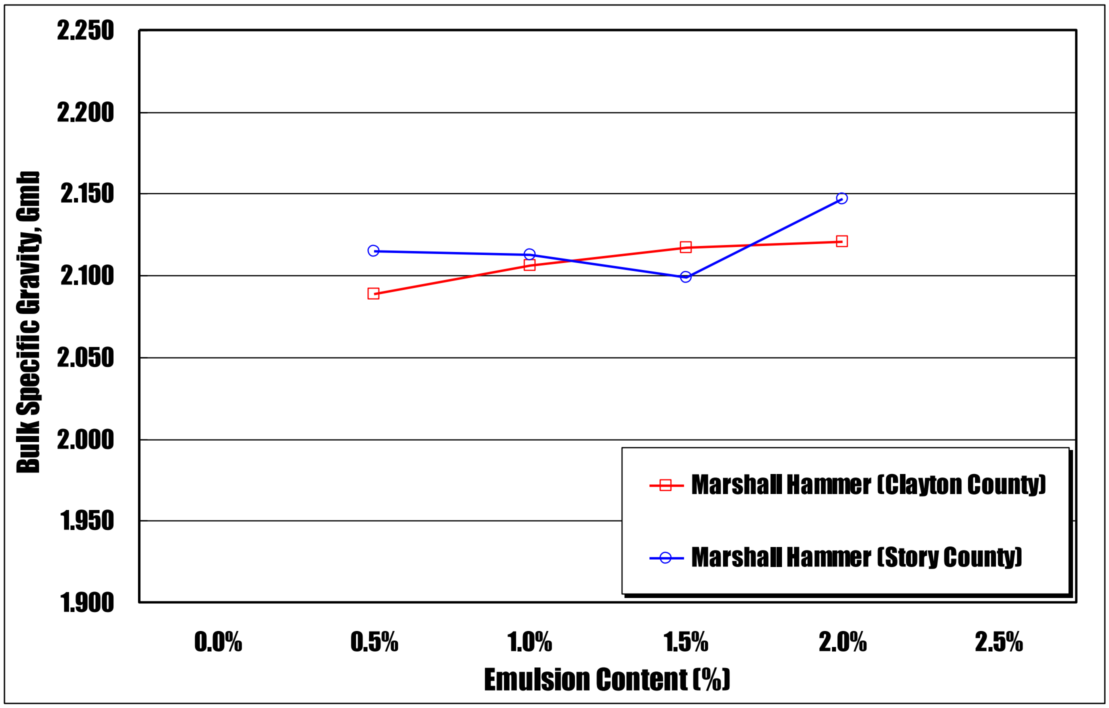


Figure 7-2. Plots of bulk specific gravity against emulsified asphalt content for Marshall compacted CIR-CSS-1h specimens using different RAP materials

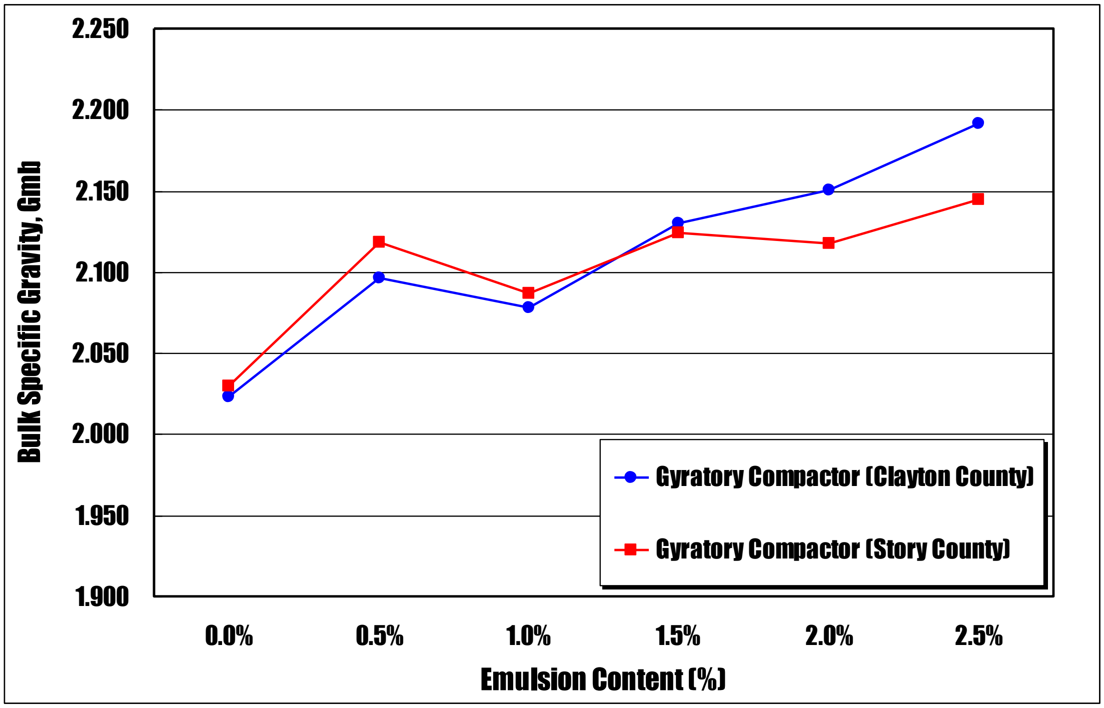


Figure 7-3. Plots of bulk specific gravity against emulsified asphalt content for gyratory compacted CIR-HEMS-2p specimens using different RAP materials

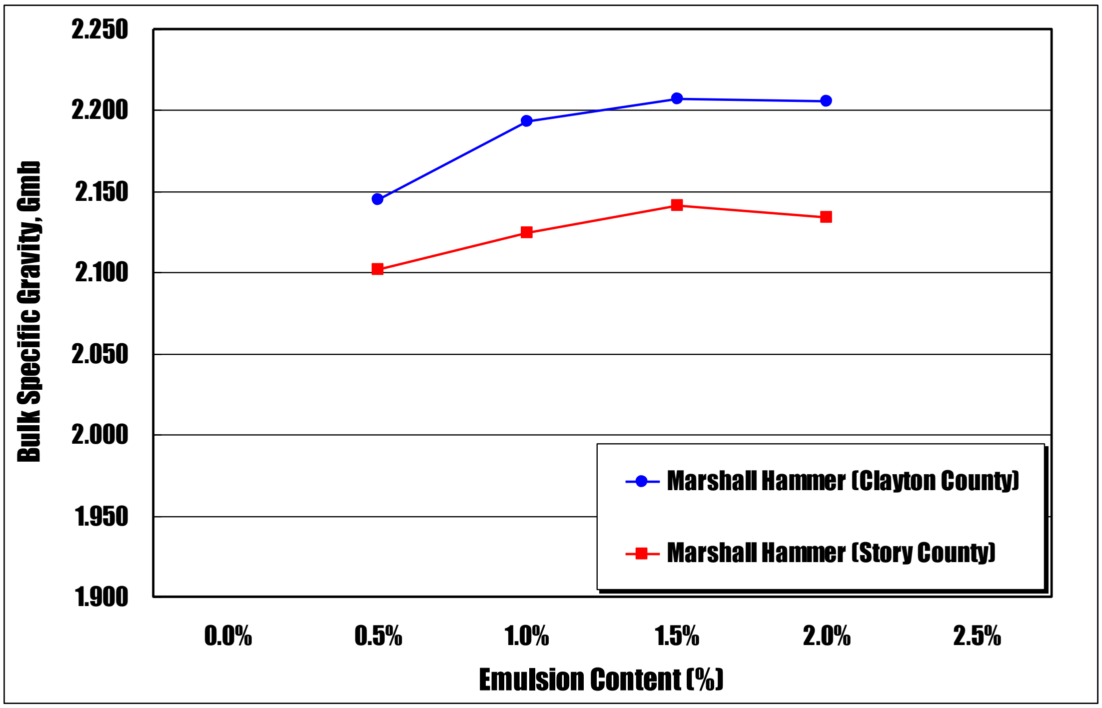


Figure 7-4. Plots of bulk specific gravity against emulsified asphalt content for Marshall compacted CIR-HFMS-2p specimens using different RAP materials

7.1.2 Theoretical Maximum Specific Gravities

The maximum theoretical gravity was measured at six different emulsified asphalt contents for CIR-CSS-1h and CIR-HFMS-2p mixtures using two different RAP materials. As shown in Figure 7-5, the theoretical maximum gravity decreases as the emulsion content increases.

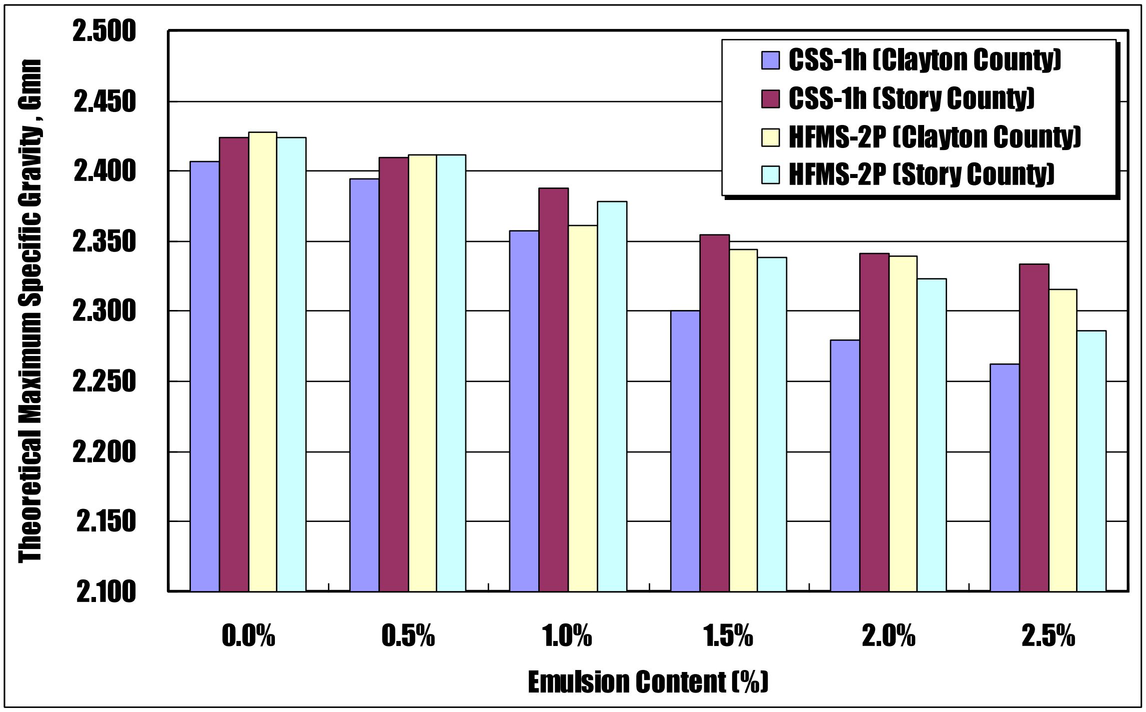


Figure 7-5. Bar charts of theoretical maximum specific gravities against emulsified asphalt content for two emulsion types and two RAP sources

7.1.3 Air Voids

Table 7-5 and Table 7-6 summarize the computed air voids of CIR-emulsion specimens compacted by gyratory compactor and Marshall hammer using CSS-1h and HFMS-2p, respectively. Air voids of the CIR-CSS-1h specimens (gyratory and Marshall compacted) and CIR-HFMS-2p specimens (gyratory and Marshall compacted) are plotted against emulsion contents in Figure 7-6, Figure 7-7, Figure 7-8, and Figure 7-9, respectively. As expected, air voids decreased as emulsion contents increased.

Table 7-5. Calculated air void of CIR-CSS-1h specimens compacted by Gyratory compactor and Marshall hammer

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
Clayton County	15.9	16.0	12.7	6.8	3.8	2.4	12.8	10.7	8.0	7.0
Story County	16.3	15.8	12.0	10.8	9.2	8.2	12.2	11.5	10.9	8.3

Table 7-6. Calculated air void of CIR-HFMS-2p specimens compacted by Gyratory compactor and Marshall hammer

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
Clayton County	16.7	13.1	12.0	9.1	8.1	5.4	11.0	7.1	5.8	5.7
Story County	14.7	10.9	12.3	9.2	8.9	6.2	12.9	10.7	8.4	8.2

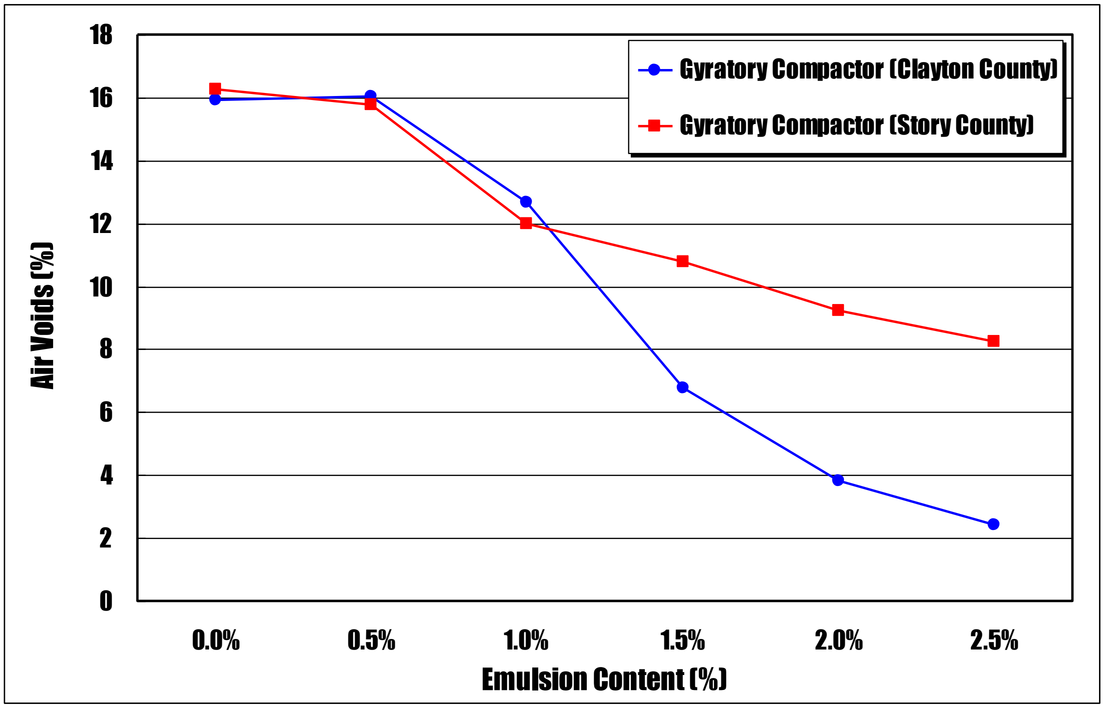


Figure 7-6. Plots of air void against emulsified asphalt content for gyratory compacted CIR-CSS-1h specimens using two different RAP materials

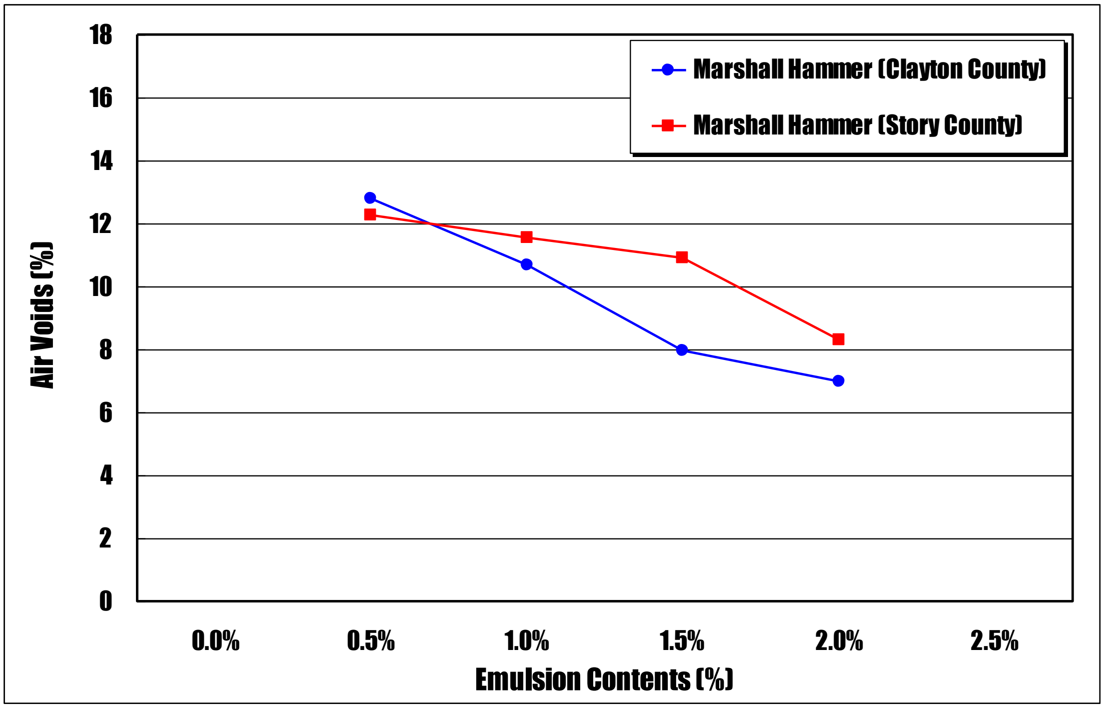


Figure 7-7. Plots of air void against emulsified asphalt content for Marshall compacted CIR-CSS-1h specimens using two different RAP materials

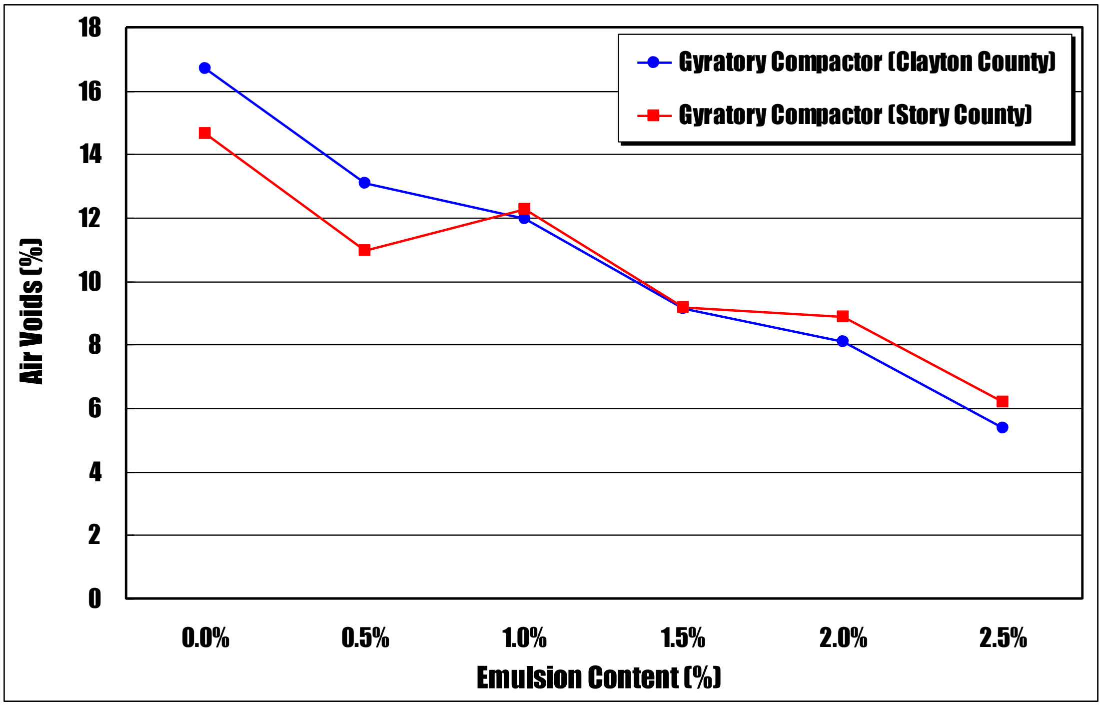


Figure 7-8. Plots of air void against emulsified asphalt content for gyratory compacted CIR-HFMS-2p specimens using two different RAP materials

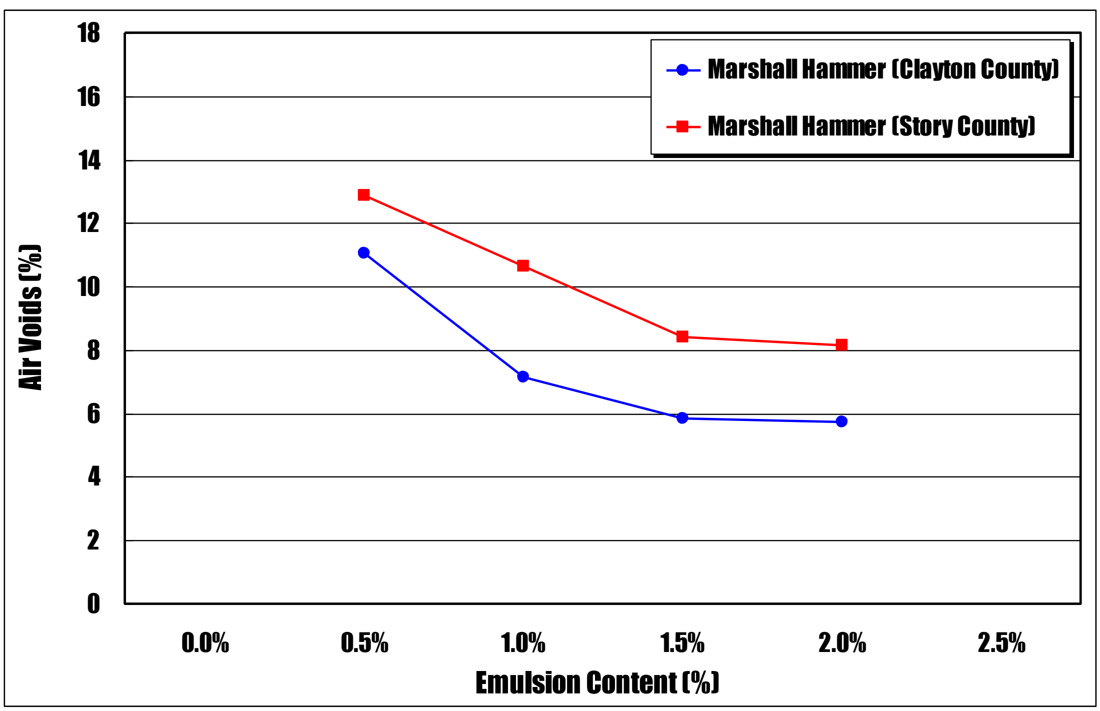


Figure 7-9. Plots of air void against emulsified asphalt content for Marshall compacted HFMS-2p specimens using two different RAP materials

7.2 Wet Indirect Tensile Strength

To measure the indirect tensile test, a total of twelve specimens were prepared for each emulsion type: three specimens using gyratory compactor and RAP materials form Clayton County, three specimens using Marshall hammer and RAP materials from Clayton County, three specimens using gyratory compactor and RAP materials from Story County, and three specimens using Marshall hammer and RAP materials from Story County. After curing in the oven for 3 days at 40^{o}C, the CIR-emulsion specimens were allowed to cool down to a room temperature. CIR-emulsion specimens were placed in 25^{o}C water for 30 minutes as shown in Figure 7-10 (a), vacuumed at 20 mm Hg for 30 minutes as shown Figure 7-10 (b), and remained under water for additional 30 minutes as shown in Figure 7-10 (c).

(a) soaking (b) vacuuming (c) soaking

Figure 7-10. Vacuum saturation procedure for making wet specimens

Table 7-7 and Table 7-8 summarize the indirect tensile strengths of CIR-emulsion specimens using CSS-1h and HFMS-2p, respectively. The indirect tensile strengths of the CIR-CSS-1h specimens (gyratory and Marshall compacted) and CIR-HFMS-2p specimens (gyratory and Marshall compacted) are plotted against emulsion contents in Figure 7-11, Figure 12, Figure 13, and Figure 14, respectively. Overall, the indirect tensile strengths of gyratory compacted specimens are slightly higher than those of Marshall compacted specimens. As shown in Figure 7-11, a clear peak could be observed at 1.0% of emulsified asphalt content for gyratory compacted CIR-CSS-1h specimens using RAP materials from both Clayton and Story Counties. For the Marshall compacted CIR-CSS-1h specimens, as shown in Figure 7-12, a peak was observed at 1.0% of emulsified asphalt content for RAP materials from Story County and at 1.5% emulsion content for RAP materials from Clayton County. As shown in Figure 7-13, a clear peak was observed at 1.0% of emulsified asphalt content for the gyratory compacted CIR-HFMS-2p specimens prepared using RAP materials from both Clayton and Story Counties. As shown in Figure 7-14, a peak was observed at emulsified asphalt content between 1.0% and 1.5% for the Marshall compacted CIR-HFMS-2p specimens using RAP materials from Clayton County and no peak was observed for RAP materials from Story County.

Table 7-7. Wet indirect tensile strength (psi) of CIR-CSS-1h specimens compacted by Gyratory compactor and Marshall hammer

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
Clayton County	21.7	28.6	32.9	25.7	20.9	14.8	23.4	25.7	25.2	23.1
Story County	20.4	28.6	37.7	32.8	26.2	21.0	21.8	23.6	29.5	26.2

Table 7-8. Indirect tensile strength (psi) of CIR-HFMS-2p specimens compacted by Gyratory compactor and Marshall hammer

	Compaction Method									
	Gyratory Compactor (25 gyrations)						Marshall Hammer (75 blows)			
Emulsion Content (%)	0.0	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0
Clayton County	21.7	24.8	37.4	31.4	27.6	20.3	19.3	22.8	22.7	20.1
Story County	20.4	24.9	37.9	33.8	31.2	31.8	25.2	21.7	23.3	20.6

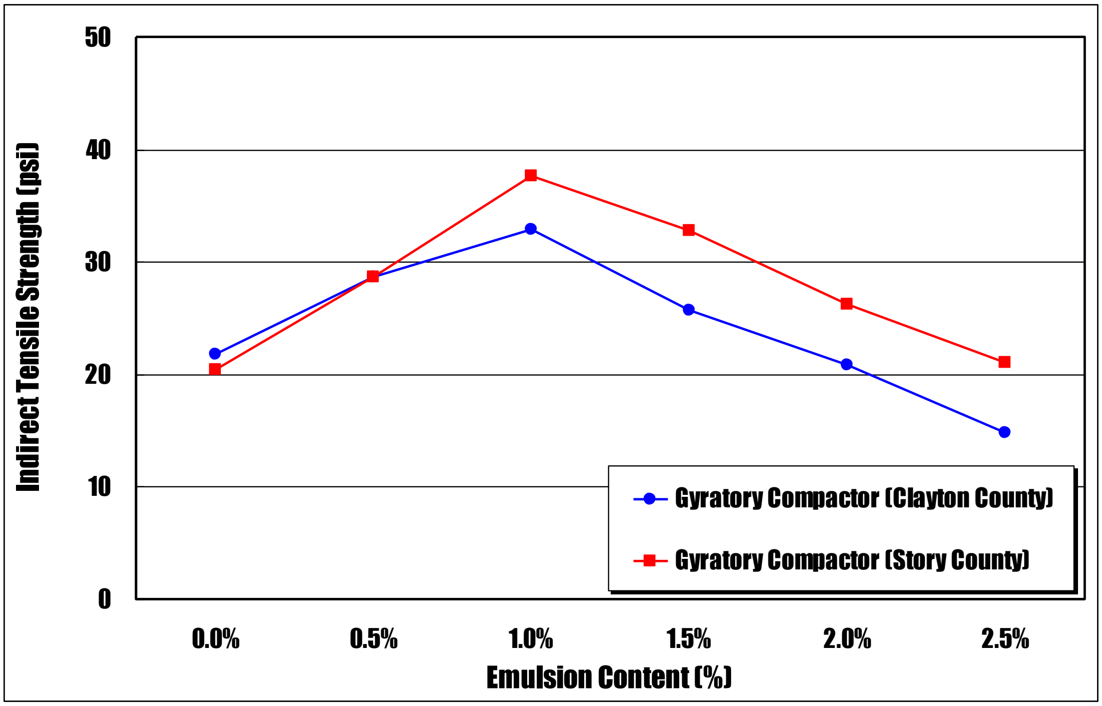


Figure 7-11. Plots of indirect tensile strength against emulsified asphalt content for Gyratory compacted CIR-CSS-1 specimens using two different RAP materials

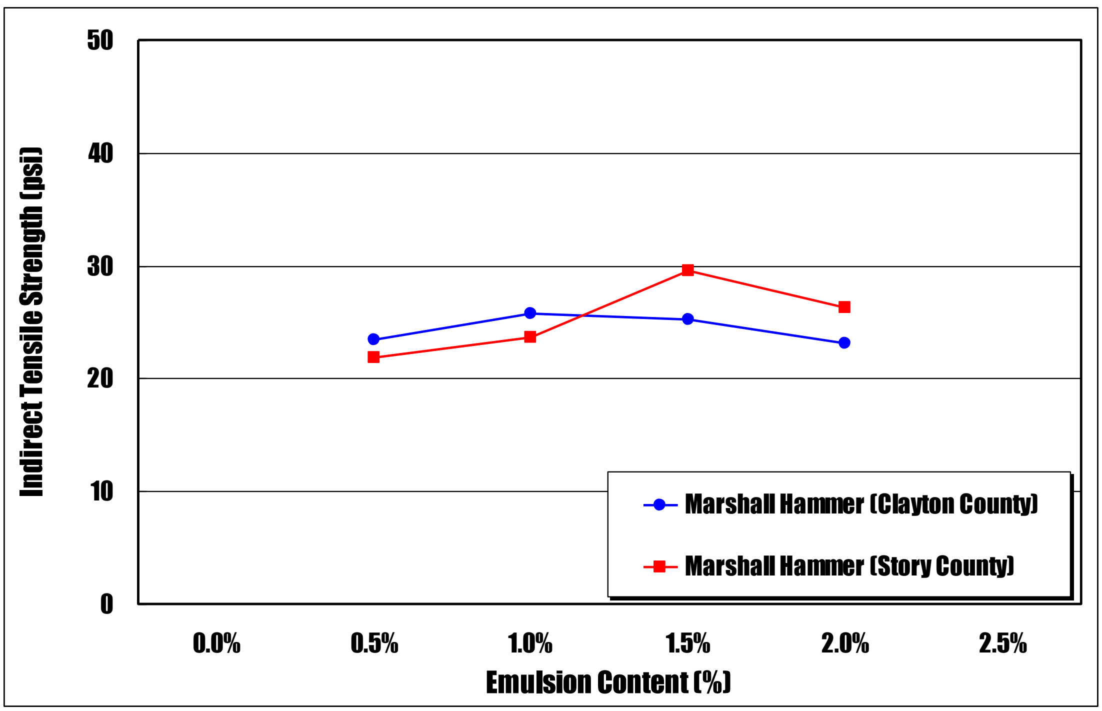


Figure 7-12. Plots of indirect tensile strength against emulsified asphalt content for Marshall compacted CIR-CSS-1 specimens using two different RAP materials

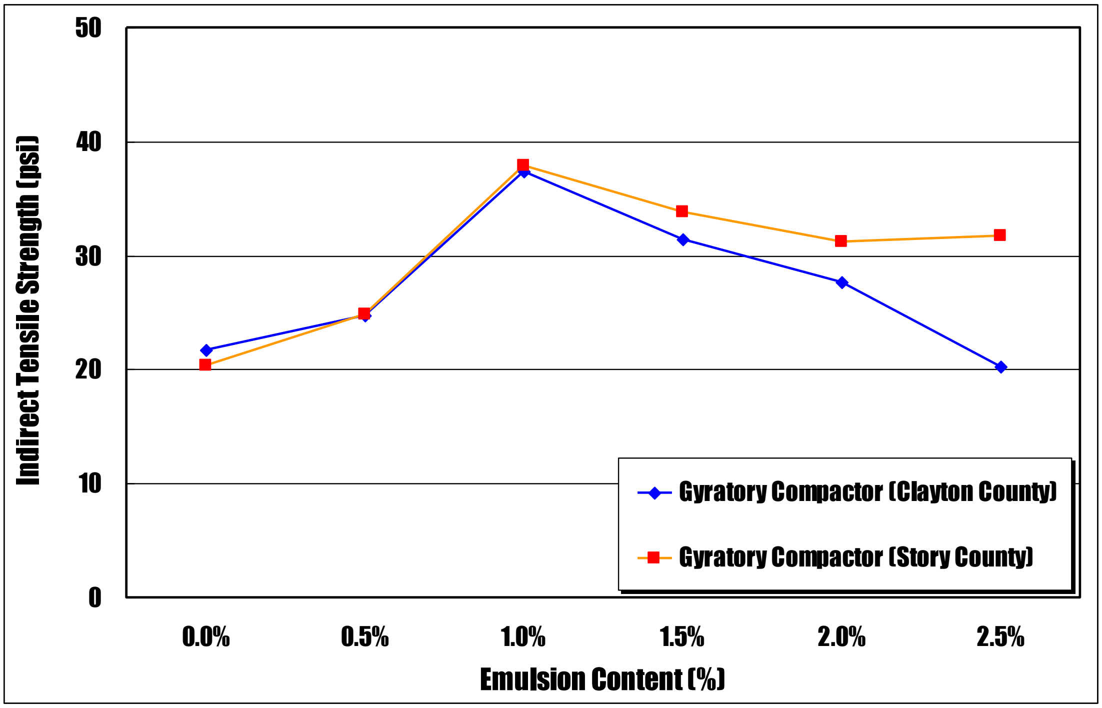


Figure 7-13. Plots of indirect tensile strength against emulsified asphalt content for gyratory compacted CIR- HFMS-2p specimens using two different RAP materials

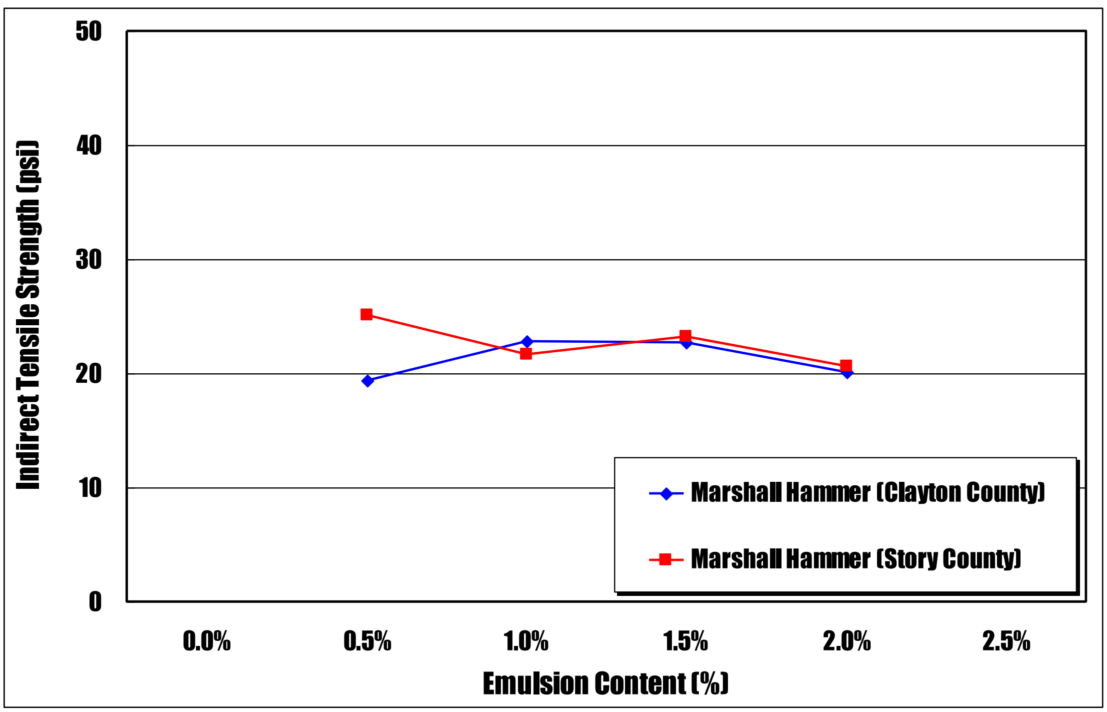


Figure 7-14. Plots of indirect tensile strength against emulsified asphalt content for Marshall compacted CIR- HFMS-2p specimens using two different RAP materials

7.3 Comparisons against CIR-foam Test Results

The indirect tensile strength results of CIR-emulsion mixtures were compiled and compared against the CIR-foam test results obtained during the phase 2 study. Table 7-9 and Table 7-10 summarize the indirect tensile strengths of CIR-foam and CIR-emulsion specimens using gyratory compactor and Marshall hammer, respectively. As shown in Table 7-9, the peak indirect tensile strengths of gyratory-compacted CIR-foam mixtures were obtained at foamed asphalt contents between 1.5% and 2.5% with the indirect tensile strengths raging from 31.0 psi to 44.1 psi whereas the peak indirect tensile strengths of CIR-emulsion mixtures were obtained consistently at 1.0% with the values raging from 32.9 psi to 37.9 psi. As shown in Table 7-10, the peak indirect tensile strengths of Marshall-compacted CIR-foam mixtures were observed at foamed asphalt contents between 1.5% and 2.5% with the indirect tensile strengths ranging from 28.6 psi to 38.5 psi whereas the peak indirect tensile strengths of CIR-emulsion mixtures were obtained at the emulsion content between 0.5% and 1.5% with indirect tensile strengths ranging from 22.8 psi to 29.5 psi.

Table 7-9. ITS comparisons between CIR-foam and CIR-emulsion mixtures compacted by gyratory compactor

FAC	1.0%	1.5%	2.0%	2.5%	3.0%
Compaction Method	Gyratory Compactor (30 gyrations)				
Curing Temperature	40°C				
RAP Sources	Indirect Tensile Strength (psi)				
Muscatine County	29.7	33.2	37.6	36.8	33.6
Webster County	28.2	29.8	31.2	32.0	29.0
Hardin County	32.2	40.9	44.1	40.2	39.0
Montgomery County	31.1	33.8	33.3	32.3	31.7
Bremer County	25.6	26.9	29.3	31.0	28.6
Lee County	26.3	30.8	31.7	31.4	31.0
Wapello County	29.2	34.9	35.0	33.2	32.8

EAC	0.0%	0.5%	1.0%	1.5%	2.0%	2.5%
Compaction Method	Gyratory Compactor (25 gyrations)					
Curing Temperature	40°C					
RAP Sources (Emulsion Type)	Indirect Tensile Strength (psi)					
Clayton County (CSS-1h)	21.7	28.6	32.9	25.7	20.9	14.8
Story County (CSS-1h)	20.4	28.6	37.7	32.8	26.2	21.0
Clayton County (HFMS-2p)	21.7	24.8	37.4	31.4	27.6	20.3
Story County (HFMS-2p)	20.4	24.9	37.9	33.8	31.2	31.8

Table 7-10. ITS comparisons between CIR-foam and CIR-emulsion mixtures compacted by Marshall hammer

FAC	1.0%	1.5%	2.0%	2.5%	3.0%
Compaction Method			Marshall Hammer (75 blows)		
Curing Temperature			40°C		
RAP Sources			Indirect Tensile Strength (psi)		
Muscatine County	26.0	27.9	30.9	28.7	28.1
Webster County	25.6	29.9	28.0	27.7	27.1
Hardin County	24.4	25.9	31.3	30.3	28.3
Montgomery County	27.1	30.2	28.0	27.4	26.0
Bremer County	25.5	26.4	26.7	28.6	26.3
Lee County	25.7	26.5	27.4	28.7	27.6
Wapello County	28.8	34.5	31.3	29.2	29.2

EAC	0.5%	1.0%	1.5%	2.0%
Compaction Method		Marshall Hammer (75 blows)		
Curing Temperature		40°C		
RAP Sources (Emulsion Type)		Indirect Tensile Strength (psi)		
Clayton County (CSS-1h)	23.4	25.7	25.2	23.1
Story County (CSS-1h)	21.8	23.6	29.5	26.2
Clayton County (HFMS-2p)	19.3	22.8	22.7	20.1
Story County (HFMS-2p)	25.2	21.7	23.3	20.6

8. PERFORMANCE PREDICTION OF CIR-EMULSION MIXTURES USING SIMPLE PERFORMANCE TESTS

During the previous study, the simple performance tests, which include dynamic modulus, dynamic creep, and raveling tests, were conducted to evaluate the performance characteristics of CIR-foam mixtures to ensure reliable mixture performance over a wide range of traffic and climate conditions (Lee and Kim, 2007). As summarized in Table 8-1, to predict the long-term performance characteristics of CIR-emulsion mixtures, the simple performance tests were conducted under a wide range of loading and temperature conditions.

Table 8-1. Laboratory testing conditions for four simple performance tests

Simple Performance Test	Testing Condition
Dynamic modulus Test	• Testing Temperature: 4.4°C, 21.1°C, and 37.8°C • Loading Frequency: 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz
Dynamic Creep Test	• Testing Temperature: 40°C • Loading Pressure: 20 psi • Applied Loading Cycle: 10,000 cycles
Static Creep Test	• Testing Temperature: 40°C • Loading Pressure: 20 psi and 10 psi • Applied Loading Time: 10,000 seconds
Raveling Test	• Testing Temperature: 25°C • Curing Period: at room temperature for 4hrs

8.1 Dynamic Modulus Test

The dynamic modulus test is to determine the stiffness of asphalt mixtures on the response to loading and various temperature conditions. Many researchers measured the dynamic modulus of hot mix asphalt (HMA) mixtures and discovered that the dynamic modulus was affected by a combined effect of asphalt binder stiffness and aggregate size distribution (Clyne et al. 2003; Ekingen 2004; Brown et al. 2004; Birgisson et al. 2004; Lundy et al. 2005).

8.1.1 Theory

The fundamental concept behind the dynamic modulus test is a linear visco-elasticity of asphalt mixtures. The stress to strain relationship under a continuous sinusoidal loading for linear visco-elastic materials is defined by a complex number called complex modulus, where its absolute value is defined as the dynamic modulus. The dynamic modulus is mathematically defined as the maximum dynamic stress (σ_0) divided by peak recoverable axial strain (ε_0) as follows:

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0}$$

The measured dynamic modulus at different temperatures can be then shifted relative to the frequency so that several curves can be aligned to form a single master curve. In constructing the master curve, as shown in Figure 8-1, the measured dynamic moduli at test temperatures higher than the reference temperature are horizontally shifted to lower frequencies and those measured at test temperatures lower than the reference temperature are shifted to the higher frequencies. A master curve can be constructed based on the time-temperature correspondence principle, which utilizes the equivalency between frequency and temperature. The master curve of an asphalt mixture allows comparisons to be made over extended ranges of frequencies and temperature.

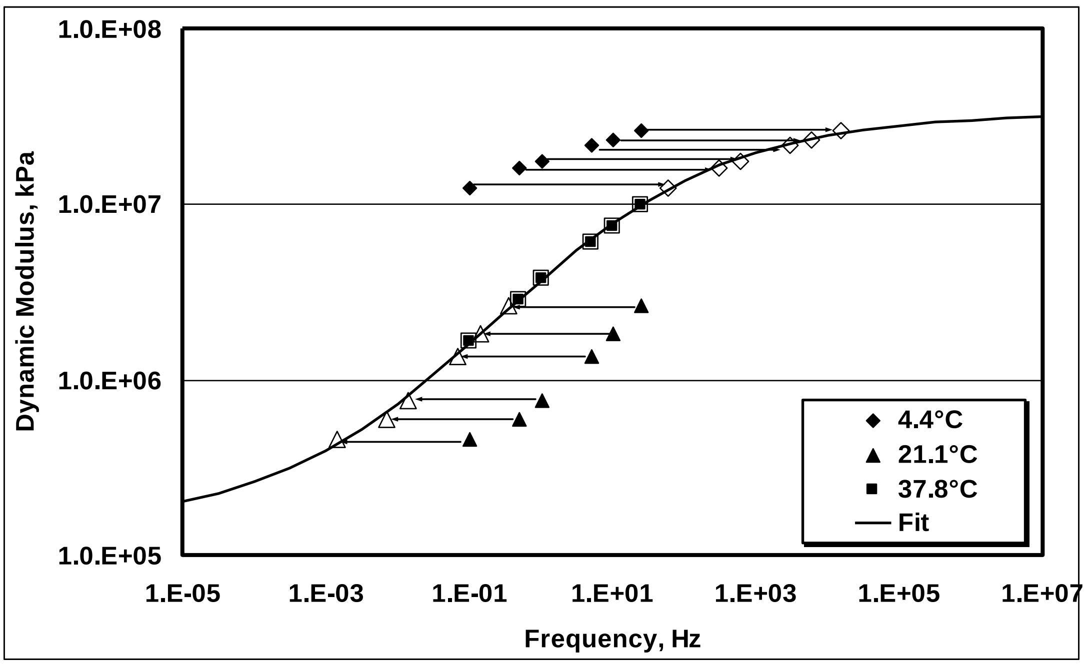


Figure 8-1. Construction of master curve

8.1.2 Dynamic Modulus Testing Procedure

Witczak et al. (2002) and Bonaquist et al. (2003) described the development of the Superpave Simple Performance Test (SPT) equipment, which can perform dynamic modulus, static creep and dynamic creep tests at various loading and temperature conditions. As shown in Figure 8-2, it is easy to access the test specimen from all sides when the temperature and pressure vessel is at an open position. Also, this system utilizes a magnetic mounted extensometer, which snaps on the test specimen with a minimum disruption to temperature control. A stand-alone environmental unit can provide heated and refrigerated air to the environmental test chamber, which ranges from 4˚C to 60˚C.

Figure 8-2. Simple performance testing equipment

Based upon the NCHRP Project 9-19, Witzack et al. (2002) investigated the proper size and geometry of the dynamic modulus test specimens and recommended using 100-mm diameter cored specimens from a 150-mm diameter gyratory compacted specimen, with cut height of 150-mm. In this study, however, the gyratory compacted CIR-emulsion specimens with 100-mm diameter and 150-mm height were prepared for dynamic modulus test because CIR-emulsion specimens were not strong enough to be cored from 150mm-diameter CIR-emulsion specimens.

The 62-03 protocol: Determining Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures (ASSHTO, 2007) was modified to be performed at three temperatures of 4.4°C, 21.1°C, and 37.8°C and six frequencies of 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz. To minimize a potential damage to the specimens, testing began at the lowest temperature and proceeded to a higher temperature. For a given temperature, the testing began with the highest frequency of loading and proceeded to a lower frequency.

Before beginning the test, two linear variable displacement transducers (LVDT's) were adjusted to the end of its linear range to allow a full range to be available for the accumulation of compressive permanent deformation. A minimum contact load equal to 5.0% of the dynamic load was applied to the CIR-emulsion specimen. A sinusoidal axial compressive load was applied to CIR-emulsion specimen while maintaining the axial strain at 100 microstrain. The test results during the last ten cycles were recorded for each frequency.

8.1.3 Experimental Plan

Table 8-2 summarizes mix design parameters, which were adopted to prepare CIR-emulsion specimens using two different RAP sources and two different types of emulsified asphalt. For each RAP source, two CIR-emulsion specimens were prepared for each of three emulsified asphalt contents (EAC), 0.5%, 1.0% and 1.5%, given a constant moisture content of 3.0%. CIR-emulsion specimens were compacted using a gyratory compactor at 25 gyrations and were cured in the oven at 40°C for three days. The cured specimens were allowed to cool to a room temperature for 24 hours before testing.

Table 8-2. Design parameters selected for simple performance test specimens

Parameters	Condition
Emulsion Type	CSS-1h and HFMS-2p
Water Content (%)	3.0 %
Emulsion Content (%)	0.5%, 1.0%, and 1.5%
RAP Source	Clayton County and Story County
Compaction Method	Gyratory Compaction at 25 gyrations
Curing Condition	Oven at 40˚C for 3 days
Number of Specimens	2 specimens at each emulsion content

8.1.4 Results and Discussion

The bulk specific gravities and air voids were measured for each CIR-emulsion specimen. The dynamic modulus test was performed to determine: 1) variations in dynamic modulus values among two different RAP sources and two different types of emulsified asphalt; 2) effect of the emulsified asphalt content on dynamic modulus; 3) effects of test temperature and loading frequency on dynamic modulus; and 4) comparisons against the CIR-foam test results obtained from the previous study.

8.1.4.1 Volumetric Characteristics

For each RAP source, two CIR-emulsion specimens were prepared for dynamic modulus test for each of three emulsified asphalt contents. The bulk specific gravities of each CIR-emulsion specimen were determined following the AASHTO T 166 by measuring the dry mass and height (AASHTO, 2007). As summarized in Table 8-3, overall, the bulk specific gravities of CIR-emulsion mixtures increased as the emulsified asphalt content increased. Air voids of CIR-emulsion specimens decreased as the emulsified asphalt content increased.

Table 8-3. Bulk specific gravity and air void of CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources for dynamic modulus test

Emulsion Type	RAP Source	EAC (%)	G_{mb}			Air Void (%)	
			Individual		Average	Individual	Average
CSS-1h	Clayton County	0.5	# 1	2.056	2.050	14.1	14.4
			# 2	2.043		14.7	
		1.0	# 1	2.051	2.047	13.0	13.2
			# 2	2.042		13.4	
		1.5	# 1	2.097	2.106	8.9	8.5
			# 2	2.114		8.1	
	Story County	0.5	# 1	2.041	2.047	15.3	15.1
			# 2	2.052		14.9	
		1.0	# 1	2.064	2.059	13.6	13.8
			# 2	2.053		14.0	
		1.5	# 1	2.059	2.056	12.6	12.7
			# 2	2.053		12.8	
HFMS-2p	Clayton County	0.5	# 1	2.060	2.065	14.6	14.4
			# 2	2.069		14.2	
		1.0	# 1	2.085	2.082	12.3	12.5
			# 2	2.079		12.6	
		1.5	# 1	2.103	2.101	10.0	10.1
			# 2	2.099		10.2	
	Story County	0.5	# 1	2.073	2.070	14.1	14.2
			# 2	2.067		14.3	
		1.0	# 1	2.085	2.091	11.7	11.5
			# 2	2.096		11.2	
		1.5	# 1	2.112	2.136	9.9	8.9
			# 2	2.160		7.8	

8.1.4.2 Dynamic Modulus Test Results

The dynamic modulus tests were performed on CIR-emulsion mixtures at six different loading frequencies and three different test temperatures. The dynamic modulus was measured from each specimen twice. Table 8-4 to Table 8-7 summarize the average dynamic moduli of two different type of emulsified asphalt and two different RAP sources measured for three different emulsified asphalt contents. Given the same RAP material, dynamic modulus value of CIR-emulsion mixtures using CSS-1h was consistently higher than that of HFMS-2p.

Table 8-8 summarizes the rankings of dynamic modulus at three different emulsified asphalt contents for a combination of two emulsion types and two RAP sources. As can be easily observed from the table, the ranking of CIR-emulsion mixtures changed when the emulsified asphalt was increased from 0.5% to 1.5%, which indicates that the dynamic modulus values are affected by both emulsion types and emulsified asphalt contents, and RAP aggregate structure.

Table 8-4. Summary of dynamic moduli of CIR-CSS-1h mixtures from Clayton County

Dynamic Modulus (kPa) at EAC=0.5%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,535,450	9,317,154	9,426,302	5,187,792	4,800,804	4,994,298	2,484,066	2,207,531	2,345,799
10	8,805,916	8,672,800	8,739,358	4,444,258	4,203,633	4,323,946	1,894,561	1,708,774	1,801,668
5	8,196,155	8,070,862	8,133,509	3,905,935	3,633,233	3,769,584	1,535,479	1,411,643	1,473,561
1	6,836,701	6,650,576	6,743,639	2,650,878	2,443,036	2,546,957	764,402	679,245	721,824
0.5	6,168,103	5,964,469	6,066,286	2,179,588	2,033,794	2,106,691	668,020	589,705	628,862
0.1	4,915,186	4,773,761	4,844,474	1,465,035	1,371,241	1,418,138	474,782	423,366	449,074
Dynamic Modulus (kPa) at EAC=1.0%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,302,465	8,391,834	8,347,150	4,005,721	4,257,670	4,131,696	1,984,968	2,082,426	2,033,697
10	7,730,112	7,555,919	7,643,016	3,492,393	3,711,381	3,601,887	1,477,362	1,542,523	1,509,943
5	7,194,408	6,853,575	7,023,992	3,031,959	3,199,454	3,115,707	1,197,504	1,289,735	1,243,620
1	5,912,369	5,308,999	5,610,684	1,937,085	2,094,840	2,015,963	539,628	596,872	568,250
0.5	5,332,237	4,594,829	4,963,533	1,577,041	1,718,164	1,647,603	473,063	521,381	497,222
0.1	4,252,521	3,433,164	3,842,843	1,028,146	1,137,529	1,082,838	324,700	377,609	351,154
Dynamic Modulus (kPa) at EAC=1.5%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,532,614	7,480,565	7,506,590	4,498,770	3,900,446	4,199,608	1,776,833	1,694,961	1,735,897
10	7,034,529	6,953,864	6,994,197	3,676,384	3,246,138	3,461,261	1,081,934	1,200,068	1,141,001
5	6,489,097	6,404,645	6,446,871	3,097,918	2,687,783	2,892,851	906,761	792,529	849,645
1	5,273,434	5,148,709	5,211,072	1,915,351	1,611,411	1,763,381	397,225	337,464	367,344
0.5	4,739,041	4,563,217	4,651,129	1,539,574	1,281,359	1,410,467	356,475	305,589	331,032
0.1	3,692,425	3,532,102	3,612,264	980,451	778,077	879,264	283,465	263,294	273,379

Table 8-5. Summary of dynamic moduli of CIR-CSS-1h mixtures from Story County

Dynamic Modulus (kPa) at EAC=0.5%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,157,083	8,137,948	8,147,516	3,836,001	3,762,131	3,799,066	1,859,383	1,759,027	1,809,205
10	7,395,450	7,484,156	7,439,803	3,329,874	3,011,906	3,170,890	1,139,272	1,205,592	1,172,432
5	6,869,963	7,009,719	6,939,841	2,860,181	2,507,969	2,684,075	889,138	946,332	917,735
1	5,636,895	5,769,874	5,703,385	1,855,113	1,511,199	1,683,156	392,012	428,350	410,181
0.5	5,041,127	5,230,790	5,135,959	1,587,568	1,276,701	1,432,135	340,761	383,010	361,886
0.1	3,907,214	4,127,857	4,017,536	1,089,927	844,045	966,986	250,068	283,901	266,984

Dynamic Modulus (kPa) at EAC=1.0%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,446,412	7,591,910	7,519,161	3,963,827	4,062,802	4,013,315	1,622,694	1,687,319	1,655,007
10	7,043,296	6,961,436	7,002,366	3,422,963	3,278,254	3,350,609	1,257,995	1,065,672	1,161,834
5	6,516,264	6,465,969	6,491,117	2,904,121	2,780,931	2,842,526	842,220	716,948	779,584
1	5,222,502	5,270,850	5,246,676	1,855,755	1,806,763	1,831,259	391,144	339,026	365,085
0.5	4,690,259	4,760,303	4,725,281	1,568,512	1,476,824	1,522,668	358,941	307,234	333,087
0.1	3,614,283	3,698,340	3,656,312	1,063,343	962,072	1,012,707	252,372	243,972	248,172

Dynamic Modulus (kPa) at EAC=1.5%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,045,826	7,109,997	7,077,912	4,120,115	4,021,557	4,070,836	1,559,751	1,588,254	1,574,003
10	6,452,356	6,560,592	6,506,474	3,493,008	3,295,520	3,394,264	1,093,854	1,235,237	1,164,546
5	5,952,166	6,028,943	5,990,555	2,940,284	2,778,629	2,859,457	696,004	708,553	702,278
1	4,714,139	4,732,101	4,723,120	1,820,597	1,757,347	1,788,972	314,318	295,815	305,067
0.5	4,182,940	4,150,729	4,166,835	1,490,098	1,408,115	1,449,107	284,217	256,817	270,517
0.1	3,141,958	3,143,872	3,142,915	953,602	928,924	941,263	234,200	205,122	219,661

Table 8-6. Summary of dynamic moduli of CIR-HFMS-2p mixtures from Clayton County

Dynamic Modulus (kPa) at EAC=0.5%

Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,173,884	8,276,116	8,225,000	4,431,330	4,350,710	4,391,020	1,858,846	1,747,653	1,803,250
10	7,388,710	7,655,734	7,522,222	3,869,726	3,626,438	3,748,082	1,530,683	1,433,220	1,481,952
5	6,907,607	7,121,465	7,014,536	3,383,199	3,196,945	3,290,072	1,275,910	1,222,704	1,249,307
1	5,716,845	5,892,274	5,804,560	2,292,274	2,120,708	2,206,491	737,116	710,996	724,056
0.5	5,183,089	5,353,285	5,268,187	1,916,649	1,774,331	1,845,490	613,774	594,160	603,967
0.1	4,165,214	4,300,148	4,232,681	1,285,065	1,210,554	1,247,810	430,187	413,962	422,074

Dynamic Modulus (kPa) at EAC=1.0%

Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,435,213	7,834,918	7,635,066	3,336,631	3,916,895	3,626,763	1,177,576	1,338,793	1,258,185
10	6,563,287	7,043,248	6,803,268	2,596,084	3,088,885	2,842,485	885,199	987,318	936,259
5	5,974,046	6,442,485	6,208,266	2,200,268	2,583,012	2,391,640	724,299	806,795	765,547
1	4,538,355	5,008,698	4,773,527	1,251,420	1,612,659	1,432,040	413,639	450,946	432,293
0.5	3,977,713	4,355,434	4,166,574	1,018,129	1,303,698	1,160,914	353,231	381,751	367,491
0.1	2,945,426	3,263,877	3,104,652	632,163	819,240	725,701	263,798	285,116	274,457

Dynamic Modulus (kPa) at EAC=1.5%

Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	6,825,225	6,869,362	6,847,294	3,053,983	2,943,920	2,998,952	1,148,063	1,114,173	1,131,118
10	6,441,157	6,063,273	6,252,215	2,354,651	2,306,406	2,330,529	799,452	831,717	815,584
5	5,809,296	5,446,481	5,627,889	1,948,232	1,926,798	1,937,515	656,056	682,883	669,470
1	4,389,617	4,068,179	4,228,898	1,143,958	1,027,987	1,085,973	374,530	360,614	367,572
0.5	3,807,175	3,530,630	3,668,903	926,376	855,400	890,888	311,565	311,485	311,525
0.1	2,775,018	2,533,322	2,654,170	611,042	525,096	568,069	252,811	245,077	248,944

Table 8-7. Summary of dynamic moduli of CIR-HFMS-2p mixtures from Story County

Dynamic Modulus (kPa) at EAC=0.5%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	6,928,345	7,100,527	7,014,436	3,532,305	3,965,536	3,748,921	1,706,182	1,611,499	1,658,841
10	6,194,372	6,447,178	6,320,775	2,898,885	3,146,198	3,022,542	1,115,250	1,063,238	1,089,244
5	5,682,082	5,967,502	5,824,792	2,539,022	2,755,306	2,647,164	942,324	887,268	914,796
1	4,516,555	4,804,358	4,660,457	1,646,454	1,808,501	1,727,478	551,326	518,389	534,857
0.5	4,023,005	4,297,664	4,160,335	1,389,873	1,524,785	1,457,329	464,937	432,832	448,884
0.1	3,103,365	3,322,080	3,212,723	958,586	1,055,036	1,006,811	318,253	317,306	317,779

Dynamic Modulus (kPa) at EAC=1.0%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,203,607	7,291,302	7,247,455	4,119,437	3,789,756	3,954,597	1,375,652	1,305,268	1,340,460
10	6,782,041	6,706,388	6,744,215	3,386,214	3,114,635	3,250,425	1,117,252	1,040,565	1,078,909
5	5,823,862	6,216,540	6,020,201	2,954,019	2,708,268	2,831,144	942,605	865,563	904,084
1	4,650,137	5,025,117	4,837,627	1,934,300	1,801,152	1,867,726	547,214	501,937	524,576
0.5	4,120,214	4,537,966	4,329,090	1,623,869	1,514,519	1,569,194	454,786	414,519	434,652
0.1	3,209,112	3,578,519	3,393,816	1,104,648	1,028,605	1,066,627	315,960	297,180	306,570

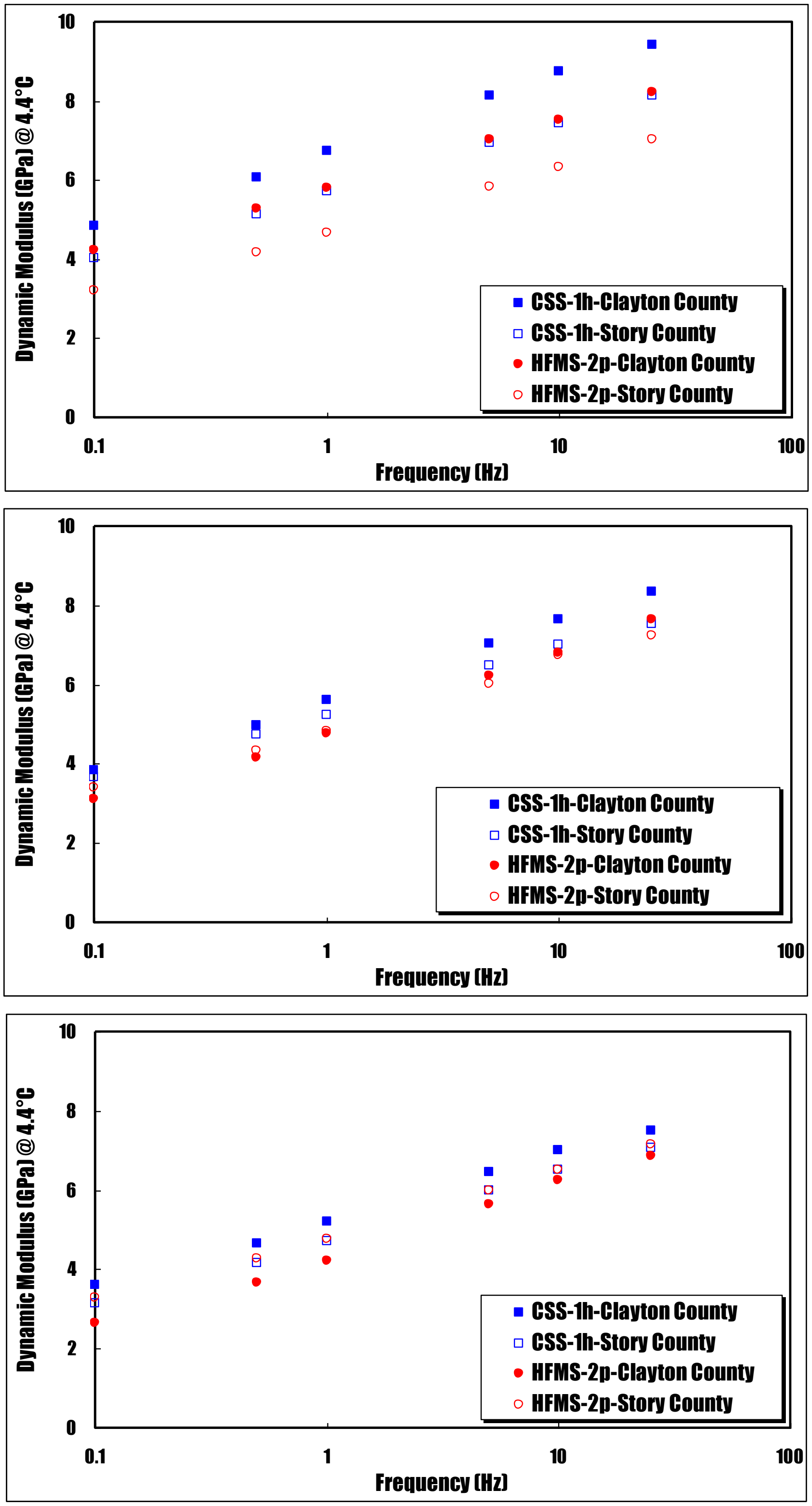
Dynamic Modulus (kPa) at EAC=1.5%									
Freq. (Hz)	4.4°C			21.1°C			37.8°C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,230,692	7,100,527	7,165,610	4,171,686	4,129,329	4,150,508	1,333,512	1,378,873	1,356,193
10	6,552,842	6,447,178	6,500,010	3,295,638	3,310,411	3,303,025	1,018,536	1,078,685	1,048,611
5	6,021,099	5,967,502	5,994,301	2,813,880	2,844,975	2,829,428	849,458	889,499	869,478
1	4,759,245	4,804,358	4,781,802	1,845,722	1,873,473	1,859,598	471,091	505,375	488,233
0.5	4,240,672	4,297,664	4,269,168	1,539,396	1,537,794	1,538,595	393,391	419,480	406,436
0.1	3,274,762	3,322,080	3,298,421	1,018,771	988,433	1,003,602	275,195	287,997	281,596

Table 8-8. Rankings of dynamic modulus at three emulsified asphalt contents and three different testing temperatures for two different emulsion types and two different RAP sources

EAC (%)	Temp.	4.4°C							21.1°C							37.8°C							Total Ave.	Overall Rank.
	Freq.	25	10	5	1	0.5	0.1	Rank	25	10	5	1	0.5	0.1	Rank	25	10	5	1	0.5	0.1	Rank		
0.5	CSS-1h (Clayton Co.)	1	1	1	1	1	1	**1**	1	1	1	1	1	1	**1**	1	1	1	1	1	1	**1**	1.00	**1**
	CSS-1h (Story Co.)	3	3	3	3	3	3	**3**	3	3	3	4	4	4	**3**	2	3	3	4	4	4	**3**	3.28	**3**
	HFMS-2p (Clayton Co.)	2	2	2	2	2	2	**2**	2	2	2	2	2	2	**2**	3	2	2	2	2	2	**2**	2.06	**2**
	HFMS-2p (Story Co.)	4	4	4	4	4	4	**4**	4	4	4	3	3	3	**4**	4	4	4	3	3	3	**4**	3.67	**4**
1.0	CSS-1h (Clayton Co.)	1	1	1	1	1	1	**1**	1	1	1	1	1	1	**1**	1	1	1	1	1	1	**1**	1.00	**1**
	CSS-1h (Story Co.)	3	2	2	2	2	2	**2**	2	2	2	3	3	3	**2**	2	2	3	4	4	4	**3**	2.61	**2**
	HFMS-2p (Clayton Co.)	2	3	3	4	4	4	**3**	4	4	4	4	4	4	**4**	4	4	4	3	3	3	**4**	3.61	**4**
	HFMS-2p (Story Co.)	4	4	4	3	3	3	**4**	3	3	3	2	2	2	**3**	3	3	2	2	2	2	**2**	2.78	**3**
1.5	CSS-1h (Clayton Co.)	1	1	1	1	1	1	**1**	1	1	1	3	3	3	**2**	1	1	2	3	2	2	**2**	1.61	**1**
	CSS-1h (Story Co.)	3	2	3	3	3	3	**3**	3	2	2	2	2	2	**3**	2	2	3	4	4	4	**3**	2.78	**3**
	HFMS-2p (Clayton Co.)	4	4	4	4	4	4	**4**	4	4	4	4	4	4	**4**	4	4	4	2	3	3	**4**	3.78	**4**
	HFMS-2p (Story Co.)	2	3	2	2	2	2	**2**	2	3	3	1	1	1	**1**	3	3	1	1	1	1	**1**	1.89	**2**

The dynamic moduli for a combination of two emulsion types and two different RAP sources are plotted against six loading frequencies at 4.4°C, 21.1°C, and 37.8°C in Figure 8-3, Figure 8-4 and Figure 8-5, respectively. Under a constant loading frequency, the dynamic modulus decreased as temperature increased. Under a constant testing temperature, the dynamic modulus increased with an increase in the frequency. As expected, the dynamic moduli measured at three emulsified asphalt contents were different among emulsion types and RAP sources.

As shown in these figures, it is interesting to note that RAP materials from Clayton County exhibited the highest dynamic modulus values at all loading frequencies and testing temperatures for both CSS-1h emulsion and HFMS-2p emulsion.

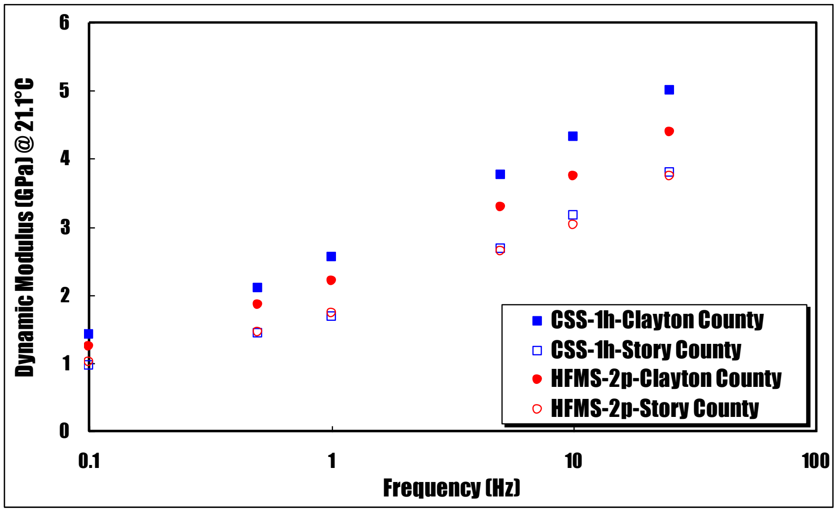


(a) EAC=0.5%

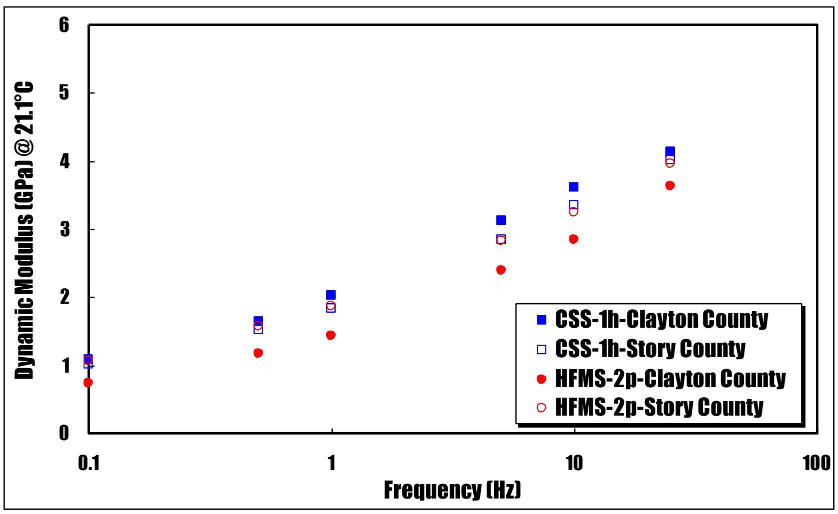
(b) EAC=1.0%

(c) EAC=1.5%

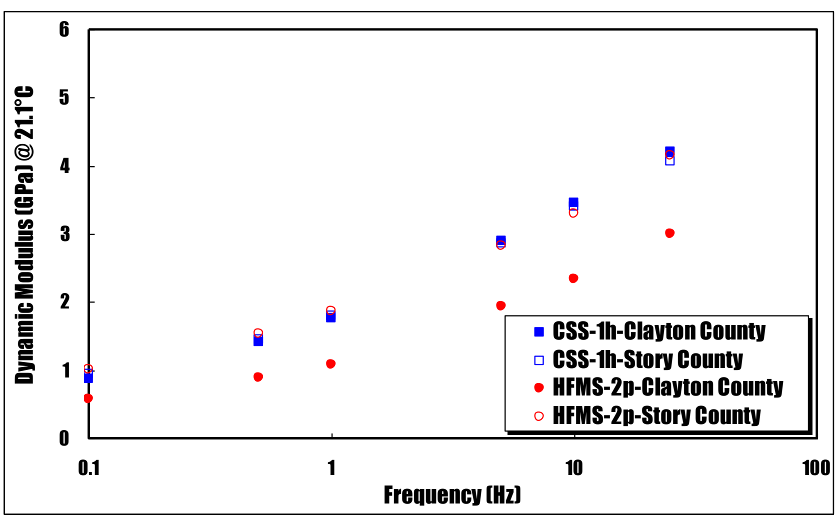
Figure 8-3. Plots of dynamic moduli against six loading frequencies for three emulsified asphalt contents at 4.4˚C



(a) EAC=0.5%

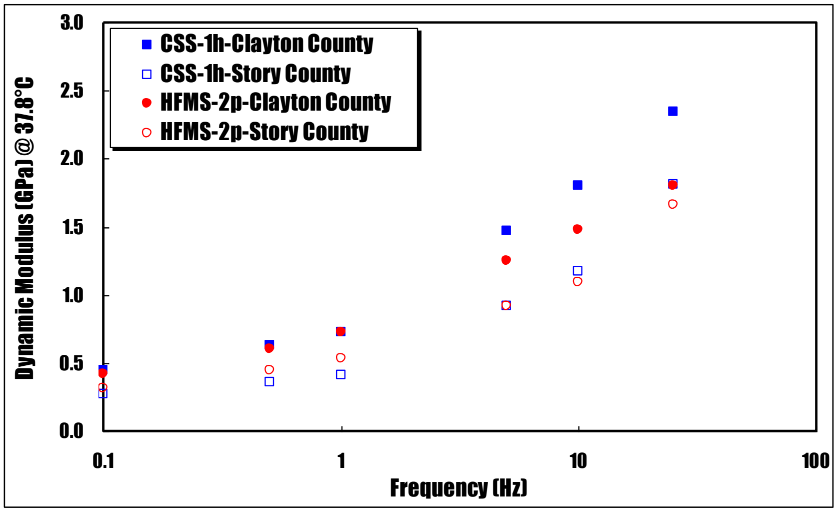


(b) EAC=1.0%

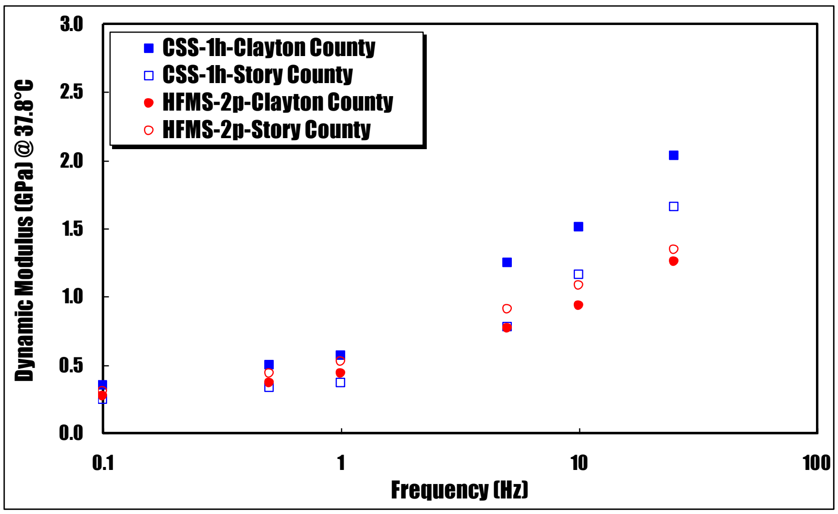


(c) EAC=1.5%

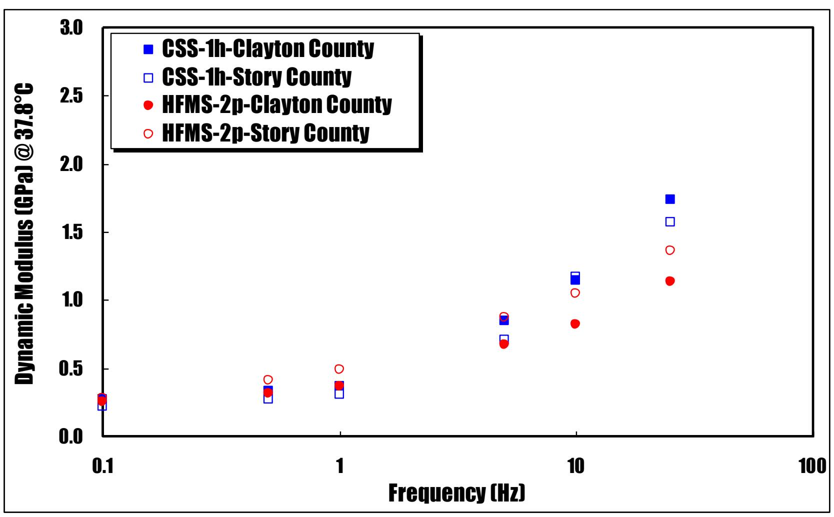
Figure 8-4. Plots of dynamic moduli against six loading frequencies for three emulsified asphalt contents at 21.1˚C



(a) EAC=0.5%



(b) EAC=1.0%



(c) EAC=1.5%

Figure 8-5. Plots of dynamic modulus value against six loading frequencies for three emulsified asphalt contents at 37.8°C

8.1.4.3 Master Curve

Using the dynamic modulus test results measured at three different temperatures and six different loading frequencies, a master curve was constructed for a reference temperature of 21.1˚C for each of seven RAP sources. As discussed earlier, all model parameters and the empirical parameters of the WLF equation were obtained by minimizing the sum of the square of the error of the Sigmoidal model using the Excel's Optimization Solver function. Table 8-9 summarizes all model parameters and the empirical parameters from the WLF equation.

Figure 8-6 To Figure 8-9 show measured dynamic modulus data and a master curve constructed for each of three emulsified asphalt contents for two RAP sources. A master curve constructed for each of three different emulsified asphalt contents matches the measured moduli quite well. As can be seen from these figures, master curves are relatively flat compared to HMA mixtures, which supports that emulsified asphalt mixtures are not as viscoelastic as HMA. Figure 8-10 shows a plot of shift factors against temperatures at each of three emulsified asphalt content for two RAP sources.

Table 8-9. Model parameters of constructed master curves

Parameter	CSS-1h (Clayton County)			CSS-1h (Story County)		
	EAC=0.5%	EAC=1.0%	EAC=1.5%	EAC=0.5%	EAC=1.0%	EAC=1.5%
α	2.233	2.362	1.872	2.407	2.199	2.061
β	-0.844	-0.782	-0.624	-0.774	-0.819	-0.841
δ	4.850	4.691	5.044	4.605	4.756	4.837
γ	0.564	0.563	0.818	0.580	0.654	0.774
Parameter	**HFMS-2p (Clayton County)**			**HFMS-2p (Story County)**		
	EAC=0.5%	EAC=1.0%	EAC=1.5%	EAC=0.5%	EAC=1.0%	EAC=1.5%
α	2.158	1.980	1.909	2.202	2.308	2.159
β	-0.728	-0.283	-0.093	-0.664	-0.693	-0.688
δ	4.896	5.037	5.056	4.800	4.744	4.843
γ	0.521	0.650	0.701	0.538	0.494	0.569

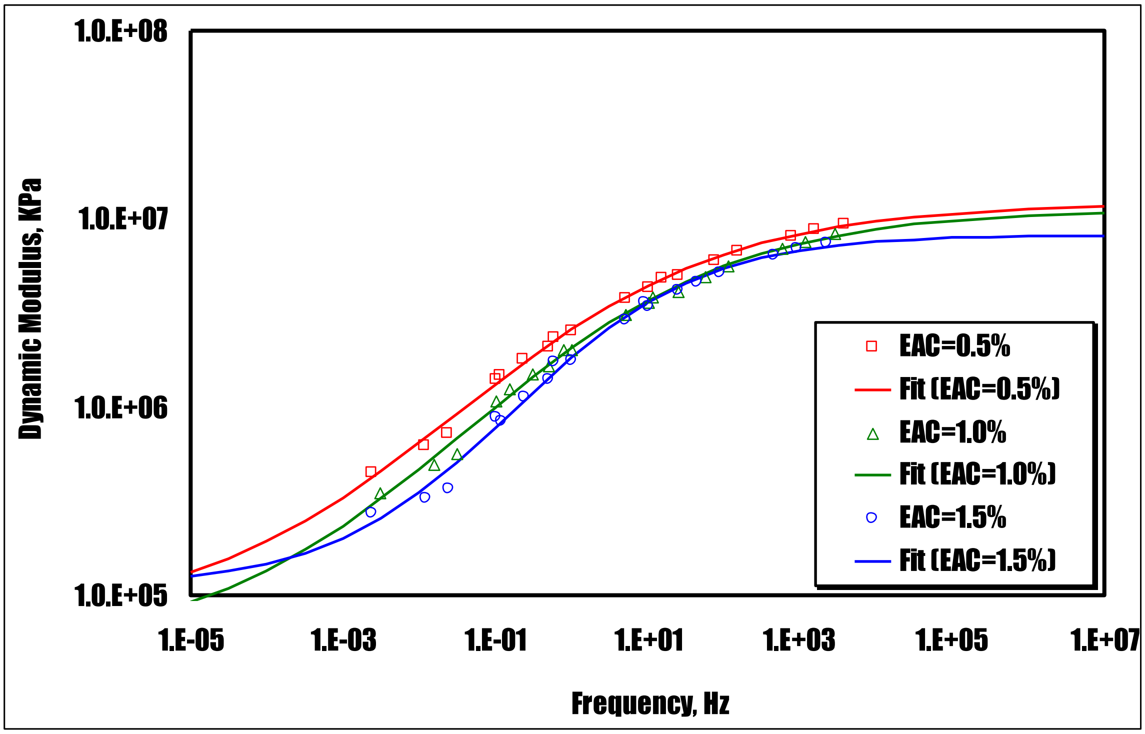


Figure 8-6. Mater curves for CIR-CSS-1h from Clayton County at three EACs

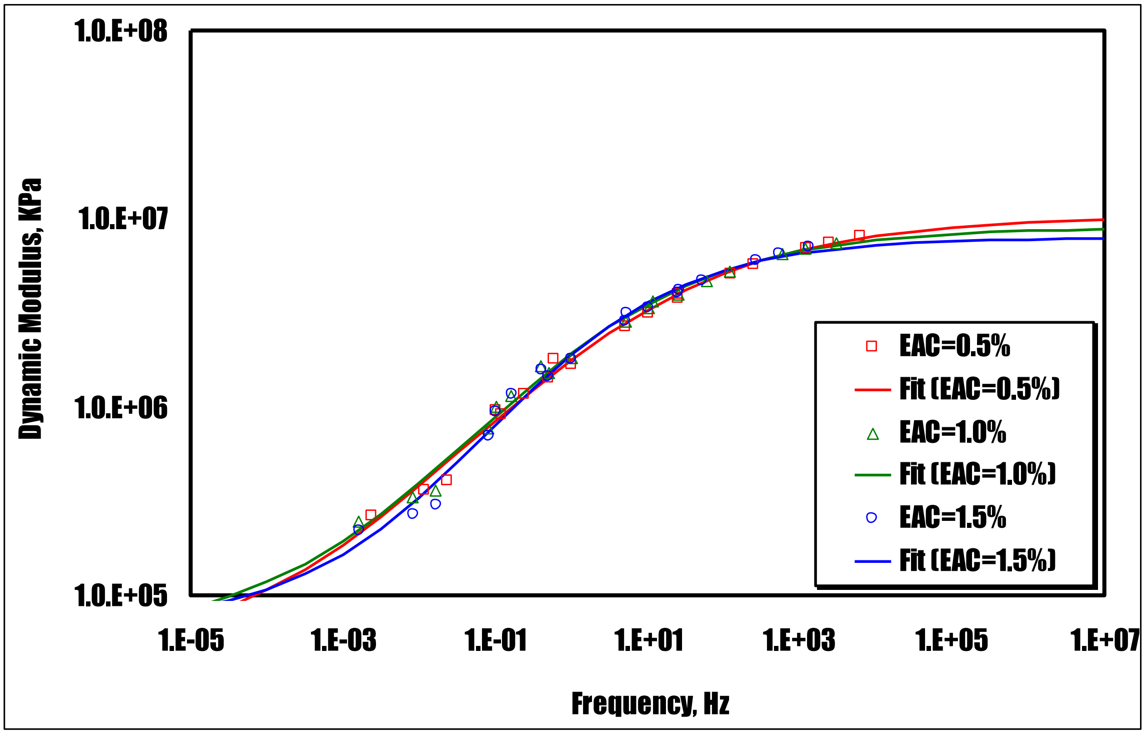


Figure 8-7. Mater curves for CIR-CSS-1h from Story County at three EACs

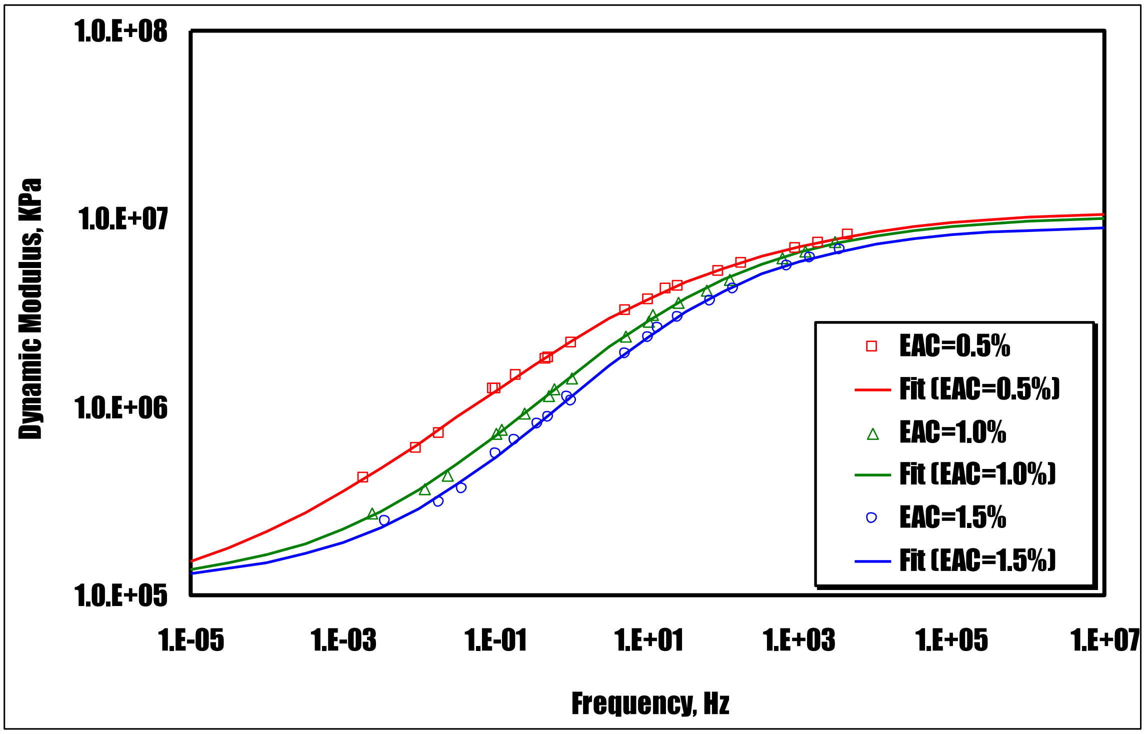


Figure 8-8. Mater curves for CIR-HFMS-2p from Clayton County at three EACs

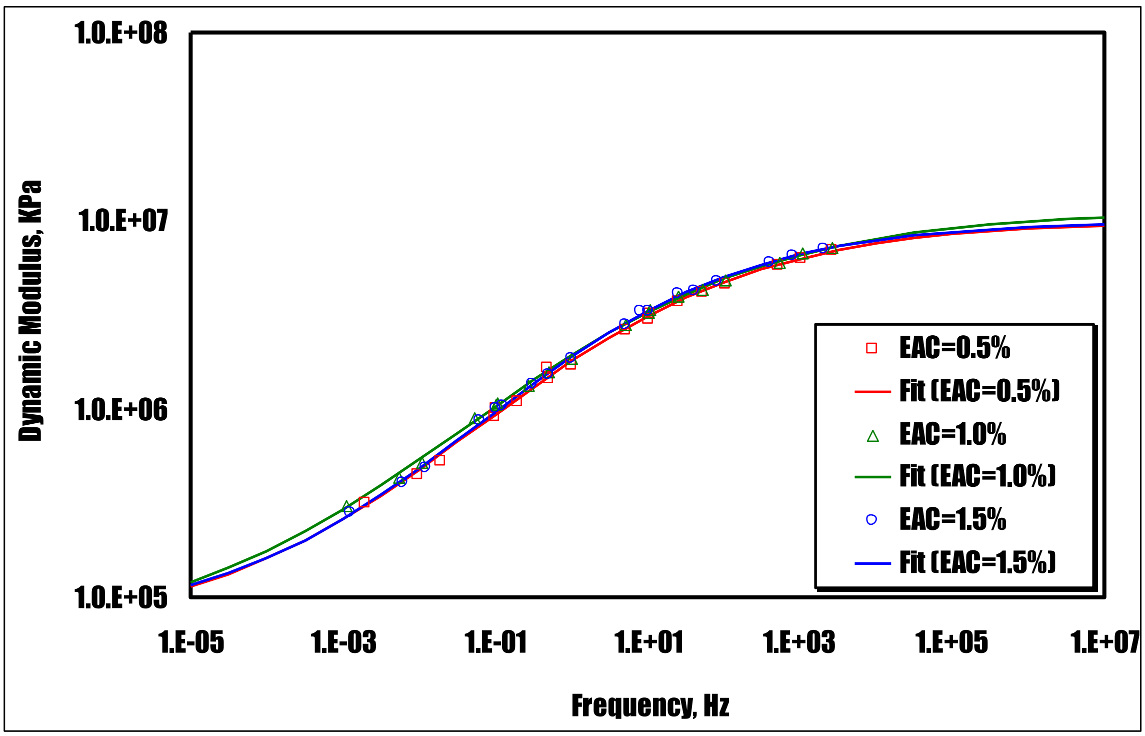


Figure 8-9. Mater curves for CIR- HFMS-2p from Story County at three EACs

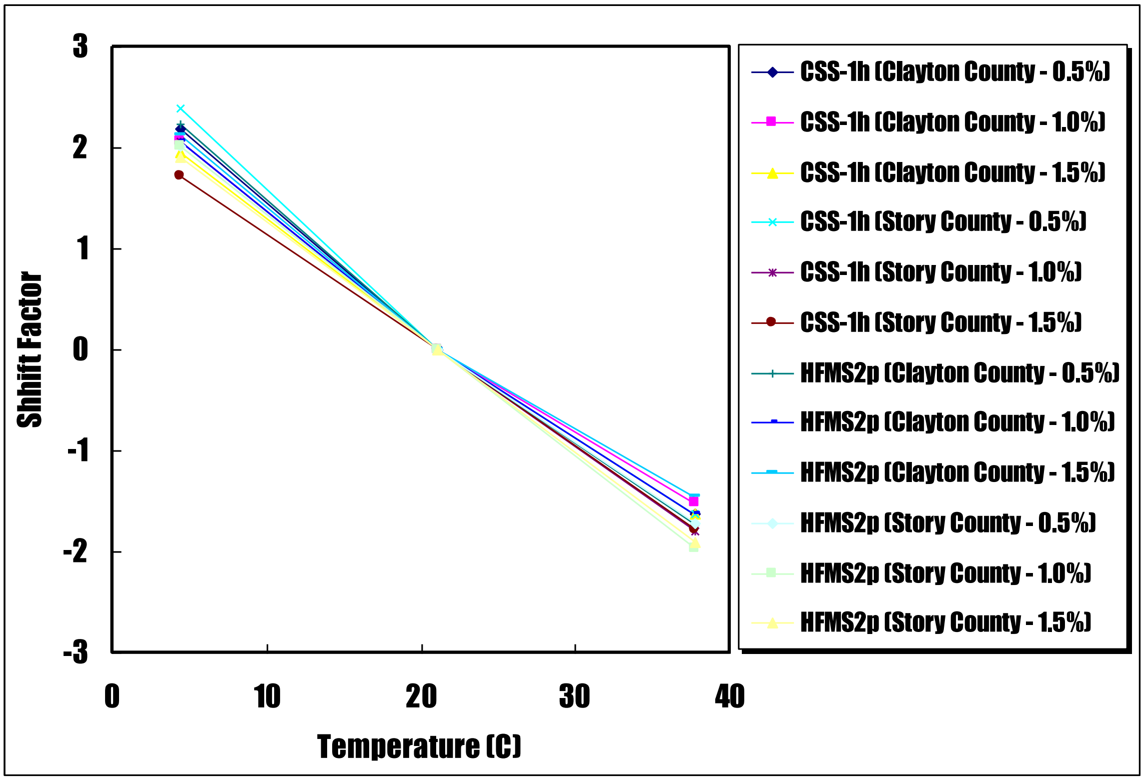


Figure 8-10. Shift factors against three temperatures

8.1.4.4 Comparisons against CIR-foam Test Results

The dynamic moduli of CIR-emulsion mixtures are compiled and compared against the CIR-foam test results obtained from the previous study. Table 8-10 to Table 8-15 show dynamic moduli of CIR-foam and CIR-emulsion mixtures. The test results consistently indicate that the dynamic moduli decrease as the foamed asphalt content and emulsified asphalt content increases. It should be noted that CIR-foam mixtures consistently achieved the higher dynamic modulus than CIR-emulsion mixtures at all frequencies.

Table 8-10. Comparisons of dynamic modulus between CIR-foam and CIR-emulsion mixtures at 25 Hz

		Foamed Asphalt Content (%)					Emulsified Asphalt Content (%)		
RAP Source	Temp.	1.0	2.0	3.0	RAP Source	Temp.	0.5	1.0	1.5
Muscatine County	4.4C	10,862,045	10,991,905	11,496,203	Clayton County (CSS-1h)	4.4C	9,426,302	8,347,150	7,506,590
	21.1C	5,560,018	5,259,306	5,183,134		21.1C	4,994,298	4,131,696	4,199,608
	37.8C	2,206,767	2,066,166	1,933,412		37.8C	2,345,799	2,033,69	1,735,897
Webster County	4.4C	9,123,268	10,523,014	9,973,676	Story County (CSS-1h)	4.4C	8,147,516	7,519,161	7,077,912
	21.1C	5,691,998	5,333,118	5,079,990		21.1C	3,799,066	4,013,315	4,070,836
	37.8C	2,477,536	2,627,609	2,000,642		37.8C	1,809,205	1,655,007	1,574,003
Hardin County	4.4C	6,981,974	8,309,077	8,234,184	Clayton County (HFMS-2p)	4.4C	8,225,000	7,635,066	6,847,294
	21.1C	4,454,985	4,355,122	3,897,340		21.1C	4,391,020	3,626,763	2,998,952
	37.8C	2,005,272	2,003,287	1,583,825		37.8C	1,803,250	1,258,185	1,131,118
Montgomery County	4.4C	9,270,718	9,477,250	9,470,962	Story County (HFMS-2p)	4.4C	7,014,436	7,247,455	7,165,610
	21.1C	4,975,961	5,040,401	4,824,499		21.1C	3,748,921	3,954,597	4,150,508
	37.8C	2,323,365	2,029,464	1,957,315		37.8C	1,658,841	1,340,460	1,356,193
Bremer County	4.4C	9,460,124	9,455,961	8,692,960					
	21.1C	5,507,534	4,777,631	4,392,799					
	37.8C	2,083,548	1,686,006	1,631,569					
Lee County	4.4C	7,969,025	7,615,739	4,056,574					
	21.1C	4,246,000	4,106,763	4,210,038					
	37.8C	1,963,395	2,051,062	1,892,149					
Wapello County	4.4C	9,920,999	9,327,830	9,306,020					
	21.1C	5,638,839	5,127,021	4,636,127					
	37.8C	2,419,748	2,281,425	2,107,593					

Table 8-11. Comparisons of dynamic modulus between CIR-foam and CIR-emulsion mixtures at 10 Hz

		Foamed Asphalt Content (%)		
RAP Source	Temp.	1.0	2.0	3.0
Muscatine County	4.4C	10,002,513	9,983,311	10,174,377
	21.1C	4,513,794	4,221,965	4,056,780
	37.8C	1,497,959	1,355,957	1,343,895
Webster County	4.4C	8,574,260	9,933,472	9,090,763
	21.1C	4,978,889	4,551,246	4,210,610
	37.8C	2,043,933	2,154,167	1,574,137
Hardin County	4.4C	6,340,929	7,465,103	7,292,951
	21.1C	3,755,858	3,724,402	3,216,713
	37.8C	1,726,544	1,657,778	1,300,700
Montgomery County	4.4C	8,459,838	8,565,322	8,519,182
	21.1C	3,986,151	4,190,038	3,828,679
	37.8C	1,706,544	1,467,555	1,386,172
Bremer County	4.4C	4,691,672	8,557,351	7,940,241
	21.1C	4,680,931	3,834,665	3,569,015
	37.8C	1,739,365	1,353,784	1,275,692
Lee County	4.4C	6,987,698	6,871,934	6,805,296
	21.1C	3,435,034	3,401,267	3,431,233
	37.8C	1,665,678	1,774,703	1,563,075
Wapello County	4.4C	9,018,049	8,404,801	8,278,663
	21.1C	4,725,041	3,959,198	3,676,577
	37.8C	1,737,001	1,622,379	1,478,143

		Emulsified Asphalt Content (%)		
RAP Source	Temp.	0.5	1.0	1.5
Clayton County (CSS-1h)	4.4C	8,739,358	7,643,016	6,994,197
	21.1C	4,323,946	3,601,887	3,461,261
	37.8C	1,801,668	1,509,943	1,141,001
Story County (CSS-1h)	4.4C	7,439,803	7,002,366	6,506,474
	21.1C	3,170,890	3,350,609	3,394,264
	37.8C	1,172,432	1,161,834	1,164,546
Clayton County (HFMS-2p)	4.4C	7,522,222	6,803,268	6,252,215
	21.1C	3,748,082	2,842,485	2,330,529
	37.8C	1,481,952	936,259	815,584
Story County (HFMS-2p)	4.4C	6,320,775	6,744,215	6,500,010
	21.1C	3,022,542	3,250,425	3,303,025
	37.8C	1,089,244	1,078,909	1,048,611

Table 8-12. Comparisons of dynamic modulus between CIR-foam and CIR-emulsion mixtures at 5Hz

		Foamed Asphalt Content (%)		
RAP Source	Temp.	1.0	2.0	3.0
Muscatine County	4.4C	9,180,371	9,121,951	9,118,324
	21.1C	3,810,100	3,510,521	3,343,858
	37.8C	1,163,072	1,023,112	905,363
Webster County	4.4C	8,099,631	9,064,668	8,419,998
	21.1C	4,299,403	3,814,785	3,551,912
	37.8C	1,667,202	1,748,724	1,270,187
Hardin County	4.4C	5,812,187	6,832,798	6,574,383
	21.1C	3,205,106	3,226,876	2,704,940
	37.8C	1,438,943	1,359,439	1,062,463
Montgomery County	4.4C	7,642,139	7,628,591	7,645,225
	21.1C	3,304,670	3,503,103	3,138,026
	37.8C	1,359,350	1,150,393	1,073,900
Bremer County	4.4C	8,023,216	7,725,430	6,830,521
	21.1C	4,038,295	3,182,999	2,941,016
	37.8C	1,401,883	1,103,308	1,020,963
Lee County	4.4C	6,437,550	6,225,184	6,085,517
	21.1C	2,924,039	2,853,526	2,838,679
	37.8C	1,399,099	1,433,081	1,267,247
Wapello County	4.4C	8,205,216	7,527,753	7,462,912
	21.1C	3,991,876	3,266,873	3,037,524
	37.8C	1,388,758	1,328,637	1,196,837

		Emulsified Asphalt Content (%)		
RAP Source	Temp.	0.5	1.0	1.5
Clayton County (CSS-1h)	4.4C	8,133,509	7,023,992	6,446,871
	21.1C	3,769,584	3,115,707	2,892,851
	37.8C	1,473,561	1,243,620	849,645
Story County (CSS-1h)	4.4C	6,939,841	6,491,117	5,990,555
	21.1C	2,684,075	2,842,526	2,859,457
	37.8C	917,735	779,584	702,278
Clayton County (HFMS-2p)	4.4C	7,014,536	6,208,266	5,627,889
	21.1C	3,290,072	2,391,640	1,937,515
	37.8C	1,249,307	765,547	669,470
Story County (HFMS-2p)	4.4C	5,824,792	6,020,201	5,994,301
	21.1C	2,647,164	2,831,144	2,829,428
	37.8C	914,796	904,084	869,478

Table 8-13 Comparisons of dynamic modulus between CIR-foam and CIR-emulsion mixtures at 1Hz

		Foamed Asphalt Content (%)		
RAP Source	Temp.	1.0	2.0	3.0
Muscatine County	4.4C	7,190,836	6,927,588	6,713,458
	21.1C	2,448,444	2,207,674	2,033,288
	37.8C	764,928	660,761	566,561
Webster County	4.4C	6,643,809	6,991,015	6,491,279
	21.1C	2,800,888	2,521,913	2,228,247
	37.8C	1,024,940	1,058,539	775,476
Hardin County	4.4C	4,527,880	5,331,259	4,913,019
	21.1C	2,202,086	2,364,752	1,771,960
	37.8C	989,792	941,727	706,324
Montgomery County	4.4C	6,089,708	5,774,707	5,641,251
	21.1C	2,132,082	2,204,555	1,997,053
	37.8C	856,953	682,279	634,764
Bremer County	4.4C	6,302,619	5,774,428	4,977,566
	21.1C	2,655,183	1,968,983	1,774,295
	37.8C	901,209	805,403	718,269
Lee County	4.4C	5,027,468	4,705,623	4,457,358
	21.1C	1,930,631	1,810,873	1,748,459
	37.8C	921,227	972,122	856,177
Wapello County	4.4C	6,331,421	5,530,118	5,437,081
	21.1C	2,608,923	2,069,784	1,893,121
	37.8C	905,648	914,728	865,829

		Emulsified Asphalt Content (%)		
RAP Source	Temp.	0.5	1.0	1.5
Clayton County (CSS-1h)	4.4C	6,743,639	5,610,684	5,211,072
	21.1C	2,546,957	2,015,963	1,763,381
	37.8C	721,824	568,250	367,344
Story County (CSS-1h)	4.4C	5,703,385	5,246,676	4,723,120
	21.1C	1,683,156	1,831,259	1,788,972
	37.8C	410,181	365,085	305,067
Clayton County (HFMS-2p)	4.4C	5,804,560	4,773,527	4,228,898
	21.1C	2,206,491	1,432,040	1,085,973
	37.8C	724,056	432,293	367,572
Story County (HFMS-2p)	4.4C	4,660,457	4,837,627	4,781,802
	21.1C	1,727,478	1,867,726	1,859,598
	37.8C	534,857	524,576	488,233

Table 8-14. Comparisons of dynamic modulus between CIR-foam and CIR-emulsion mixtures at 0.5Hz

		Foamed Asphalt Content (%)		
RAP Source	Temp.	1.0	2.0	3.0
Muscatine County	4.4C	6,405,455	6,118,348	5,836,335
	21.1C	1,999,019	1,720,420	1,545,840
	37.8C	604,095	488,680	406,375
Webster County	4.4C	6,099,811	6,444,455	5,757,417
	21.1C	2,325,696	2,106,838	1,838,814
	37.8C	846,040	869,106	647,768
Hardin County	4.4C	4,088,502	4,789,163	4,324,589
	21.1C	1,830,923	1,879,837	1,437,700
	37.8C	815,880	783,045	577,006
Montgomery County	4.4C	5,502,947	5,110,399	4,968,597
	21.1C	1,774,118	1,757,812	1,521,587
	37.8C	684,676	560,385	532,029
Bremer County	4.4C	5,620,713	5,112,196	4,280,110
	21.1C	2,221,626	1,626,756	1,458,653
	37.8C	783,946	682,381	574,749
Lee County	4.4C	4,504,429	4,202,729	3,891,785
	21.1C	1,606,024	1,466,242	1,429,193
	37.8C	752,116	786,655	685,915
Wapello County	4.4C	5,632,703	4,773,249	4,704,742
	21.1C	2,165,971	1,627,074	1,444,807
	37.8C	715,123	729,895	658,120

		Emulsified Asphalt Content (%)		
RAP Source	Temp.	0.5	1.0	1.5
Clayton County (CSS-1h)	4.4C	6,066,286	4,963,533	4,651,129
	21.1C	2,106,691	1,647,603	1,410,467
	37.8C	628,862	497,222	331,032
Story County (CSS-1h)	4.4C	5,135,959	4,725,281	4,166,835
	21.1C	1,432,135	1,522,668	1,449,107
	37.8C	361,886	333,087	270,517
Clayton County (HFMS-2p)	4.4C	5,268,187	4,166,574	3,668,903
	21.1C	1,845,490	1,160,914	890,888
	37.8C	603,967	367,491	311,525
Story County (HFMS-2p)	4.4C	4,160,335	4,329,090	4,269,168
	21.1C	1,457,329	1,569,194	1,538,595
	37.8C	448,884	434,652	406,436

Table 8-15. Comparisons of dynamic modulus between CIR-foam and CIR-emulsion mixtures at 0.1Hz

		Foamed Asphalt Content (%)		
RAP Source	Temp.	1.0	2.0	3.0
Muscatine County	4.4C	4,983,865	4,624,651	4,275,338
	21.1C	1,323,793	1,079,006	924,678
	37.8C	458,349	313,902	295,125
Webster County	4.4C	4,924,178	5,142,342	4,515,800
	21.1C	1,607,632	1,516,274	1,186,991
	37.8C	594,114	611,826	449,563
Hardin County	4.4C	3,231,875	3,708,669	3,213,340
	21.1C	1,319,769	1,328,200	947,775
	37.8C	583,550	575,411	427,080
Montgomery County	4.4C	4,317,648	3,953,301	3,743,339
	21.1C	1,144,500	1,157,501	973,392
	37.8C	488,651	408,003	398,408
Bremer County	4.4C	4,524,645	3,929,951	3,111,334
	21.1C	1,535,537	1,078,124	917,341
	37.8C	577,513	534,461	391,040
Lee County	4.4C	3,610,054	3,263,729	2,914,306
	21.1C	1,119,100	1,032,252	967,452
	37.8C	548,138	572,266	510,867
Wapello County	4.4C	4,439,033	3,523,434	3,468,325
	21.1C	1,527,271	1,088,260	973,848
	37.8C	559,622	583,154	540,788

		Emulsified Asphalt Content (%)		
RAP Source	Temp.	0.5	1.0	1.5
Clayton County (CSS-1h)	4.4C	4,844,474	3,842,843	3,612,264
	21.1C	1,418,138	1,082,838	879,264
	37.8C	449,074	351,154	273,379
Story County (CSS-1h)	4.4C	4,017,536	3,656,312	3,142,915
	21.1C	966,986	1,012,707	941,263
	37.8C	266,984	248,172	219,661
Clayton County (HFMS-2p)	4.4C	4,232,681	3,104,652	2,654,170
	21.1C	1,247,810	725,701	568,069
	37.8C	422,074	274,457	248,944
Story County (HFMS-2p)	4.4C	3,212,723	3,393,816	3,298,421
	21.1C	1,006,811	1,066,627	1,003,602
	37.8C	317,779	306,570	281,596

8.2 Dynamic Creep Test

With increasing truck traffic and tire pressure, rutting is one of the most critical types of load-associated distresses occurring in asphalt pavements. Therefore, it is important to characterize the permanent deformation behavior of asphalt mixtures in order to identify problematic mixes before they are placed in roadways. Numerous studies have been conducted in the past to correlate the result from dynamic creep test with the rutting of HMA mixtures in the field (Witczak et al. 2002; Kaloush et al. 2002; Pan et al. 2006; Mohammand et al. 2006).

8.2.1 Theory

The dynamic creep test was originally developed to identify the permanent deformation characteristics of HMA mixtures by applying haversine load and recording the cumulative deformation as a function of the number of load cycles. The load is applied for 0.1 second with a rest period of 0.9 second in one cycle and repeated up to 10,000 loading cycles. As shown in Figure 8-11, results from the dynamic creep test are normally presented in terms of the cumulative permanent strain (ε_p) versus the number of loading cycles. The cumulative permanent deformation strain curve is generally defined by three stages: 1) primary stage, 2) secondary stage and 3) tertiary stage (EI-Basyoung et al., 2005). The permanent deformation increases rapidly in the primary stage and the incremental deformation decreases in the secondary stage. In the tertiary stage, the permanent deformations increase rapidly and the flow number (FN) is defined as number of loading cycles until the beginning of tertiary stage.

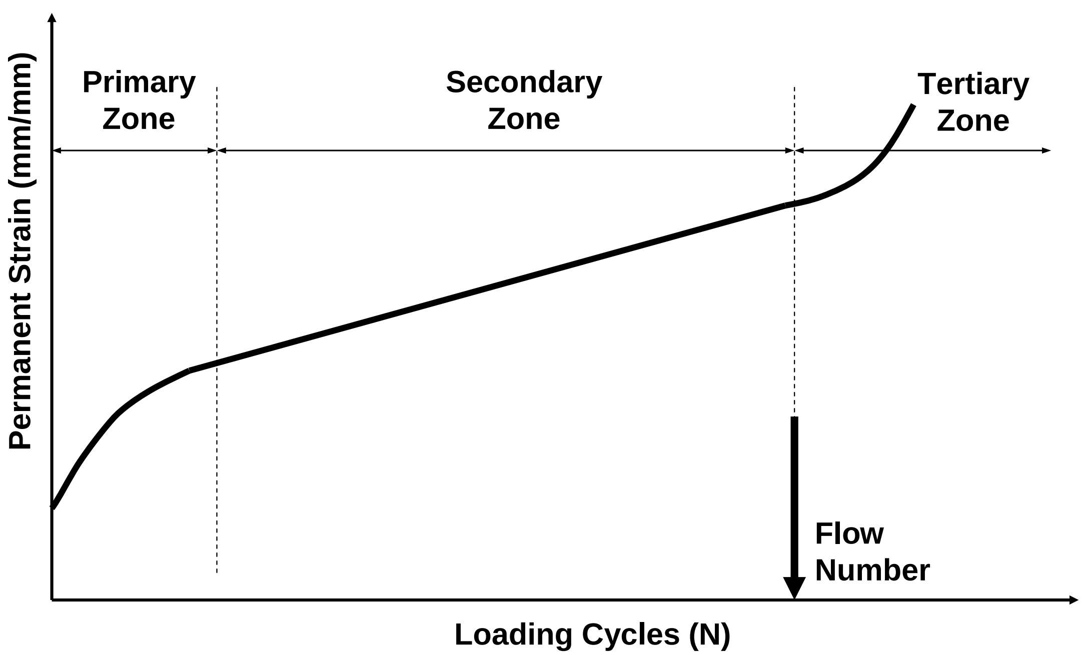


Figure 8-11. Permanent deformation behavior against loading cycles

8.2.2 Dynamic Creep Testing Procedure

NCHRP's dynamic creep testing protocol requires a specimen with 100-mm diameter should be cored from a Gyratory compacted specimen with 150-mm diameter. However, because CIR-emulsion specimens are not sufficiently stiff enough to be cored from a 150mm-diameter specimen, a specimen with 100-mm diameter and 150-mm height was prepared using a Gyratory compactor.

The uniaxial compression load without confinement was applied to obtain a loading stress level of 20 psi at 40˚C. A loading stress level of 20 psi was selected to attain tertiary flow in a reasonable number of cycles not exceeding 10,000. Testing temperature of 40˚C was selected to represent a temperature of CIR base layer in the field. The loading stress was applied in the form of a haversine curve with a loading time of 0.1 second with a rest period of 0.9 second in one cycle. The test was conducted up to 10,000 cycles or until achieving 5.0% of cumulative permanent stain.

8.2.3 Experimental Plan

As summarized in Table 8-2, CIR-emulsion specimens were prepared to measure a flow number using two different RAP sources and two different types of emulsified asphalt. For each RAP source, two CIR-emulsion specimens with 100-mm diameter and 150-mm height were prepared for each of three emulsion contents, 0.5%, 1.0% and 1.5%. Using RAP materials from each source, a total of six CIR-emulsion specimens were prepared using the gyratory compactor at 25 gyrations and cured in the oven at 40°C for three days. The cured specimens were allowed to cool to a room temperature for 24 hours before testing.

8.2.4 Results and Discussion

The bulk specific gravities and air voids were measured for each CIR-emulsion specimen. The dynamic creep test was performed to evaluate: 1) rutting resistance of CIR-emulsion mixtures in a combination of two different RAP sources and two different types of emulsified asphalt; 2) effects of the emulsified asphalt content on rutting resistance; and 3) comparisons against the CIR-foam test results obtained during the previous study.

8.2.4.1 Volumetric Characteristics

The bulk specific gravities and air voids of each CIR-emulsion specimen were determined following the AASHTO T 166 by measuring the dry mass and height. As summarized in Table 8-16, overall, no certain patterns were observed in terms of emulsion types, RAP materials or emulsion contents. As shown in Table 8-16, the bulk specific gravities seem to stay close to 2.100 and the air voids remain at around 10.0%.

Table 8-16. Bulk specific gravity and air void of CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources for dynamic creep test

Emulsion Type	RAP Source	EC (%)	G_{mb}			Air Void (%)	
			Individual		Average	Individual	Average
CSS-1h	Clayton	0.5	# 1	2.095	2.124	12.5	13.1.
			# 2	2.069		13.6	
		1.0	# 1	2.090	2.129	11.3	11.5
			# 2	2.085		11.6	
		1.5	# 1	2.119	2.156	7.9	8.1
			# 2	2.108		8.4	
	Story	0.5	# 1	2.060	2.057	14.5	14.7
			# 2	2.053		14.8	
		1.0	# 1	2.061	2.068	13.7	13.4
			# 2	2.075		13.1	
		1.5	# 1	2.056	2.049	12.7	13.0
			# 2	2.042		13.3	
HFMS-2p	Clayton	0.5	# 1	2.044	2.081	15.3	15.4
			# 2	2.035		15.6	
		1.0	# 1	2.110	2137	10.6	11.3
			# 2	2.079		11.9	
		1.5	# 1	2.069	2.090	11.7	12.6
			# 2	2.029		13.4	
	Story	0.5	# 1	2.053	2.087	14.9	15.3
			# 2	2.031		15.8	
		1.0	# 1	2.106	2.137	11.4	12.1
			# 2	2.075		12.8	
		1.5	# 1	2.065	2.090	11.7	12.5
			# 2	2.025		13.4	

8.2.4.2 Results of Dynamic Creep Test

The dynamic creep tests were performed on CIR-emulsion mixtures under a loading stress level of 138 kPa at 40˚C. For each RAP source, a total of six specimens were prepared using three different emulsion contents of 0.5%, 1.0% and 1.5%. Table 8-17 summarizes the flow number and cumulative strain at three different emulsified asphalt contents for a combination of two different emulsion types and two different RAP sources. Figure 8-12, Figure 8-13 and Figure 8-14 show plots of cumulative strain against the number of loading cycles measured from eight specimens prepared using two emulsion types and two RAP materials at the emulsified asphalt contents of 0.5%, 1.0% and 1.5%, respectively. As shown in these figures, it is interesting to note that CIR-emulsion specimens consistently failed early as the emulsified asphalt content was increased from

0.5% to 1.5%. It can be postulated that the lower the emulsified asphalt content, the flow number was higher, which indicates the emulsified asphalt content with 0.5% is more resistant to rutting than 1.0% and 1.5%. Characteristics of two RAP materials are summarized in Table 8-18 along with the rankings in terms of flow number. As can be easily observed from the table, rankings of RAP materials did not change when the emulsified asphalt content was increased from 0.5% to 1.5%, which confirms the consistency of the dynamic creep test in evaluating the rutting susceptibility of emulsion type and RAP aggregate structure. It can be observed that the increased emulsified asphalt content may reduce the rutting resistance of CIR-emulsion mixtures.

Table 8-17. Flow number and cumulative strain at flow number for CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources

Emulsion Type	RAP Source	EAC (%)	No. of Specimen	Flow Number		Cumulative Stain at FN
				Individual	Average	
CSS-1h	Clayton County	0.5	# 1	4061	3651	2.72%
			# 2	3241		2.35%
		1.0	# 1	1781	1421	2.31%
			# 2	1061		1.99%
		1.5	# 1	601	661	1.98%
			# 2	721		2.01%
	Story County	0.5	# 1	4981	4461	2.52%
			# 2	3941		2.46%
		1.0	# 1	1601	2021	2.02%
			# 2	2441		2.22%
		1.5	# 1	901	941	1.94%
			# 2	981		1.78%
HFMS-2p	Clayton County	0.5	# 1	1761	1631	2.33%
			# 2	1501		2.46%
		1.0	# 1	861	761	1.64%
			# 2	661		1.73%
		1.5	# 1	421	341	1.91%
			# 2	261		1.74%
	Story County	0.5	# 1	2881	2711	2.39%
			# 2	2541		2.31%
		1.0	# 1	1321	1071	2.03%
			# 2	821		1.67%
		1.5	# 1	641	721	1.72%
			# 2	801		2.20%

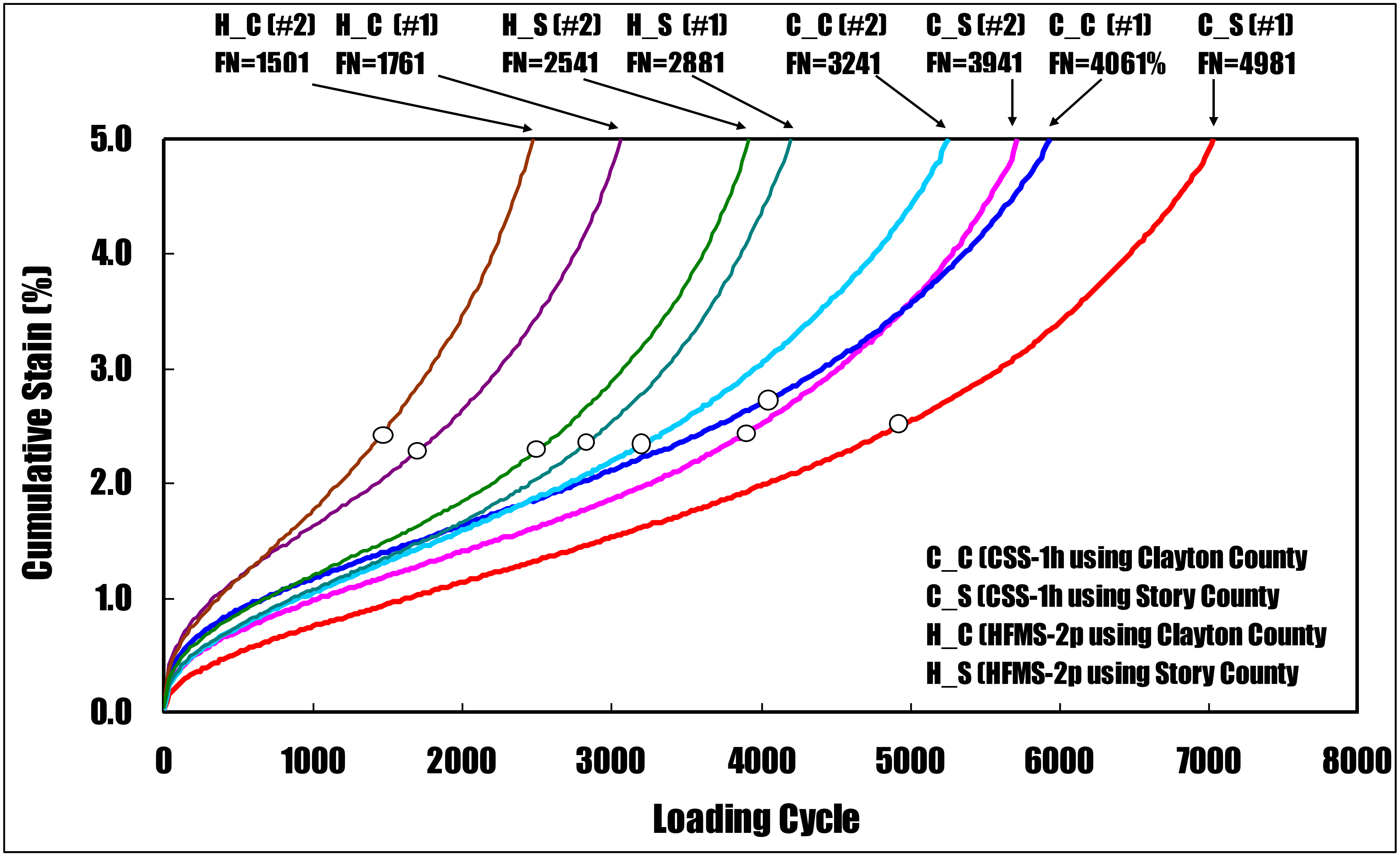


Figure 8-12. Plots of permanent strain versus loading cycle at EAC=0.5%

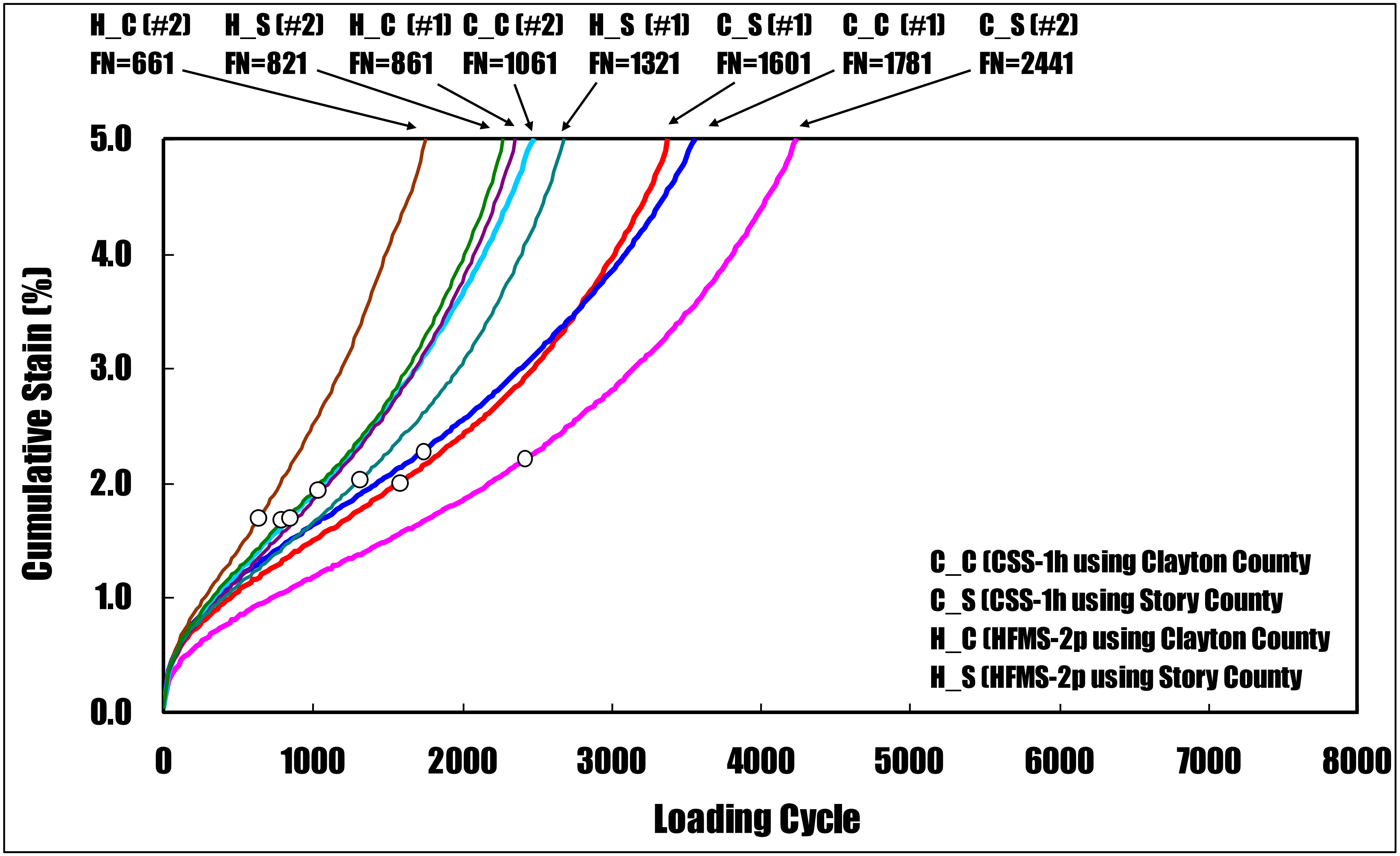


Figure 8-13. Plots of permanent strain versus loading cycle at EAC=1.0%

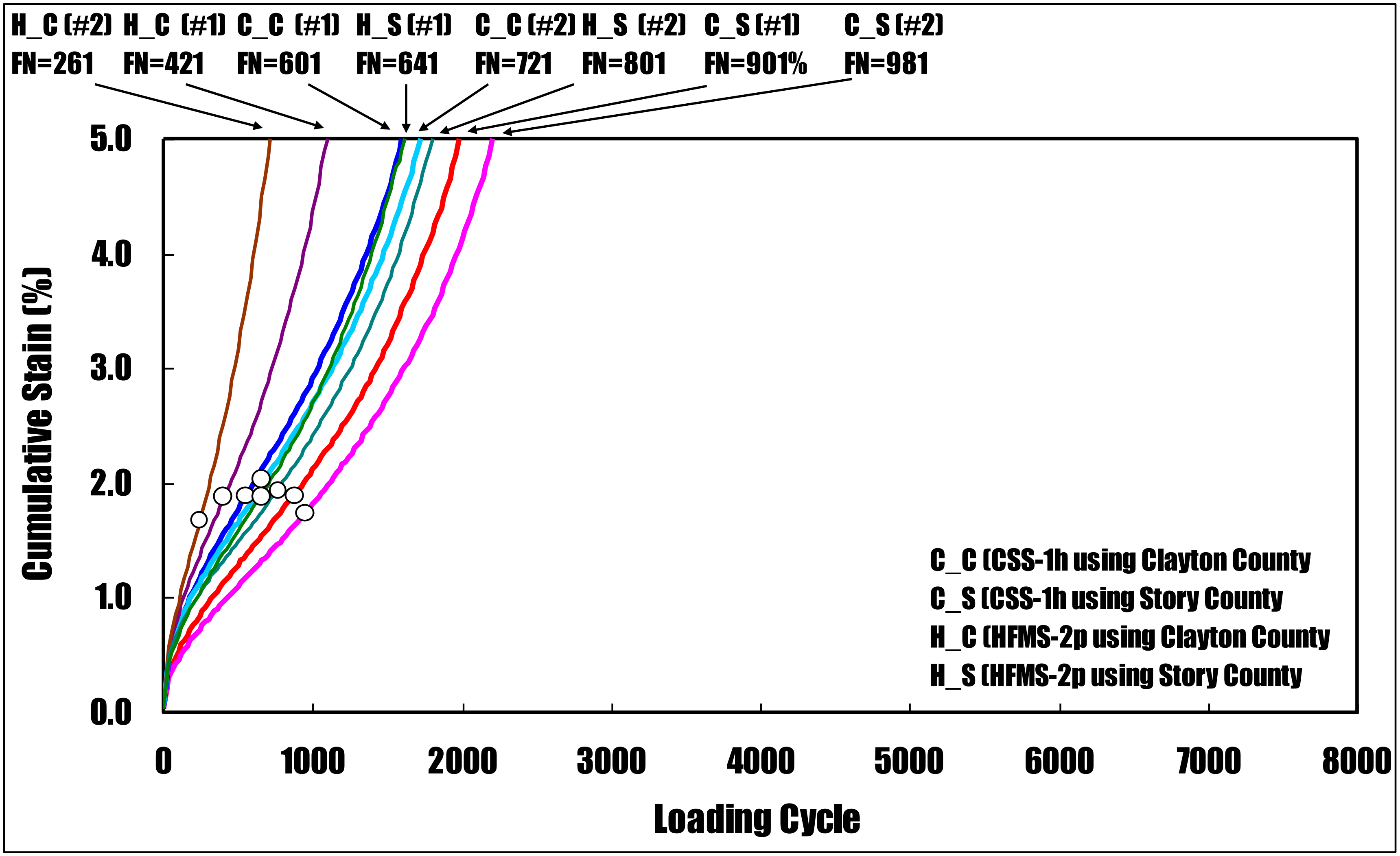


Figure 8-14. Plots of permanent strain versus loading cycle at EAC=1.5%

Table 8-18. Ranking of flow number from two different emulsion types and two different RAP sources

RAP Source	Emulsion Type	Stiffness		Residual AC (%)	% Passing No.8 Sieve	Ranking of Flow Number		
		Pen.	G*/sin δ @ 76°C			EAC=0.5%	EAC=1.0%	EAC=1.5%
Clayton County	CSS-1h	14	4.26	5.80	22.1%	2	2	3
	HFMS-2p					4	4	4
Story County	CSS-1p	18	1.94	5.81	18.3%	1	1	1
	HFMS-2p					3	3	2

8.2.4.3 Comparisons against CIR-foam Test Results

Table 8-19 shows flow numbers of CIR-foam and CIR-emulsion mixtures. The test results consistently indicate that the flow number decreases as the foamed asphalt content and emulsion content increases. It should be noted that CIR-foam mixtures consistently achieved the higher flow number than CIR-emulsion mixtures.

Table 8-19. Comparisons of flow number between CIR-foam and CIR-emulsion mixtures

RAP Source	FAC (%)	Flow Number	Cumulative Stain at FN	RAP Source	EAC (%)	Flow Number	Cumulative Stain at FN
Hardin County	1.0	10000	1.75%	Clayton County (CSS-1h)	0.5	3651	2.54%
	2.0	3841	2.00%		1.0	1421	2.15%
	3.0	1471	1.80%		1.5	661	2.00%
Lee County	1.0	10000	0.95%	Story County (CSS-1h)	0.5	4461	2.49%
	2.0	8301	3.66%		1.0	2021	2.12%
	3.0	2381	1.69%		1.5	941	1.86%
Webster County	1.0	10000	1.91%	Clayton County (HFMS-2p)	0.5	1631	2.40%
	2.0	7431	2.05%		1.0	761	1.69%
	3.0	2401	2.17%		1.5	341	1.83%
Bremer County	1.0	4911	1.57%	Story County (HFMS-2p)	0.5	2711	2.35%
	2.0	1671	1.55%		1.0	1071	1.85%
	3.0	591	1.43%		1.5	721	1.96%
Wapello County	1.0	8271	3.28%				
	2.0	2651	1.97%				
	3.0	561	1.73%				
Montgomery County	1.0	3441	1.75%				
	2.0	1131	1.73%				
	3.0	731	1.67%				
Muscatine County	1.0	481	1.45%				
	2.0	381	1.31%				
	3.0	511	1.73%				

8.3 Static Creep Test

Permanent deformation of asphalt pavement mixtures is a complex phenomenon where aggregate, asphalt, and aggregate-asphalt interface properties control the overall performance. Furthermore, over time, these properties change until failure occurs due to excessive permanent deformation or crack development. Current Superpave volumetric mix design procedure lacks a basic design criterion to evaluate fundamental engineering properties of the asphalt mixture that directly affect performance. The selection of the design binder content and aggregate structure can be enhanced by evaluating the mix resistance to flow time in static creep test. This fundamental engineering property can be used as a performance indicator for permanent deformation resistance of asphalt mixtures.

8.3.1 Theory

In a static creep test, a total strain-time relationship for a mixture can be measured in the laboratory under unconfined or confined conditions. The static creep test provides sufficient information to determine the instantaneous elastic (i.e., recoverable) and plastic (i.e., irrecoverable) components (which are time independent), as well as the viscoelastic and viscoplastic components (which are time dependent) of the material's response. Figure 8-15 shows a typical relationship between the cumulative permanent deformation strain and loading time. The total cumulative permanent deformation strain can be divided into three major zones: 1) primary zone, 2) secondary zone, and 3) tertiary flow zone. Ideally, the large increase in permanent deformation strain occurs at a constant volume within the tertiary zone. The starting point of tertiary deformation is defined as the flow time, which has been found to be a significant parameter in evaluating an HMA mixture's rutting resistance (Hafze, 1997).

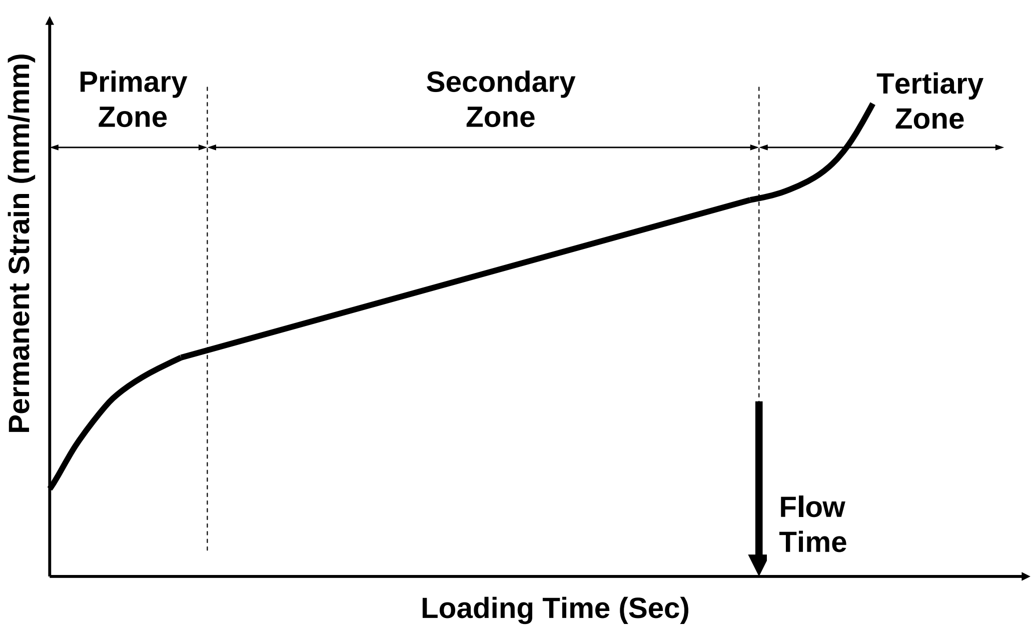


Figure 8-15. Permanent deformation behavior against loading time

8.3.2 Static Creep Testing Procedure

As noted in dynamic creep testing procedure, a specimen with 100-mm diameter and 150-mm height was prepared using a Gyratory compactor because CIR-emulsion specimens are not sufficiently stiff enough to be cored from a 150mm-diameter specimen. Two static loading stress levels of 20 psi and 10 psi were selected to attain tertiary flow in a reasonable time not exceeding 10,000 seconds. Testing temperature of 40˚C was selected to represent a temperature of CIR base layer in the field. A constant axial static load was applied up to 10,000 seconds or until achieving 5.0% of cumulative permanent stain.

8.3.3 Experimental Plan

As summarized in Table 8-2, CIR-emulsion specimens were prepared to measure a flow time using two different types of emulsified asphalt and two different RAP sources. For the first round of static creep test under a static loading stress level of 20 psi, one CIR-emulsion specimens were prepared for each of three emulsified asphalt contents, 0.5%, 1.0% and 1.5%. Using RAP materials from each source, a total of three CIR-emulsion specimens were prepared using the gyratory compactor at 25 gyrations and cured in the oven at 40°C for three days. For the second round of static creep test under a static loading stress level of 10 psi, two CIR-emulsion specimens were prepared for each of three emulsified asphalt contents, 0.5%, 1.0% and 1.5%. Using RAP materials from each source, a total of six CIR-emulsion specimens were prepared using the gyratory compactor at 25 gyrations and cured in the oven at 40°C for three days. The cured CIR-emulsion specimens were allowed to cool to a room temperature for 24 hours before testing.

8.3.4 Results and Discussion

The bulk specific gravities and air voids were measured for each CIR-emulsion specimen. The dynamic creep test was performed to evaluate: 1) rutting resistance of CIR-emulsion mixtures in a combination of two different RAP sources and two different types of emulsified asphalt; and 2) effect of the emulsified asphalt content on rutting resistance.

8.3.4.1 Volumetric Characteristics

The bulk specific gravities and air voids of each CIR-emulsion specimen were determined following the AASHTO T 166 by measuring the dry mass and height. Table 8-20 and Table 8-21 summarize bulk specific gravity and air void of CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources for static creep test at two different loading stress levels, which are 20 psi and 10 psi, respectively. As summarized in Table 8-20 and Table 8-21, overall, air voids of CIR-emulsion specimens decreased as the emulsified asphalt content increased. The air voids of CIR-emulsion specimens with RAP materials from Story County were higher than those of CIR-emulsion specimens with RAP materials from Clayton County.

Table 8-20. Bulk specific gravities and air voids of CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources for static creep test at 20 psi

Emulsion Type	RAP Source	EAC (%)	G_{mb}	Air Void (%)
CSS-1h	Clayton County	0.5	2.056	14.1
		1.0	2.046	13.2
		1.5	2.097	8.8
	Story County	0.5	2.055	14.7
		1.0	2.054	14.0
		1.5	2.085	11.4
HFMS-2p	Clayton County	0.5	2.073	14.1
		1.0	2.122	10.1
		1.5	2.154	8.1
	Story County	0.5	2.071	14.2
		1.0	2.100	11.7
		1.5	2.111	9.7

Table 8-21. Bulk specific gravity and air void of CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources for static creep test at 10 psi

Emulsion Type	RAP Source	EC (%)	G_{mb}			Air Void (%)	
			Individual		Average	Individual	Average
CSS-1h	Clayton County	0.5	# 1	2.053	2.057	14.2	14.1
			# 2	2.061		13.9	
		1.0	# 1	2.043	2.046	13.3	13.2
			# 2	2.049		13.1	
		1.5	# 1	2.133	2.124	7.7	7.9
			# 2	2.115		8.1	
	Story County	0.5	# 1	2.046	2.039	15.1	15.4
			# 2	2.031		15.7	
		1.0	# 1	2.073	2.072	13.2	13.3
			# 2	2.071		13.3	
		1.5	# 1	2.073	2.079	12.0	11.7
			# 2	2.085		11.4	
HFMS-2p	Clayton County	0.5	# 1	2.067	2.069	14.3	14.2
			# 2	2.071		14.1	
		1.0	# 1	2.077	2.092	12.0	11.4
			# 2	2.107		10.8	
		1.5	# 1	2.143	2.158	8.6	8.0
			# 2	2.172		7.3	
	Story County	0.5	# 1	2.054	2.057	14.9	14.8
			# 2	2.059		14.6	
		1.0	# 1	2.079	2.073	12.6	12.9
			# 2	2.066		13.1	
		1.5	# 1	2.098	2.111	10.3	9.8
			# 2	2.123		9.2	

8.3.4.2 Results of Static Creep Test

Table 22 and Table 23 summarize the flow time and cumulative strain of CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources and three different emulsified asphalt contents for static creep test at 20 psi and 10 psi, respectively.

For the loading stress level at 20 psi, Figure 8-16, Figure 8-17 and Figure 8-18 show plots of cumulative strain against loading time measured from four CIR-emulsion specimens prepared using two emulsion types and two types of RAP materials at three emulsified asphalt contents of 0.5%, 1.0% and 1.5%, respectively. For the loading stress level at 10 psi, Figure 8-19, Figure 8-20 and Figure 8-21 show plots of cumulative strain against loading time measured from eight CIR-emulsion specimens prepared using two emulsion types and two RAP sources at three emulsified asphalt contents of 0.5%, 1.0% and 1.5%, respectively. As shown in these figures, it is interesting to note that CIR-emulsion specimens consistently failed early as the emulsified asphalt was increased from 0.5% to 1.5%. It can be postulated that the lower the emulsified asphalt contents, the flow time was higher, which indicates the emulsified asphalt content with 0.5% is more resistant to rutting than 1.0% and 1.5%. Characteristics of two RAP materials are summarized in Table 8-24 along with the rankings in terms of flow time. As can be easily observed from the table, rankings of a combination of emulsion types and RAP materials did not change when the emulsified asphalt content was increased from 0.5% to 1.5%, which confirms the consistency of the static creep test in evaluating the rutting susceptibility of emulsion type and RAP aggregate structure. It can be observed that the increased emulsified asphalt content may reduce the rutting resistance of CIR-emulsion mixtures.

Table 8-22. Flow time and cumulative strain at flow time (20 psi) for CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources

Emulsion Type	RAP Source	EAC (%)	Flow Time	Cumulative Stain at FT
CSS-1h	Clayton County	0.5	205	2.26%
		1.0	85	2.07%
		1.5	55	2.26%
	Story County	0.5	245	1.92%
		1.0	90	2.01%
		1.5	60	2.09%
HFMS-2p	Clayton County	0.5	120	2.08%
		1.0	55	2.12%
		1.5	35	2.06%
	Story County	0.5	125	2.12%
		1.0	60	2.23%
		1.5	30	2.23%

Table 8-23. Flow time and cumulative strain at flow time (10 psi) for CIR-CSS-1h and CIR-HFMS-2p specimens using two different RAP sources

Emulsion Type	RAP Source	EAC (%)	No. of Specimen	Flow Time		Cumulative Stain at FT
				Individual	Average	
CSS-1h	Clayton County	0.5	# 1	1715	2130	2.18%
			# 2	2545		2.55%
		1.0	# 1	540	635	2.19%
			# 2	730		2.28%
		1.5	# 1	310	338	2.18%
			# 2	365		2.26%
	Story County	0.5	# 1	1560	1550	2.10%
			# 2	1540		2.08%
		1.0	# 1	610	583	2.11%
			# 2	555		2.17%
		1.5	# 1	510	488	2.35%
			# 2	465		2.34%
HFMS-2p	Clayton County	0.5	# 1	880	800	2.26%
			# 2	720		2.22%
		1.0	# 1	430	418	2.21%
			# 2	405		2.27%
		1.5	# 1	165	188	1.86%
			# 2	210		2.26%
	Story County	0.5	# 1	1375	1238	2.39%
			# 2	1100		2.18%
		1.0	# 1	550	488	2.33%
			# 2	425		2.34%
		1.5	# 1	245	235	2.13%
			# 2	225		1.94%

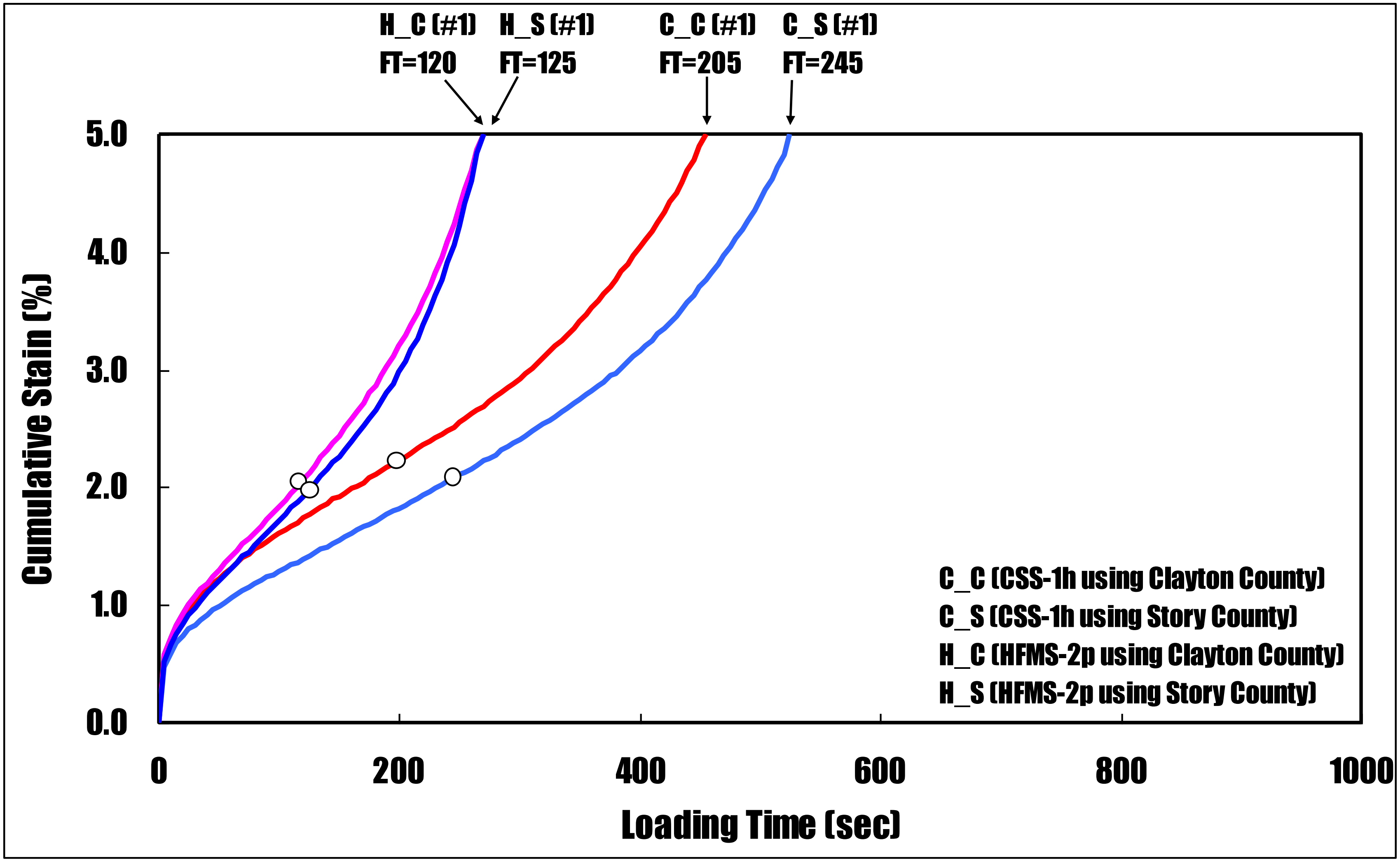


Figure 8-16. Plots of permanent strain versus loading time for 20 psi at EAC=0.5%

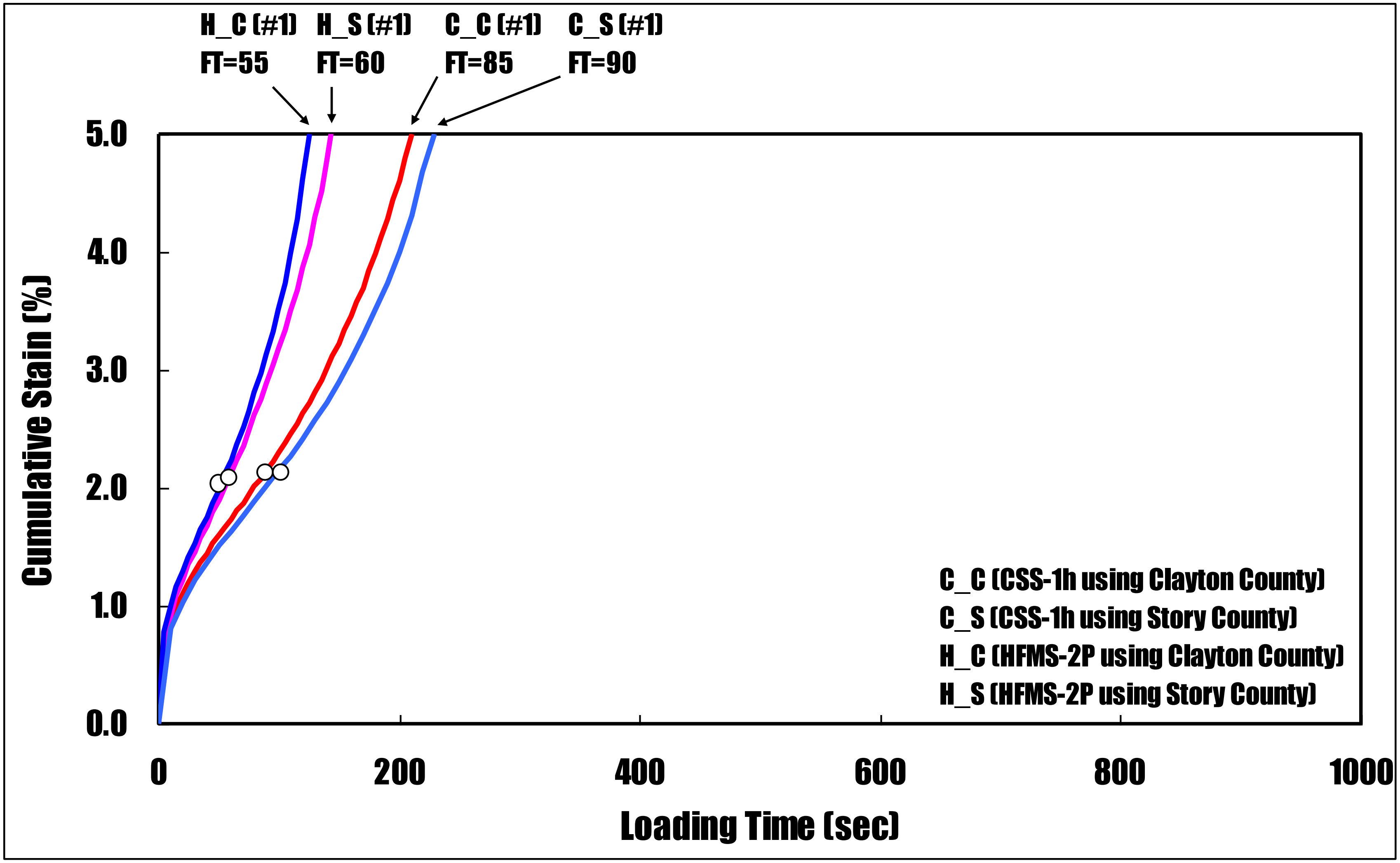


Figure 8-17. Plots of permanent strain versus loading time for 20 psi at EAC=1.0%

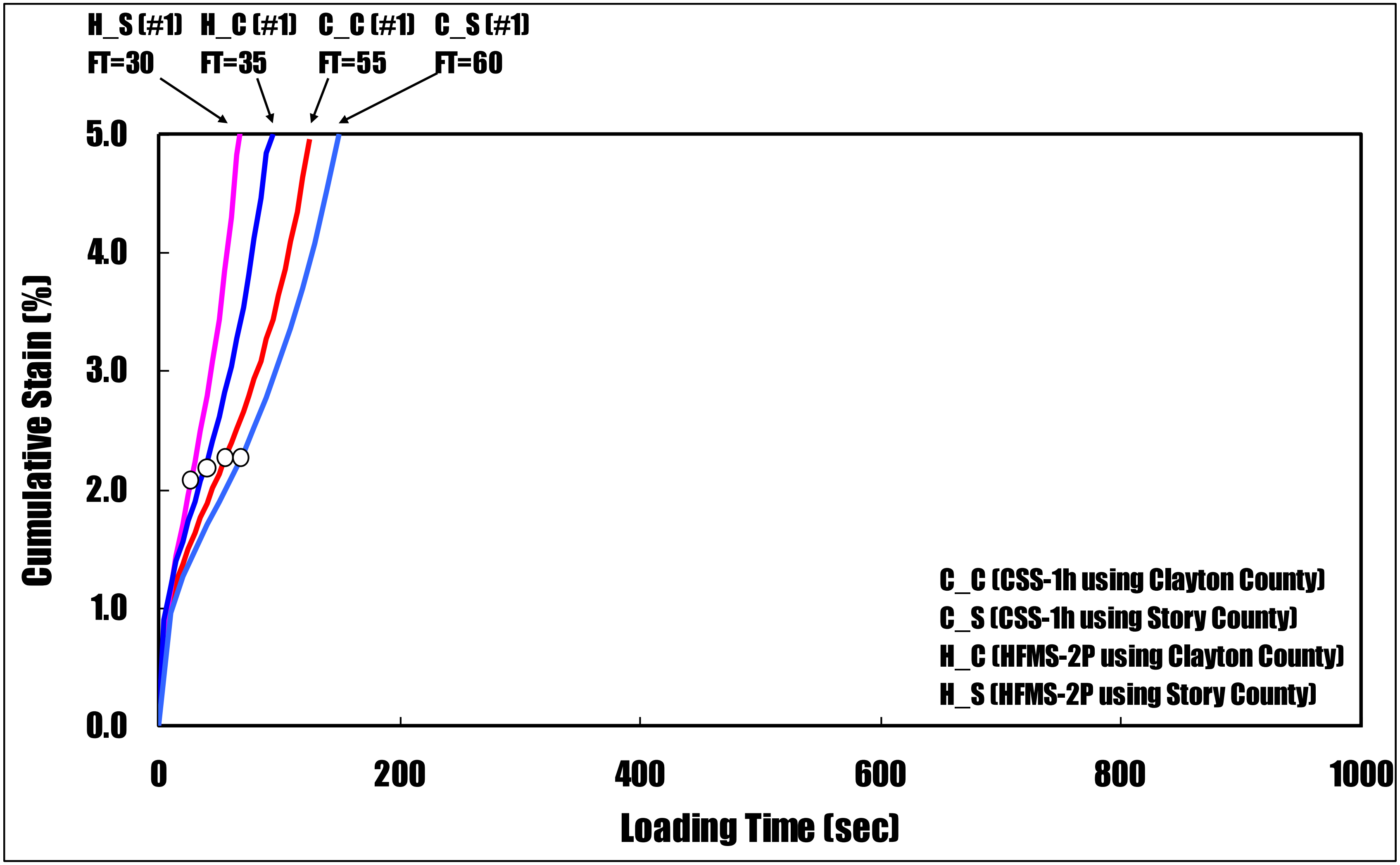


Figure 8-18. Plots of permanent strain versus loading time for 20 psi at EAC=1.5%

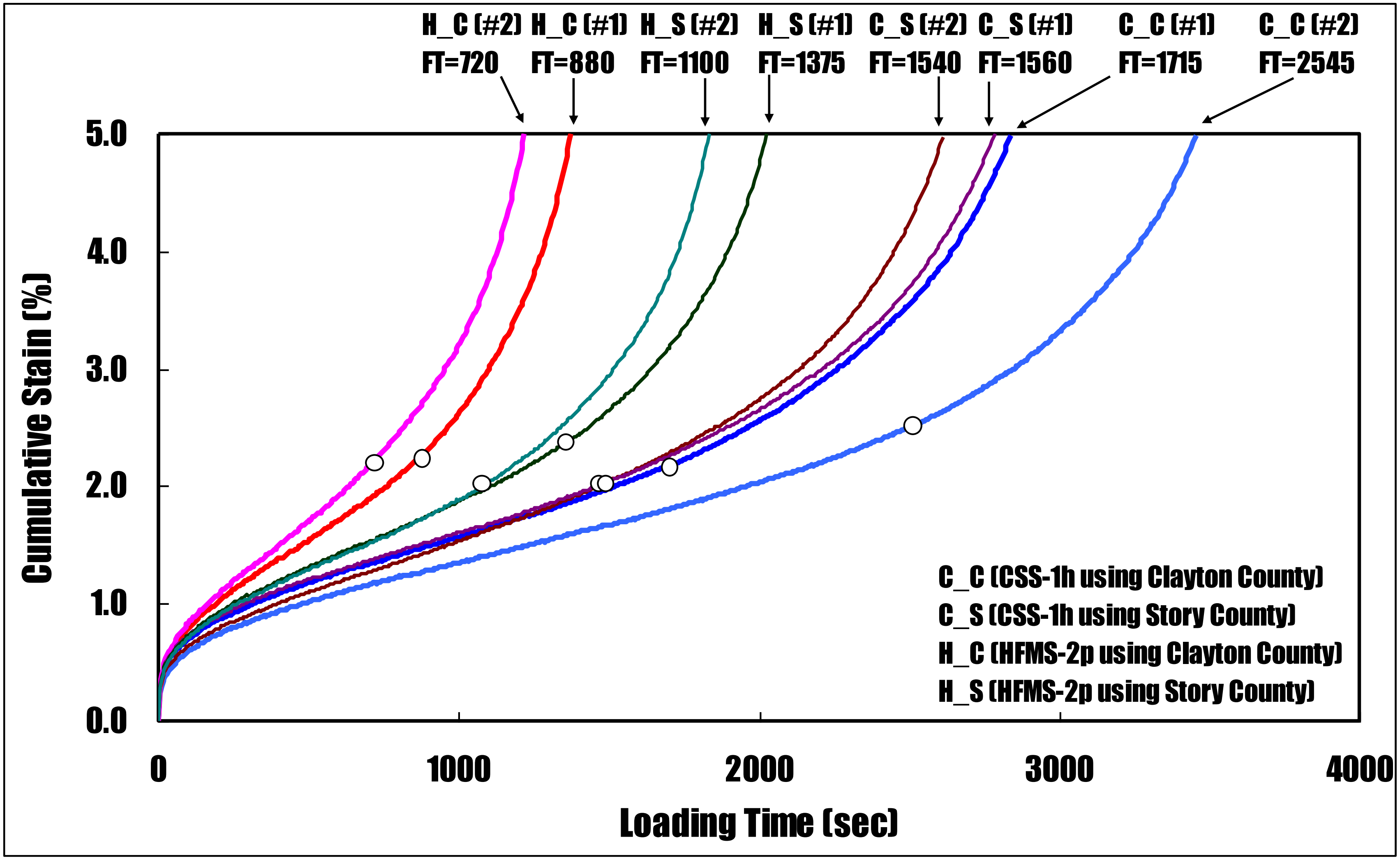


Figure 8-19. Plots of permanent strain versus loading time for 10 psi at EAC=0.5%

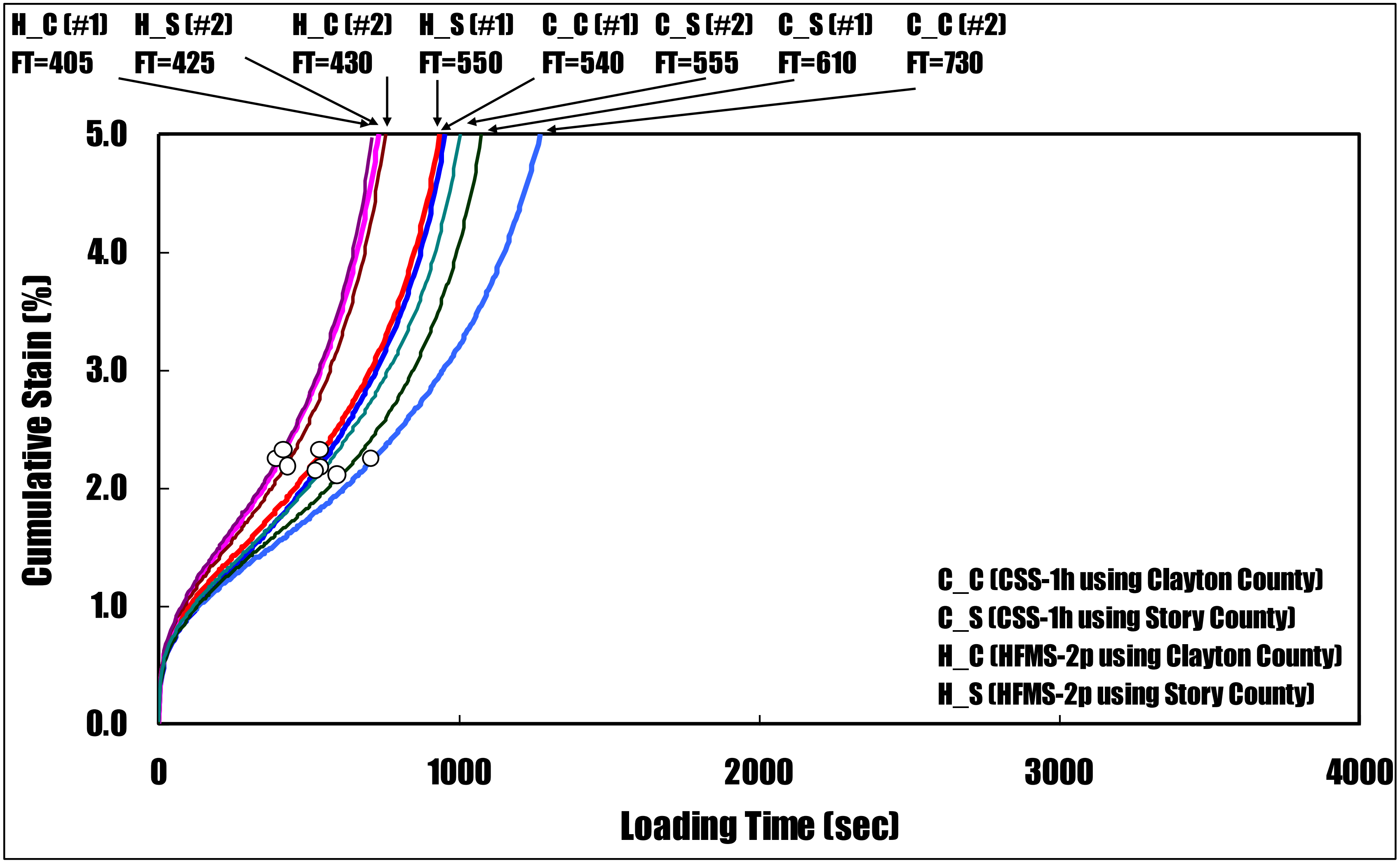


Figure 8-20. Plots of permanent strain versus loading time for 10 psi at EAC=1.0%

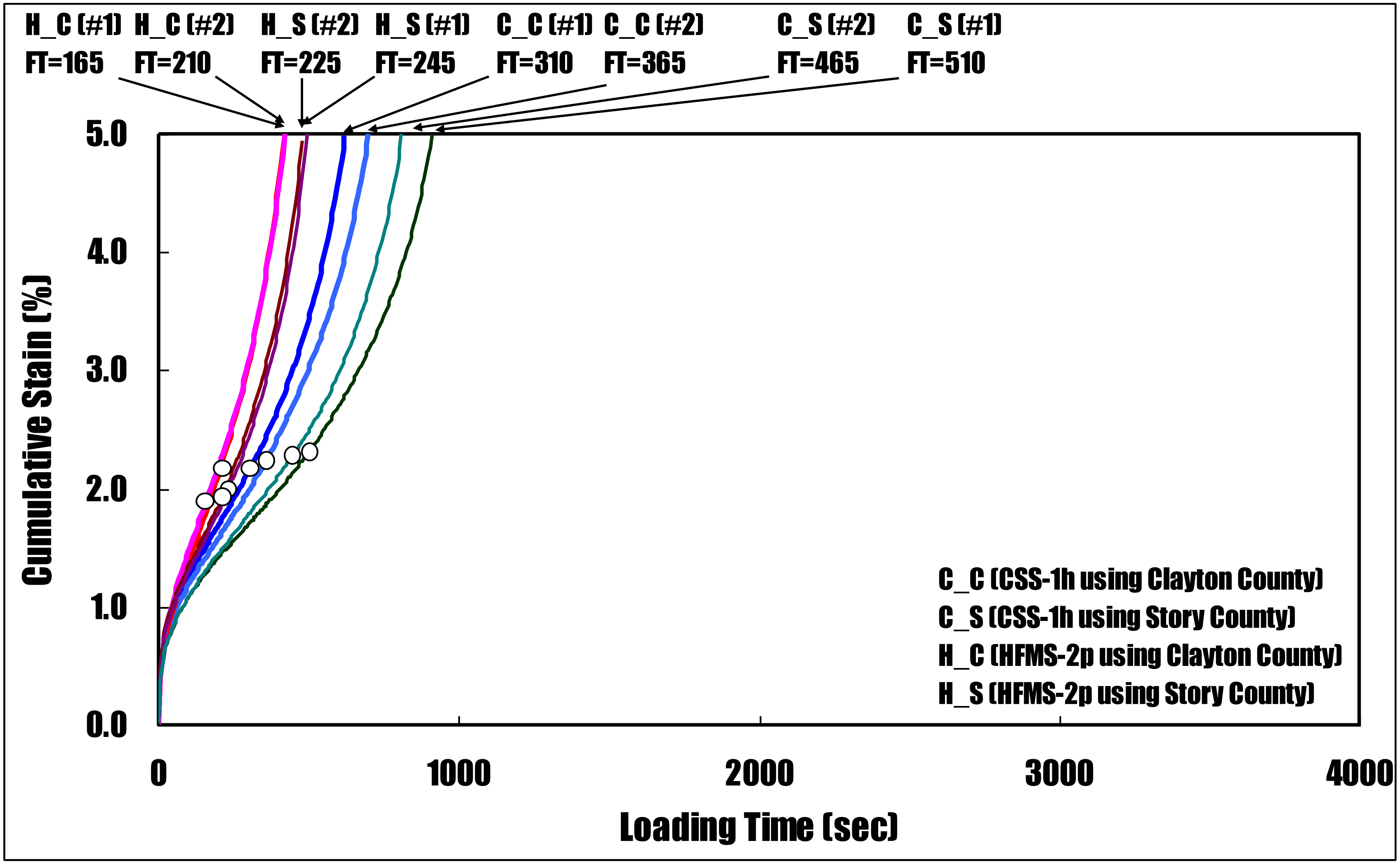


Figure 8-21. Plots of permanent strain versus loading time for 10 psi at EAC=1.5%

Table 8-24. Ranking of flow time at 20 psi and 10 psi from two different emulsion types and two different RAP sources

RAP Source	Emulsion Type	Stiffness		Residual AC (%)	% Passing No.8 Sieve	Ranking of Flow Time					
						EAC=0.5%		EAC=1.0%		EAC=1.5%	
		Pen.	G*/sin δ @ 76°C			20 psi	10 psi	20 psi	10 psi	20 psi	10 psi
Clayton County	CSS-1h	14	4.26	5.80	22.1%	2	1	2	1	2	2
	HFMS-2p					4	4	4	4	3	4
Story County	CSS-1h	18	1.94	5.81	18.3%	1	2	1	2	1	1
	HFMS-2p					3	3	3	3	4	3

8.4 Reveling Test

A CIR layer is normally covered by a hot mix asphalt (HMA) overlay or chip seal in order to protect it from water ingress and traffic abrasion and obtain the required pavement structure and texture. During the curing process in the field, the raveling occurred from the surface of CIR pavement before HMA overlay is placed. In order to determine the short-term raveling performance right after construction of CIR-emulsion, the following laboratory raveling test was conducted.

8.4.1 Raveling Testing Procedure

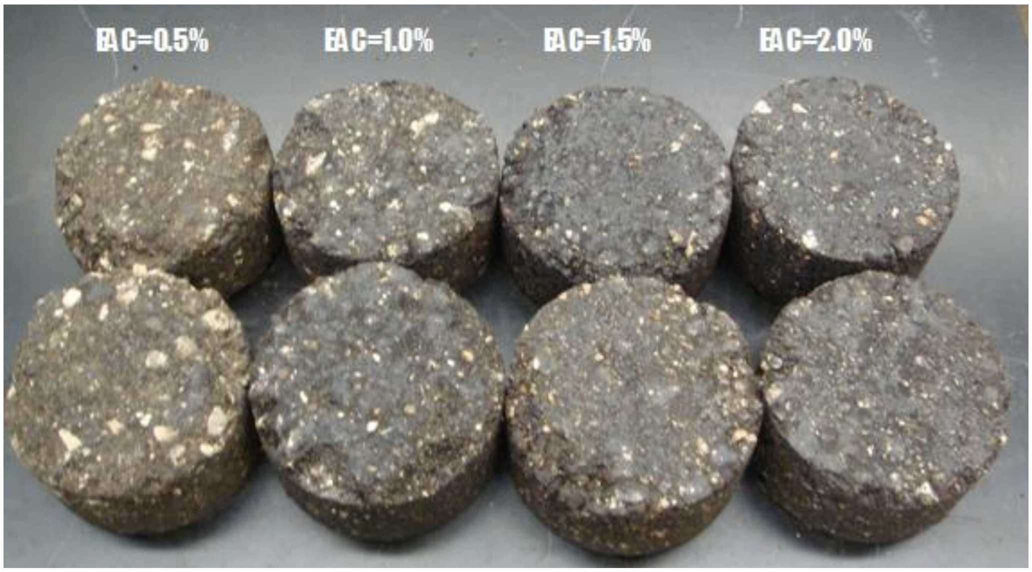
The raveling test was performed to evaluate a resistance to raveling of a CIR layer right after construction. As shown in Figure 8-22, gyratory compacted 150-mm specimen is placed on a modified Hobart asphalt mixer and subjected to abrasion by a rubber hose. The specimens are abraded for 15 minutes and the loose aggregates are measured as a percentage of the weight of the specimen.

Figure 8-22. Pictures of raveling testing specimens and equipment

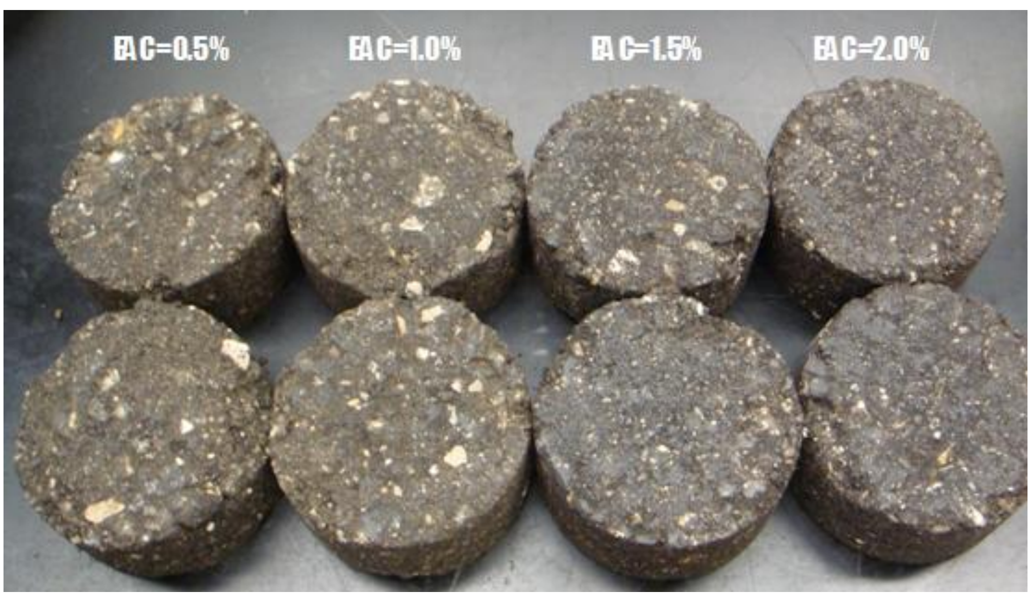
For the raveling test, 150-mm specimens at four emulsified asphalt contents, 0.5%, 1.0%, 1.5% and 2.0%, given a fixed moisture content of 3.0%, were prepared using the Superpave gyratory compactor at 25 gyrations. The CIR-emulsion specimens were cured for 4 hours at the room temperature (24˚C). The CIR-emulsion specimens were then placed on the modified Hobart mixer fitted with an abrasion head and hose assembly, and abraded for 15 minutes. Figure 8-23 shows the damaged surface of CIR-CSS-1h specimens after the raveling test. The repeatability of raveling test results should be ± 5.0% and the percent raveling loss is computed as follows:

$$\text{The percent raveling loss (\%)} = \frac{(W_b - W_a)}{W_b} \times 100$$

W_a = Weight after raveling test
W_b = Weight before raveling test



(a) Clayton County



(a) Story County

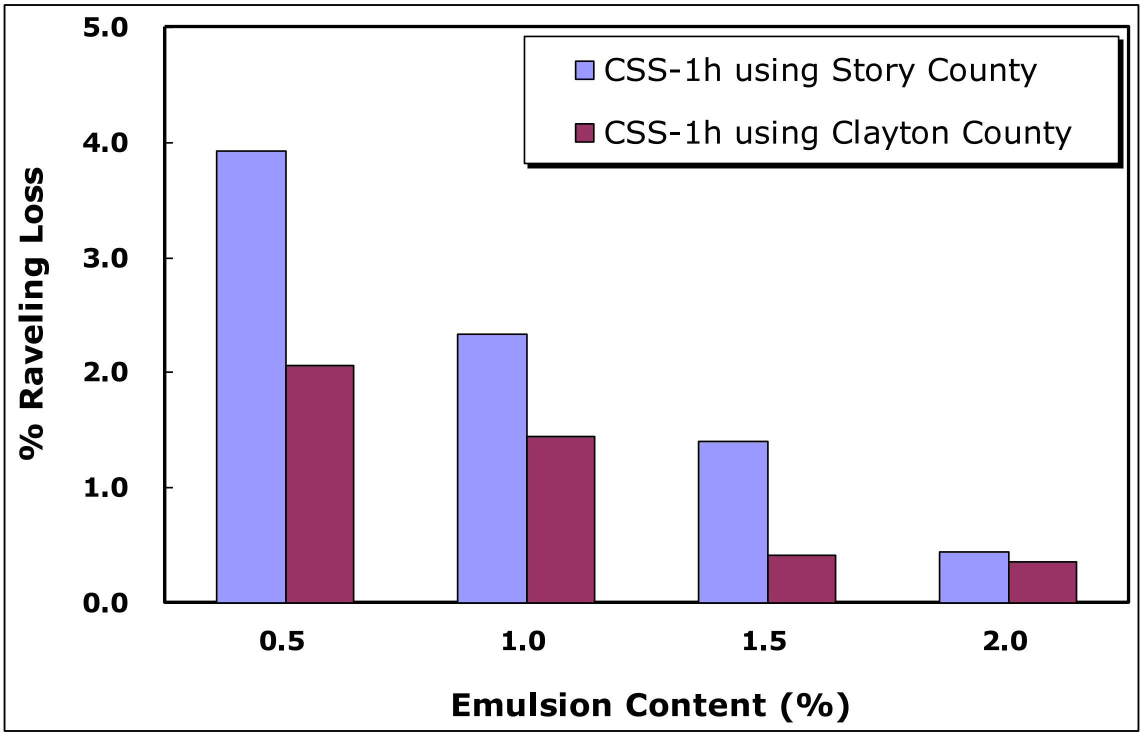
Figure 8-23. Damaged surface of CIR-CSS-1h specimens at four different emulsified asphalt contents using two different RAP sources

8.4.2 Test Results and Discussion

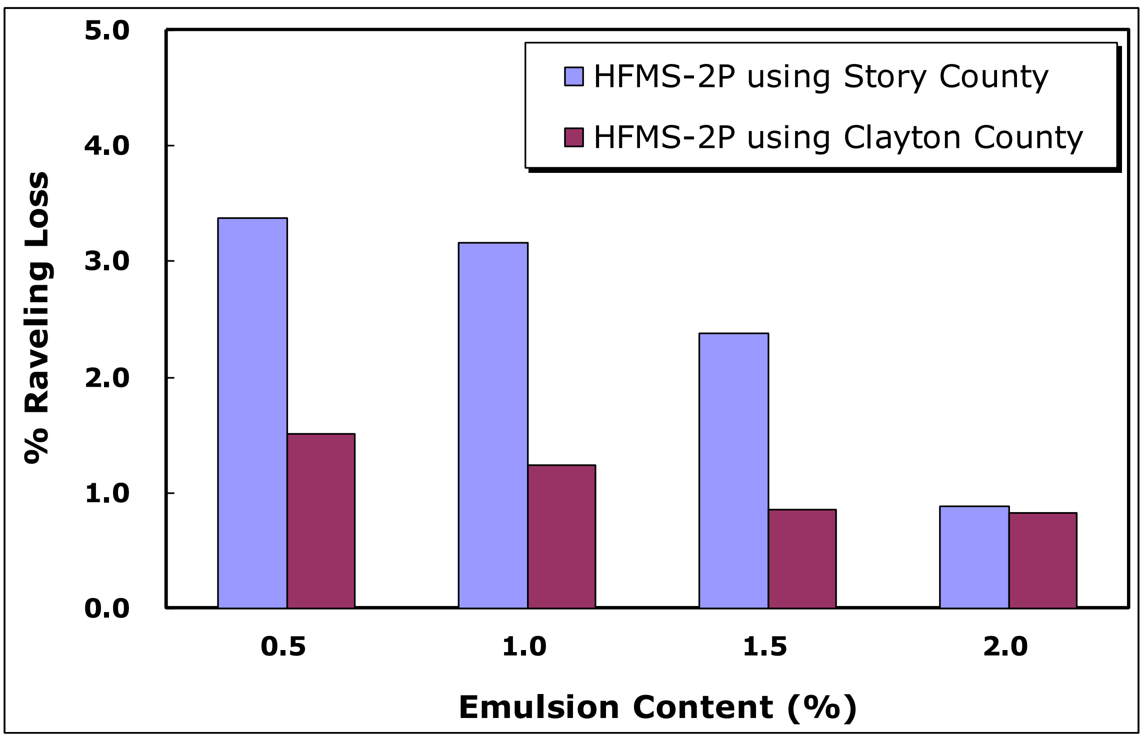
The percent mass losses of the CIR-CSS-1h and CIR-HFMS-2p specimens at four emulsified asphalt contents, 0.5%, 1.0%, 1.5% and 2.0%, are plotted in Figure 8-24. Overall, CIR-emulsion specimens using RAP materials from Clayton County show less raveling loss than those from Story County at both CSS-1h and HFMS-2p emulsions. Percent raveling loss of both CIR-CSS-1h and HFMS-2p specimens was considerably decreased as emulsified asphalt content increased up to 1.5%. It was found that the raveling test was very sensitive to RAP source and emulsified asphalt content of the CIR-emulsion specimens. The behavior after 4-hour curing would imply that, to increase cohesive strength quickly, it is necessary to use the emulsified asphalt content above 1.5%.

8.4.3 Comparisons against CIR-foam Test Results

Table 8-25 shows percent raveling losses of CIR-foam and CIR-emulsion mixtures. The test results consistently indicate that a percent raveling loss decreases as the foamed asphalt content and emulsion content increases.



(a) CIR-CSS-1h



(b) CIR-HFMS-2p

Figure 8-24. Percent raveling losses for two different CIR-emulsion specimens from two different RAP sources

Table 8-25. Comparisons of % raveling loss between CIR-foam and CIR-emulsion mixtures

	Foamed Asphalt Content (%)			
	1.5	2.5	1.5	2.5
Curing Temperature (°C)	room temperature (24°C) for 4 hours		room temperature (24°C) for 8 hours	
Muscatine County	1.13	0.52	0.25	0.10
Webster County	1.00	0.45	0.21	0.14
Hardin County	1.16	0.57	0.57	0.21
Montgomery County	1.08	0.47	0.33	0.14
Bremer County	1.30	0.54	0.53	0.17
Lee County	1.54	0.65	0.53	0.24
Wapello County	1.04	0.54	0.28	0.17

	Emulsified Asphalt Content (%)			
	0.5	1.0	1.5	2.0
Curing Temperature (°C)	room temperature (24°C) for 4 hours			
Clayton County (CSS-1h)	2.06	1.45	0.42	0.37
Story County (CSS-1h)	3.93	2.33	1.41	0.44
Clayton County (HFMS-2p)	1.52	1.25	0.86	0.83
Story County (HFMS-2p)	3.38	3.17	2.38	0.89

9. CONCLUSIONS AND RECOMMENDATIONS

The previous research developed and validated the mix design procedure for cold in-place recycling using foamed asphalt (CIR-foam). The current CIR using engineered emulsion (CIR-EE) mix design procedure is complex and requires special equipment that is not commonly available. Currently, no standard mix design is available for CIR using emulsified asphalt (CIR-emulsion) in Iowa. The main objective of the study is to determine if the CIR-foam mix design process can be applied to CIR-emulsion with some minor adjustments.

The CIR-foam mix design process was applied to CIR-emulsion mixtures with varying emulsified asphalt contents. The simple performance testing (SPT) equipment was used to predict the field performance of various CIR-emulsion mixtures. Dynamic modulus test, dynamic creep test, static creep test and raveling test were conducted to evaluate the short- and long-term performance of CIR-emulsion mixtures at various testing temperatures and loading conditions. A potential benefit of this research is a better understanding of CIR-emulsion material properties in comparison with CIR-foam materials that would allow for the selection of the most appropriate CIR technology and the type and amount of the stabilization material.

Conclusions

Based on the limited laboratory experiment, the following conclusions are derived:

1. The mix design procedure developed for CIR-foam is applicable to CIR-emulsion.
2. Indirect tensile strength of gyratory compacted specimens is higher than that of Marshall hammer compacted specimens.
3. Based on the wet indirect tensile strength of the gyratory compacted CIR-emulsion specimens, the residual asphalt content of emulsion was found at around 1.0% with a clear peak.
4. Dynamic modulus of the CIR-emulsion is not as sensitive to temperature and loading frequency as HMA.
5. Dynamic modulus, flow number and flow time of CIR-emulsion mixtures using CSS-1h were generally higher than that of HFMS-2p.
6. Dynamic modulus of CIR-emulsion using RAP materials from Clayton County was higher than that of Story County.
7. Flow number and flow time of CIR-emulsion using RAP materials from Story County was higher than those of Clayton County.
8. Flow number and flow time of CIR-emulsion with 0.5% emulsified asphalt was higher than CIR-emulsion with 1.0% or 1.5%.
9. Raveling loss of CIR-emulsion with 1.5% emulsified was significantly less than those with 0.5% and 1.0%.
10. Test results of CIR-foam mixtures are generally better than those of CIR-emulsion mixtures.

Recommendations

Based on the limited laboratory experiment, the following recommendations are made:

1. The mix design procedure for CIR-foam should be adopted for CIR-emulsion.
2. RAP materials should be characterized in terms of penetration index and amount of extracted asphalt binder and extract aggregate gradation.
3. It is recommended that flow number and raveling tests should be performed for predicting the field performance of CIR-emulsion.

Future Studies

1. In the future, the optimum target range of designing specific amount of stabilizing agent for CIR should be studied based on the test results from permanent deformation and raveling loss.

2. Given the limited RAP sources used for this study, it is recommended that the CIR-emulsion mix design procedure should be validated against several RAP sources and various emulsion types.

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