VALIDATION OF THE MIX DESIGN PROCESS FOR COLD IN-PLACE REHABILITATION USING FOAMED ASPHALT

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(IHRB Project TR 474)

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16. Abstract

Asphalt pavement recycling has grown dramatically over the last few years as a viable technology to rehabilitate existing asphalt pavements. Iowa's current Cold In-place Recycling (CIR) practice utilizes a generic recipe specification to define the characteristics of the CIR mixture. As CIR continues to evolve, the desire to place CIR mixture with specific engineering properties requires the use of a mix design process. A new mix design procedure was developed for Cold In-place Recycling using foamed asphalt (CIR-foam) in consideration of its predicted field performance. The new laboratory 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. The performance tests, which include dynamic modulus test, dynamic creep test and raveling test, were conducted to evaluate the consistency of a new CIR-foam mix design process to ensure reliable mixture performance over a wide range of traffic and climatic conditions. The "lab designed" CIR will allow the pavement designer to take the properties of the CIR into account when determining the overlay thickness.

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EXECUTIVE SUMMERY

Iowa's current Cold In-place Recycling (CIR) practice utilizes a generic recipe specification to define the characteristics of the CIR mixture. The contractor is given latitude to adjust the proportions of stabilizing agent to achieve a specified level of density. As CIR continues to evolve, the desire to place CIR mixture with specific engineering properties requires the use of a mix design process. The “lab designed” CIR will allow the pavement designer to take the properties of the CIR into account when determining the overlay thickness. A significant drawback to using emulsion as the stabilizing agent is the amount of water associated with the emulsion. High amounts of water limit the ability to increase binder content and extent the time required to cure the CIR layer. Using foamed asphalt as the stabilizing agent could significantly reduce these limitations.

During the phase I study, a new mix design process was developed for evaluating CIR-foam mixtures. Some 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 Cold In-place Recycling using foamed asphalt (CIR-foam). Based upon the critical mixture parameters identified, a new mix design procedure using indirect tensile test and vacuum-saturated wet specimens was developed. Phase II study was then launched to validate the developed laboratory mix design process against various Reclaimed Asphalt Pavement (RAP) materials to determine its consistency over a wide range of RAP materials available throughout Iowa.

Collection and Evaluation of RAP Materials

During the summer of 2004, in order to validate the mix design process developed during the phase I study, RAP materials were collected from seven different CIR project sites: three CIR-foam and four CIR-ReFlex sites. CIR project sites were selected across the state of the Iowa, which included Muscatine County, Webster County, Hardin County, Montgomery County, Bremer County, Lee County, and Wapello County.

First, RAP materials were divided into six stockpiles that were retained on the following sieves: 25mm, 19mm, 9.5mm, 4.75mm, 1.18mm, and those passing through the 1.18mm sieve. The sorted RAP materials were then weighed and their relative proportions were computed. All RAP materials were considered from dense to coarse with very small amount of fine aggregates passing through the 0.075mm (No. 200) sieve. All RAP materials passed through the 38.1 mm sieve and less than 1.0% was retained on the 25mm sieve except those at Muscatine (2.6%), Hardin (6.0%), and Wapello Counties (1.3%). Gradation analyses for seven RAP sources were conducted and the RAP materials from Muscatine County were the coarsest followed by Montgomery, Webster and Wapello Counties; and those from Hardin, Bremer and Lee Counties were finer. Overall, gradations of extracted aggregates were relatively fine with a large amount of fine material passing through a 0.075mm sieve.

The flat and elongation ratio test was performed on RAP materials in accordance with ASTM D 4791. All RAP materials exceeded the 10% limit of a 3:1 ratio and RAP materials from Lee County were the most flat and elongated, followed by Wapello County. The least flat and elongated materials were from Hardin, Montgomery and Bremer Counties. Very few RAP materials were flat and elongated at a ratio greater than 5:1. To investigate compaction characteristics of RAP materials, as a reference point, RAP materials were compacted using a gyratory compactor without adding water or foamed asphalt. There was a significant increase in bulk specific gravity by adding foamed asphalt.

The extracted asphalt content ranged from 4.59% for RAP materials collected from Wapello County to 6.06% from Hardin County. The extracted asphalt of RAP material from Montgomery County exhibited the highest penetration of 28 and a small $G^*/\sin\delta$ value of 1.08 at the lowest test temperature of 76°C whereas that of Lee County showed the lowest penetration of 15 and $G^*/\sin\delta$ value of 1.06 at the highest test temperature of 94°C.

Validation of a New Mix Design Process

The indirect tensile strength test of the vacuum-saturated specimens was conducted using seven different RAP materials at five foamed asphalt contents, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%, given a fixed moisture content of 4.0%. The specimens were compacted by gyratory compactor at 30 gyrations or by Marshall hammer at 75 blows and were cured at 40°C oven for three days or 60°C for two days. The indirect tensile strength of gyratory compacted and vacuum-saturated specimens was more sensitive to foamed asphalt contents than that of Marshall hammer compacted and vacuum-saturated specimens. The indirect tensile strength of CIR-foam specimens cured for two days at 60°C oven was significantly higher than that of CIR-foam specimens cured for three days at 40°C oven.

The optimum foamed asphalt content was determined when the highest indirect tensile strength of vacuum saturated specimens was obtained. Based on the test results, neither air voids nor flat and elongation characteristics of RAP materials affected the indirect tensile strength of the CIR-foam mixtures. The highest indirect tensile strengths were obtained from the RAP materials with a large amount of hard residual asphalt. However, the optimum foamed asphalt content was not affected by the amount of residual asphalt content.

Performance Test Results

The performance tests, which include dynamic modulus test, dynamic creep test and raveling test, were conducted to evaluate the consistency of a new CIR-foam mix design process to ensure reliable mixture performance over a wide range of traffic and climatic conditions.

The dynamic modulus tests were performed on CIR-foam mixtures at six different loading frequencies, 0.1, 0.5, 1, 5, 10 and 25 Hz, and three different test temperatures, 4.4, 21.1 and 37.8°C. Within each source of RAP materials, the dynamic moduli of RAP materials were not affected by loading frequencies but significantly affected by the test temperatures. The dynamic moduli measured at three foamed asphalt contents were significantly different among seven RAP sources. Rankings of RAP materials by the dynamic modulus value changed when the foamed asphalt was increased from 1.0% to 3.0%, which indicates that the dynamic modulus values are affected by a combination of foamed asphalt content and RAP aggregate structure.

At 4.4°C, dynamic modulus of RAP materials from Muscatine County was the highest, Webster County was second and Lee and Hardin Counties were the lowest. At 21.1°C, dynamic modulus of RAP materials from Webster County was the highest followed by Muscatine County whereas Lee and Hardin Counties stayed at the lowest level. At 37.8°C, dynamic modulus of RAP materials from Muscatine became the lowest whereas Webster County was the highest.

It can be postulated that RAP material from Muscatine is sensitive to temperature because they were the coarsest with least amount of residual asphalt content. Therefore, the coarse RAP materials with a small amount of residual asphalt content may be more fatigue resistant at a low temperature but more susceptible to rutting at a high temperature. On the other hand, fine RAP materials with a large amount of hard residual asphalt content like Hardin County may be more resistant to rutting at high temperature but more susceptible to fatigue cracking at low temperature.

A master curve was constructed for a reference temperature of 20˚C for each of seven RAP sources. Master curves are relatively flat compared to HMA mixtures, which supports that foamed asphalt mixtures are not as viscoelastic as HMA. More viscoelastic behavior was observed from the foamed asphalt mixtures with higher foamed asphalt content.

Based on the dynamic creep test, RAP materials from Muscatine County exhibited the lowest flow number at all foamed asphalt contents whereas those from Lee and Webster Counties reached the highest flow number. The lower the foamed asphalt contents, the flow number was higher, which indicates the foamed asphalt content with 1.0% is more resistant to rutting than 2.0% and 3.0%.

RAP materials from seven different sources were ranked by the flow number. Overall, the rankings of RAP materials did not change when the foamed asphalt was increased from 1.0% to 3.0%, which indicates that flow number is affected more dominantly by the RAP aggregate structure than by the foamed asphalt content. The finer RAP materials with a higher amount of the harder binder were more resistant to rutting. This result is consistent with the findings based on dynamic modulus test performed at 37.8˚C.

Based on the laboratory performance test results, it can be postulated that RAP materials from Wapello and Webster Counties would be more resistant to both fatigue and rutting.

RAP materials from Muscatine, Bremer and Montgomery Counties would be more resistant to fatigue cracking but less resistant to rutting. RAP materials from Hardin and Lee Counties would be more resistant to rutting but less resistant to fatigue cracking.

Based on the raveling test results, the foamed asphalt specimens at 2.5% foamed asphalt content showed less raveling loss than those of 1.5% foamed asphalt content. It was found that the raveling test was very sensitive to the curing period and foamed asphalt content of the CIR-foam specimens. To increase cohesive strength quickly, it is necessary to use higher foamed asphalt content of 2.5% instead of 1.5%.

Short Term Performance of CIR Pavements

To evaluate the short-term performance of CIR pavements, the digital images were collected from these CIR project sites using the Automated Image Collection System (AICS) and the images were analyzed to measure the length, extent, and severity of different types of distress. Based upon the condition survey result performed in one year after the construction, all have performed very well without any serious distress observed. Some minor longitudinal and transverse cracks were observed near the interface between rehabilitated and un-rehabilitated pavements in Montgomery, Hardin, and Bremer Counties. Transverse cracks occurred more frequently than longitudinal cracks at most pavement sections, which can be considered as the early distress type.

Conclusions

Asphalt pavement recycling has grown dramatically over the last few years as a viable technology to rehabilitate existing asphalt pavements. Rehabilitation of existing asphalt pavements has employed different techniques; one of them, Cold In-place Recycling with foamed asphalt (CIR-foam), has been effectively applied in Iowa. This research was conducted to develop and validate a new laboratory mix design process for CIR-foam in consideration of its predicted field performance.

Based on the extensive laboratory experiments, the following conclusions are 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.
- The coarse RAP materials with a small amount of residual asphalt content may be more resistant to fatigue cracking but less resistant to rutting.
- 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 with 1.0% foamed asphalt is more resistant to rutting than CIR-foam with 2.0% or 3.0%.
- Based on the dynamic creep tests performed at 40˚C, RAP aggregate structure 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 ones with 1.5%.
- There is a significant variation in distribution of foamed asphalt across the lane during the CIR-foam construction, which could affect its field performance.

Recommendations

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

- 30 gyrations are recommended for producing the equivalent laboratory specimens produced by 75-blow Marshall hammer.
- Laboratory specimens should be cured in the oven at 60°C for 2 days.
- To determine the optimum foamed asphalt content, indirect tensile strength test should be performed on vacuum saturated specimen.
- Gyratory compacted specimens should be placed in 25˚C water for 20 minutes, vacuumed saturated at 20 mm Hg 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 increases from 28 to 15.
- The proposed mix design procedure should be implemented to assure the optimum performance of CIR-foam pavements in the field.

Future Studies

- CIR-foam pavements should be constructed following the new mix design process and their long-term field performance should be monitored and verified against the laboratory performance test results.
- New mix design and laboratory simple performance tests should be performed on the CIR-foam mixtures using stiffer asphalt binder grade, i.e., PG 58-28 or 64-22.
- Static creep test should be evaluated for a possible addition to the performance test protocol.
- New mix design and laboratory performance tests should be evaluated for CIR-emulsion mixtures.

- To better simulate the field performance as a base, performance tests should be performed on both CIR-foam and CIR-emulsion specimens with a horizontal confined pressure.
- A comprehensive database of mix design, dynamic modulus, flow number and raveling for both CIR-foam and CIR-emulsion should be developed to allow for an input to the Mechanistic-Empirical Pavement Design Guide (MEPDG).

1. INTRODUCTION

During the previous phase I study, some 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 US-20 Highway in Iowa. Based upon the critical mixture parameters identified, a new mix design procedure using indirect tensile testing equipment and vacuum-saturated wet specimens was developed.

However, the proposed new mix design procedure would be only applicable to the specific RAP materials obtained from US-20 Highway, near the city of Manchester in Buchanan County, Iowa. Therefore, phase II study was launched to validate the developed laboratory mix design process against various RAP materials to determine its consistency over a wide range of RAP materials available throughout Iowa.

Figure 1-1 shows the tasks, which were performed from phase II study. Chapter 1 introduces study objective and the scope of phase II study. Chapter 2 summarizes the findings, conclusions, and recommendations obtained from phase I study. Chapter 3 presents the results of a pilot study that evaluated the mix design procedure using two different RAP materials. Chapter 4 summarizes the basic CIR design information about seven job sites where the condition of the existing pavement had been evaluated before the pavement was milled. Chapter 5 evaluates the fundamental characteristics of collected RAP materials, which may influence their compaction characteristics and field performance. Chapter 6 investigates the compaction characteristics of RAP materials, which were compacted using a gyratory compactor without adding any additional foamed asphalt. Chapter 7 validates the developed mix design process against seven different RAP materials at five different foamed asphalt contents. Chapter 8 presents the short-and long-term performance tests of CIR-foam mixtures based on the three laboratory tests: dynamic modulus, dynamic creep and raveling tests at various testing temperatures and loading conditions. Chapter 9 describes pavement surface condition after one year at seven project sites where the RAP materials collected in summer 2004. Chapter 10 presents the CIR-foam field construction process from milling operation to compaction.

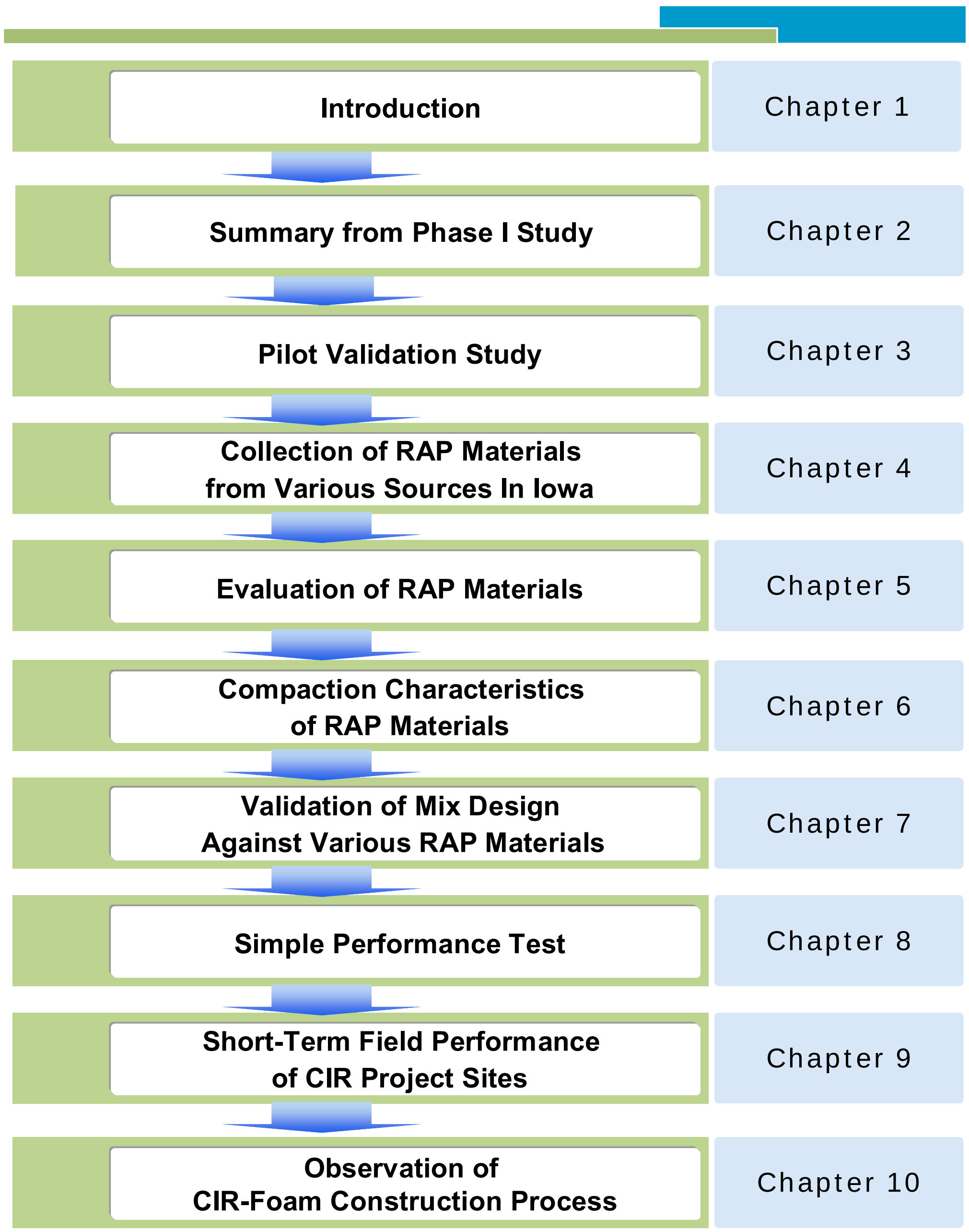


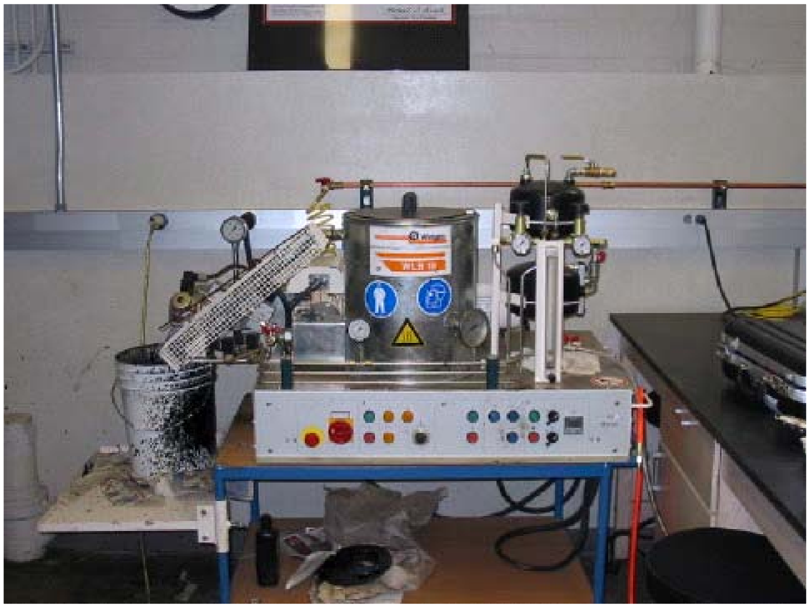
Figure 1-1. CIR-foam Phase II study flowchart

2. SUMMARY FROM PHASE I STUDY

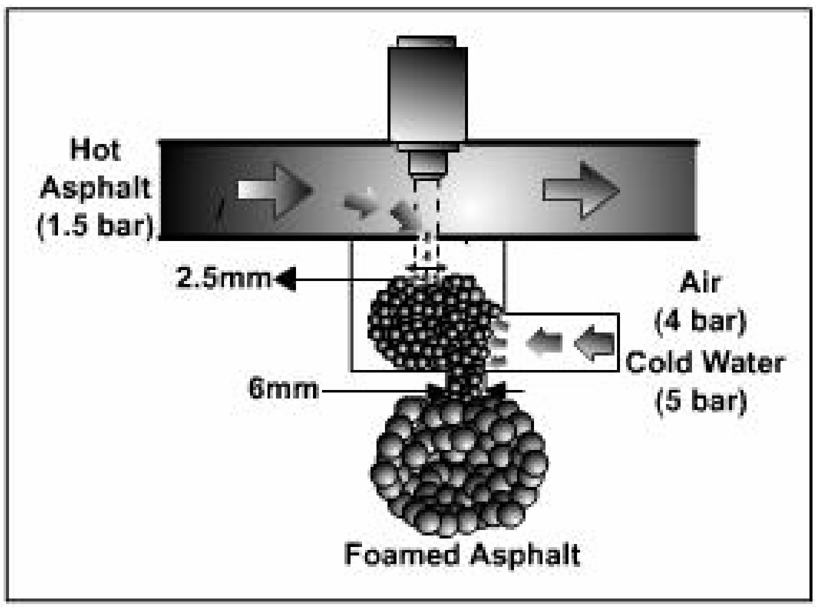
Iowa's current Cold In-Place Recycling (CIR) practice utilizes a generic recipe specification to define the characteristics of the CIR mixture. The contractor is given latitude to adjust the proportions of stabilizing agent to achieve a specified level of density. As CIR continues to evolve, the desire to place CIR mixture with specific engineering properties requires the use of a mix design process. The "lab designed" CIR will allow the pavement designer to take the properties of the CIR into account when determining the overlay thickness. A significant drawback to using emulsion as the stabilizing agent is the amount of water associated with the emulsion. High amounts of water limit the ability to increase binder content and extent the time required to cure the CIR layer. Using foamed asphalt as the stabilizing agent could significantly reduce both of these limitations. However, there is no design procedure available for the CIR using foamed asphalt (CIR-foam).

The main objective of CIR-foam phase I study was to develop a new mix design process for CIR-foam. During phase I, some 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 Cold In-place Recycling using foamed asphalt (CIR-foam). laboratory analysis of numerous mixture components was performed. The foaming process, distribution and amount of the asphalt, RAP gradation, compaction, curing, and mixture strength were examined. Various foamed asphalt mix design parameters produced from the past numerous studies for Full-Depth Reclamation (FDR) and CIR were reviewed and detailed laboratory test results were documented in the final report which was submitted to IHRB in December 2003 (Lee and Kim, 2003).

First, the foamed asphalt laboratory equipment was purchased from Wirtgen, Inc., which is capable of varying different parameters such as the asphalt temperature (140°C~200°C), water content (0%~5%), air pressure (0 bar~10 bar) and the injection rate as shown in Figure 2-1.



(a) Laboratory foaming Equipment



(b) Production of foamed asphalt in the expansion chamber

Figure 2-1. Wirtgen foaming equipment (a) and production of famed asphalt (b)

RAP materials were collected from CIR-foam project site of the US-20 Highway, which is located at about 4 miles west of the intersection of US-20 and Highway 13 near city of Manchester. The existing asphalt pavement was milled throughout the day and, to identify the possible variation in RAP gradations, temperatures of the milled RAP materials were measured throughout the day. Based on the limited study samples, the time of the milling and temperature of pavement during the milling process did significantly affect the RAP gradation. To identify the impact of the RAP gradation on the mix design, three different RAP gradations were produced as "Fine", "Field", and "Coarse."

The laboratory foaming process was validated by varying different amounts of water and asphalt content. The PG 52-34 asphalt binder was used as the stabilizing agent for the laboratory foamed asphalt mix design. The foaming water content of 1.3% created the optimum foaming characteristics in terms of an expansion ratio of 10-12.5 and a half-life of 12-15 at 170°C under an air pressure of 4 bars and a water pressure of 5 bars.

Based on the first round of tests, the maximum Marshall stability (both wet and dry), bulk specific gravity, and indirect tensile strength (both dry and wet) were all obtained at a foamed asphalt content of approximately 2.5% at the RAP aggregate Optimum Moisture Content (OMC)-0.5% or OMC-1.0%. There was a significant drop in these values (except for bulk density) at foamed asphalt contents above 2.5%. The "Fine" gradation produced the highest stability and indirect tensile strengths.

During the second round of laboratory tests, due to the vacuum saturation conditioning process, most wet specimens lost their test values significantly by up to 50%. This indicates that CIR-foam mixtures may be susceptible to water damage. Although test values of dry specimens were higher at low FAC of 1.5%, they lost significant strength after they were vacuum-saturated. Specimens at 2.5% FAC, however, retained their wet indirect tensile strengths reasonably well. For "wet" specimens, the "Fine" gradation produced the lowest stability and indirect tensile strength. For a given optimum FAC of 2.5%, the "Coarse" gradation produced the highest stability and indirect tensile strength. The highest test values were obtained at 4.5% MC for “Fine” gradation, 4.0% MC for “Field” gradation, and 3.5%~4.0% MC for “Coarse” gradation.

Optimum foamed asphalt content and moisture content for the first and second round of CIR-foam mixtures for “Fine”, “Field”, and “Coarse” gradations are summarized in Table 2-1.

Table 2-1.Optimum foamed asphalt content and moisture content for three different gradations at the first and second rounds

Gradation	First round		Second round	
	Optimum FAC	Optimum MC	Optimum FAC	Optimum MC
Fine	2.5 %	4.1 %	2.5%	4.5 %
Field	2.5 %	4.0 % ~ 4.5 %	2.5%	4.0 %
Coarse	2.5 %	3.4 %	2.5%	3.5 % ~ 4.0 %

For PG 52-34 asphalt, 1.3% foaming water content is recommended for asphalt temperature of 170°C. There were no significant differences in test results among the three different RAP gradations, and RAP materials may therefore be used in the field without additional virgin aggregates or fines. The optimum mix design of 2.5% FAC and 4.0% MC was identified for CIR-foam for field gradation. The indirect tensile strength was more sensitive to the foamed asphalt content, with a clear peak, than the Marshall stability. Due to the concern for the high moisture sensitivity of the foamed asphalt mixtures, the indirect tensile strength test was recommended to perform on the vacuum-saturated “wet” specimens. Figure 2-2 presents a flowchart of the new laboratory mix design procedure for CIR-foam (Kim and Lee, 2006).

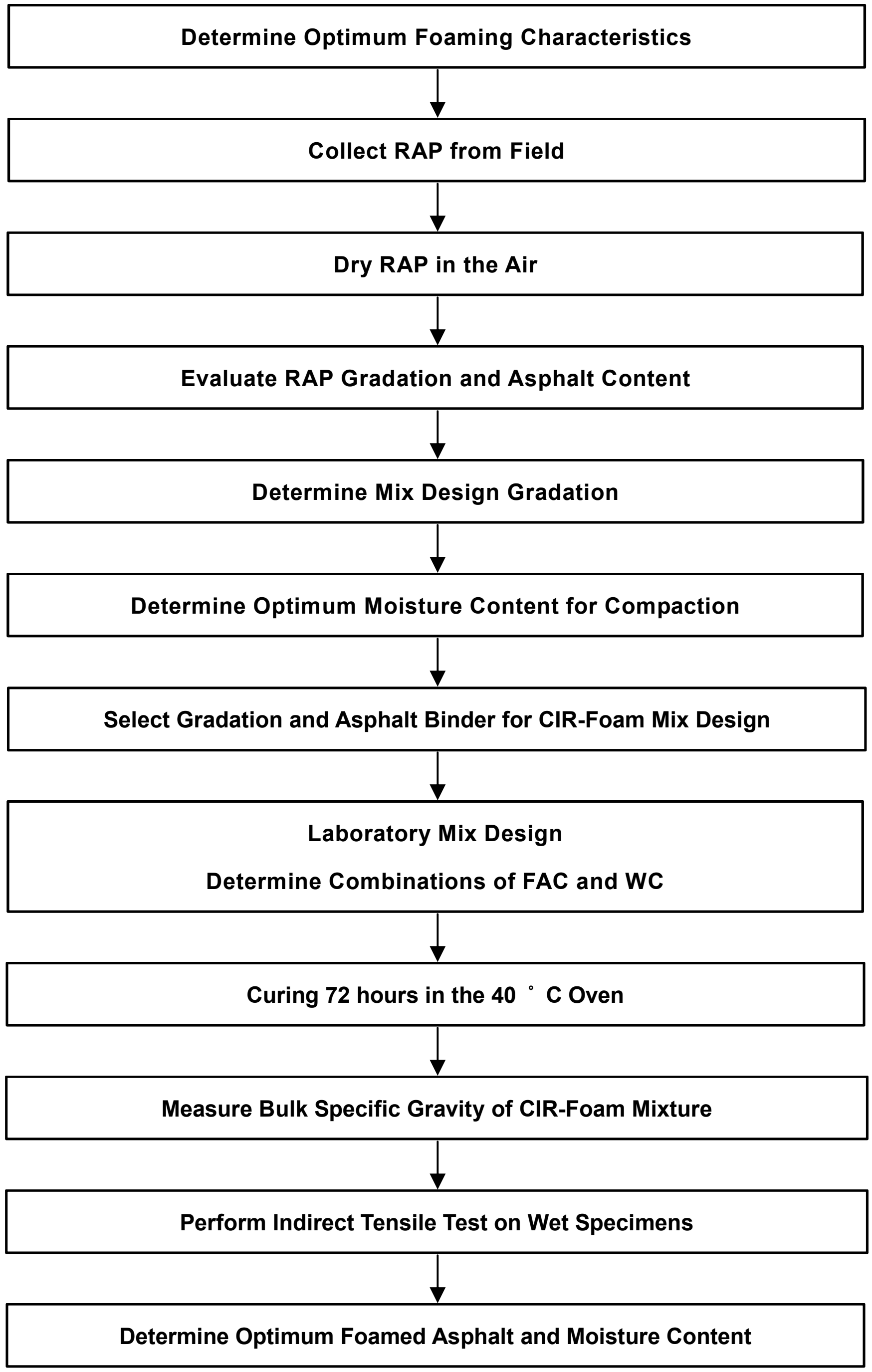


Figure 2-2. Developed new laboratory mix design procedure of CIR-foam

3. PILOT VALIDATION STUDY

A pilot study was conducted to evaluate the mix design procedure using two different RAP materials. The basic testing parameters from the pilot study are shown in Figure 3-1.

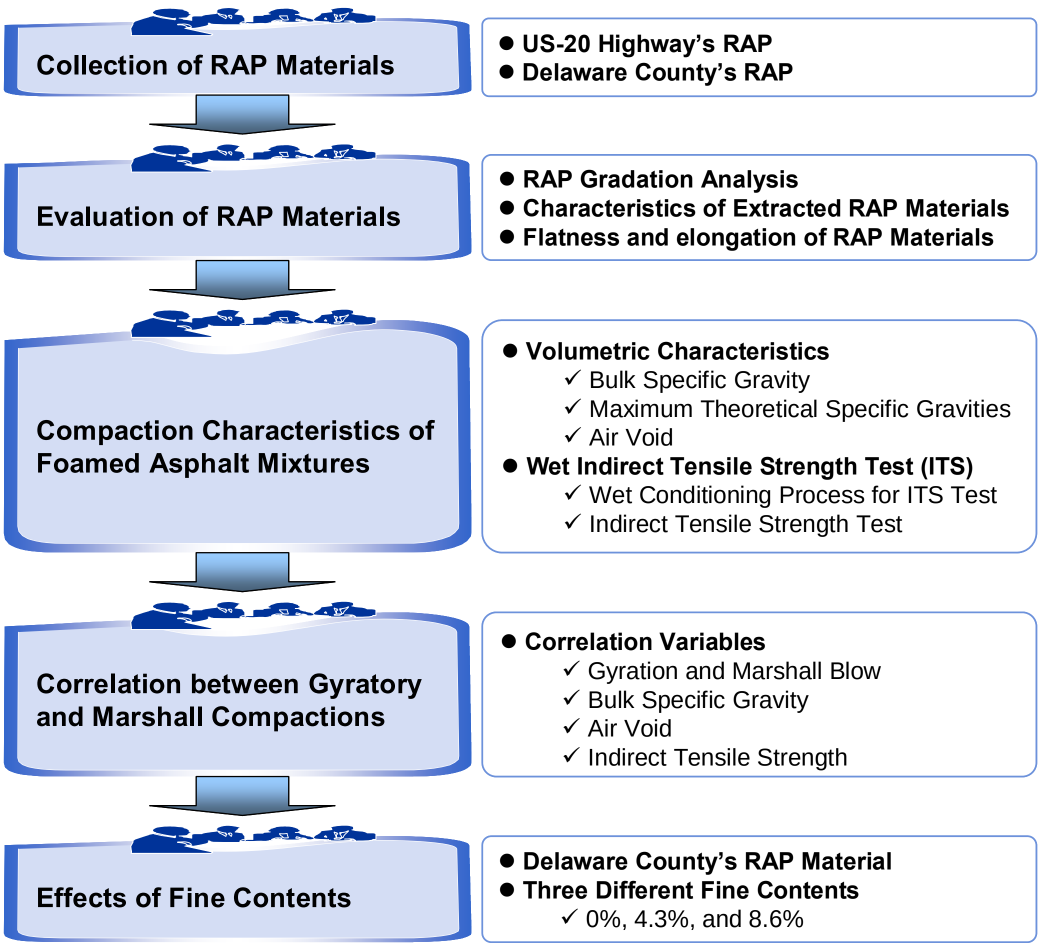


Figure 3-1. Test flowchart and parameters of pilot study

3.1 RAP Materials

Basic information on two different RAP materials used in the pilot study is summarized in Table 3-1. As shown in Table 3-1, first RAP materials were collected from US-20 Highway in June 2002 and second RAP materials were collected from Delaware County in September 2003. The roadway in Delaware County was constructed in 1956 and US-20 Highway was constructed in 1970. Due to its age, the residual asphalt extracted from RAP materials collected from Delaware County may be stiffer than the US-20 Highway.

Table 3-1. Basic information of collected RAP materials

Item \ Source	US-20 Highway	Delaware County
Performance Age	1970 – 2002 (32 years)	1956 – 2003 (47 years)
Maintenance History	2" of surface mix replaced (1989)	No maintenance
Milling Date	June, 2002	September, 2003
Pavement Surfacing Temperature during Milling	25.2°C ~ 30.4°C (7:40 a.m. ~ 8:50 a.m.) 49.0°C ~ 52.2 °C (12:50 p.m. ~ 13:55 p.m.) 44.2°C ~ 50.0°C (15:55 p.m. ~ 16:50 p.m.)	N/A
Type of Milling Machine	CMI PR-1000	N/A
Recycling Agent	Cold In-Place Recycling (CIR-foam)	Cold In-Place Recycling (CIR-foam)

3.2 Evaluation of RAP Materials

RAP materials from US-20 Highway were dried outside for two days at 32°C and the moisture contents of the dried RAP materials were between 1.0% and 0.3%. RAP materials from Delaware County were brought to the laboratory and dried at between 25°C and 27°C for 10 days. The moisture content of the dried RAP materials was between 0.2% and 0.3%.

3.2.1 RAP Gradation Analysis

The sieve analysis was performed three times for each RAP source and the results are plotted in Figure 3-2. The RAP materials from US-20 Highway were coarser than ones from Delaware County, more RAP materials passing sieves between 19.0mm and 9.5mm.

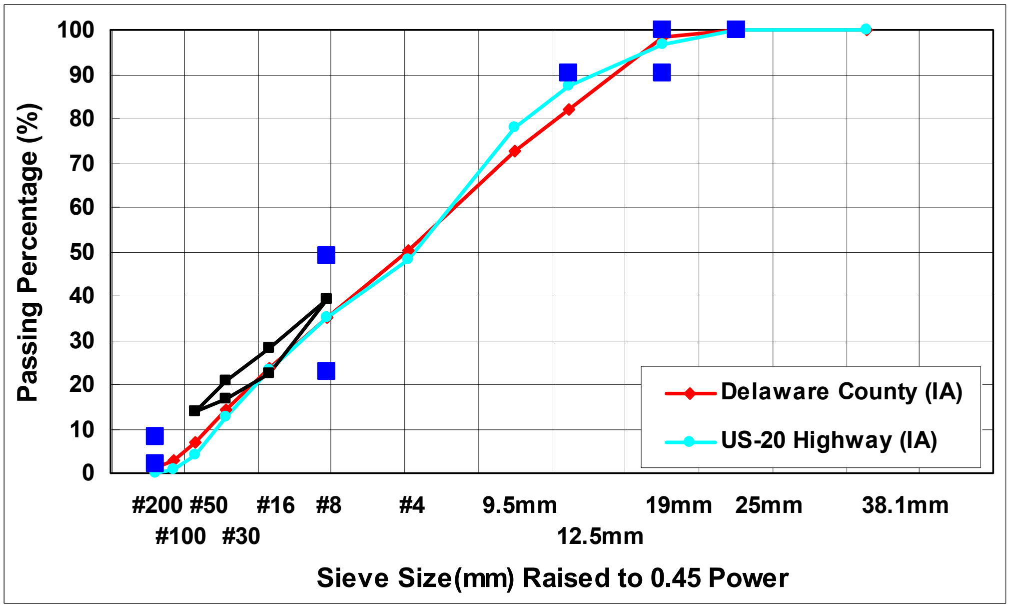


Figure 3-2. RAP gradations of two different RAP materials

3.2.2 Characteristics of Extracted Asphalt and Aggregates from RAP Materials

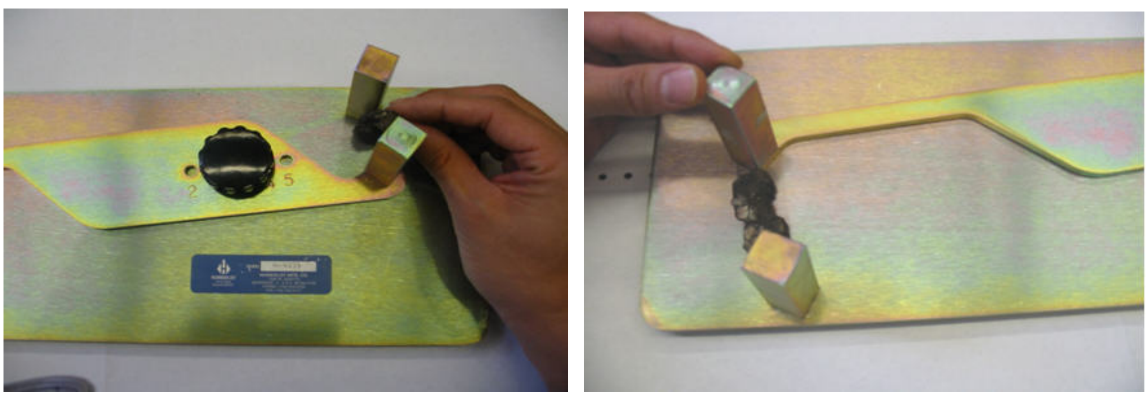
The sieve analysis result of the extracted aggregate and the extracted asphalt content of RAP material from US-20 Highway are summarized in Table 3-2.

Table 3-2. Characteristics of extracted RAP materials from US-20 Highway

Property	Sieve Size										
	25.0 mm	19.0 mm	12.5 mm	9.50 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
Passing %	100	100	93.3	84.3	61.7	46.7	38.0	30.0	20.0	13.0	10.0
Residual AC (%)	4.62%										

3.2.3 Flatness and Elongation of RAP Materials

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. Superpave specifications require hot mix asphalt to have less than 10% flat and elongated particles of 3:1 ratio measured using the caliper as shown in Figure 3-3. The percentages of flat and elongated particles were computed to the nearest 1.0% for each sieve size greater than 9.5mm. Flatness and elongation ratio of two different RAP materials are summarized in Table 3-3 and plotted in Figure 3-4. As shown in Table 3-3 and Figure 3-4, RAP materials of 12.5mm and 9.5mm collected from US-20 Highway passed whereas RAP materials of 25mm and 19mm failed. RAP particles collected from Delaware Country failed at all sizes.



(a) Checking flatness (b) Checking elongation

Figure 3-3. Measuring flatness and elongation of RAP materials

Table 3-3. Test results of flat and elongated RAP particles using a 3:1 ratio

US-20 Highway				
Sieve Size	Weight (g)		% Flat and Elongated Particles	Pass or Fail (> 10 %)
	Total Particles	Flat and Elongated Particles		
25.0 mm	1578.7	407.0	25.8	Fail
19.0 mm	1219.8	158.8	13.0	Fail
12.5 mm	638.3	41.5	6.50	Pass
9.5 mm	181.5	9.3	5.12	Pass
Delaware County				
Sieve Size	Weight (g)		% Flat and Elongated Particles	Pass or Fail (> 10 %)
	Total Particles	Flat and Elongated Particles		
25.0 mm	1607.0	801.9	49.9	Fail
19.0 mm	980.2	387.6	39.5	Fail
12.5 mm	525.3	260.7	49.6	Fail
9.5 mm	172.5	55.5	32.2	Fail

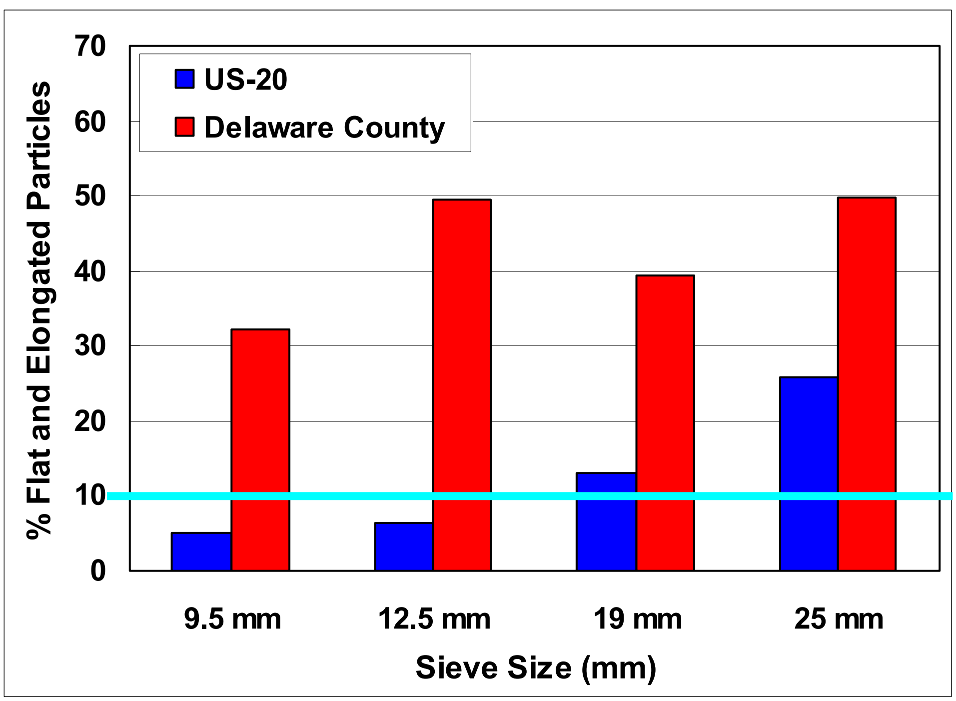


Figure 3-4. Comparison of % flat and elongated particles at two different RAP sources

3.3 Compaction Characteristics of CIR-foam

A recent survey by the Rocky Mountain User Producer Group of 38 states (1999) recommended 50-blow Marshall compaction as standard for determining optimum moisture and emulsified asphalt content of CIR mixtures. However, Salomon and Newcomb (2001) recommended that CIR-Emulsion mixtures should be compacted with gyratory compactors that produce consistent air voids. They reported that, 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. Density was reported to stay constant after 60 gyrations. To achieve a desired density of 130 pcf for a laboratory test specimen, Lee et al. (2003) recommended 37 gyrations for CIR-Emulsion. To achieve the field density, Thomas and Kadrmas (2003) suggested 30 gyrations for CIR-Emulsion mixtures. To match the field density, Stephen (2002) recommended 30 to 35 gyrations for CIR-Emulsion mixtures.

Brennen et al. (1970) reported that Marshall stability of the gyratory compacted FDR-foam specimens produced at 20 gyrations under a pressure of 200 psi was two to three times higher than that of Marshall hammer compacted specimens at 75 blows. Nataatmadja (2001) reported that the gyratory compacted FDR-foam specimens with 85 gyrations consistently produced the higher densities than Marshall hammer compacted specimens with 75 blows.

The compaction characteristics of CIR-foam mixtures by Marshall hammer and gyratory compactor were examined to identify their compaction characteristics using two different RAP materials. Table 3-4 summarizes test plan and number of specimens for this compaction study. As shown in Table 3-4, a total of 84 specimens at four levels of gyrations (20, 30, 50, and 100) and 75 blows of Marshall hammer were prepared to measure bulk specific gravity, air void, and indirect tensile strength. CIR-foam mixtures were compacted at room temperature (23˚C) and cured in the oven at 40˚C for 68 hours and 60°C for 46 hours. Table 3-5 summarizes the design parameters, which were used to produce CIR-foam mixtures. As shown in **Table 3-5**, foamed asphalt mixtures were produced at four different foamed asphalt contents, 1.0%, 2.0%, 2.5%, and 3.0% and water content was fixed at 4.0%.

Table 3-4. Number of specimens prepared under various compaction and curing conditions

Curing Temp. / FAC (%)	Number of Gyration									
	20 Gyrations		30 Gyrations		50 Gyrations		100 Gyrations		75 Blows	
	40°C	60°C	40°C	60°C	40°C	60°C	40°C	60°C	40°C	60°C
1.5 %	2	2	2	2	3	2	2	2	2	2
2.0 %	2	2	2	2	3	2	2	2	2	2
2.5 %	2	2	2	2	3	2	2	2	2	2
3.0 %	2	2	2	2	3	2	2	2	2	2

Table 3-5. Design parameters for the compaction study

Asphalt Binder	PG 52-34
Foaming Temperature (°C)	170 °C
Foaming Water Content (%)	1.3 %
Foamed Asphalt Content (%)	1.5 %, 2.0 %. 2.5 %, and 3.0 %
Moisture Content (%)	4.0 %
Curing Condition	● 40˚C oven for 68 hours ● 60°C oven for 46 hours

3.3.1 Sample Observation

The gyratory and Marshall compacted foamed asphalt specimens were visually observed. As shown in Figure 3-5 (a) and (b), Gyratory compacted CIR-foam specimen (2.5% FAC at 50 gyrations) exhibited black color on the surface and Marshall compacted specimen (2.5% FAC at 75 blows) exhibited brown color, respectively. For the same amount of water content, gyratory equipment squeezed water out of the specimen and created a wet condition on the top and at the bottom of the specimens, whereas Marshall hammer did not. For gyratory compaction, lowering the water content below 4.0% should be considered. Figure 3-6 shows the pictures of gyratory compacted CIR-foam specimens at 30 and 50 gyrations using RAP materials from US-20 Highway. As shown in Figure 3-6, as the asphalt content and gyrations increase the darker the surface of the specimens.

(a) Gyratory compacted specimens (50 G) (b) Marshall compacted specimens (75 blows)

Figure 3-5. Pictures of gyratory and Marshall compacted specimens (FAC=2.5%)


(a) 30 Gyrations (FAC=2.0%) (b) 30 Gyrations (FAC=2.5%)


(c) 30 Gyrations (FAC=3.0%) (d) 50 Gyrations (FAC=2.5%)

Figure 3-6. Pictures of gyratory compacted specimens at 30 and 50 gyrations (US-20 Highway)

3.3.2 Volumetric Characteristics

3.3.2.1 Theoretical Maximum Specific Gravities

The maximum theoretical gravity was measured at four different foamed asphalt contents. As shown in Figure 3-7**,** the theoretical maximum specific gravity of CIR-foam mixtures using RAP materials from US-20 Highway was higher than that of RAP materials from Delaware County. As expected, the theoretical maximum specific gravity of foamed asphalt mixtures using RAP materials from Delaware County decreased more foamed asphalt was added. However, the theoretical maximum specific gravity of foamed asphalt mixtures using RAP materials from US-20 Highway did not change as more foamed asphalt was added.

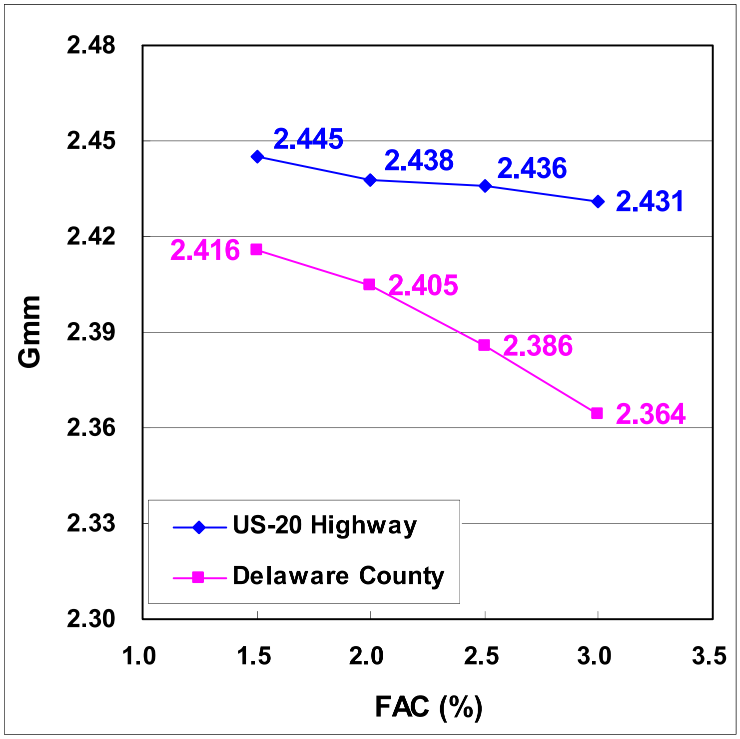


Figure 3-7. Plot of theoretical maximum specific gravity against foamed asphalt contents for two different RAP sources

3.3.2.2 Bulk Specific Gravities and Air Voids

The bulk specific gravities (Estimated G_{mb}) of the foamed asphalt specimens were estimated by measuring the volume of the compacted foamed asphalt specimens. Height and weight of gyratory and Marshall hammer compacted specimens were measured to compute the estimated bulk specific gravities and air voids.

As shown in Figure 3-8, bulk specific gravities are plotted against foamed asphalt contents for gyratory and Marshall hammer compacted specimens cured at 40°C and 60°C. The bulk specific gravities were relatively constant over the range of FAC contents from 1.5% to 3.0%. The changed curing temperature from 40ºC to 60ºC did not significantly affect the bulk specific gravities. The bulk specific gravities of the CIR-foam specimens using RAP materials from US-20 Highway are higher than that of specimens using RAP materials from Delaware County, which is the same result as the theoretical maximum specific gravity. The equivalent bulk specific gravities of 75-blow Marshall compacted specimens using RAP materials from US-20 Highway were achieved at between 30 and 50 gyrations. The equivalent bulk specific gravities of 75-blow Marshall compacted specimens using RAP materials from Delaware County were achieved at between 20 and 30 gyrations.

As shown in Figure 3-9**,** air voids are plotted against foamed asphalt contents for gyratory and Marshall hammer compacted CIR-foam specimens cured at 40°C and 60°C. As expected, air voids of the CIR-foam specimens using RAP materials collected from Delaware County decreased as the foamed asphalt content increased. However, air voids of the CIR-foam specimens using RAP materials collected from US-20 Highway stayed relatively constant as the foamed asphalt content increased. Air voids of the foamed asphalt specimens using RAP materials collected from US-20 highway were between 7.5% at 50 gyrations and 12.8% at 20 gyrations whereas air voids of the foamed asphalt specimens using RAP materials collected from Delaware County were between 8.8% at 50 gyrations and 16.4% at 20 gyrations. For Marshall compacted foamed asphalt specimens at 75 blows, air voids ranged from 9.5% to 10.8% for RAP materials collected from US-20 Highway and air voids ranged from 12.0% to 15.4% for RAP materials collected from Delaware County.

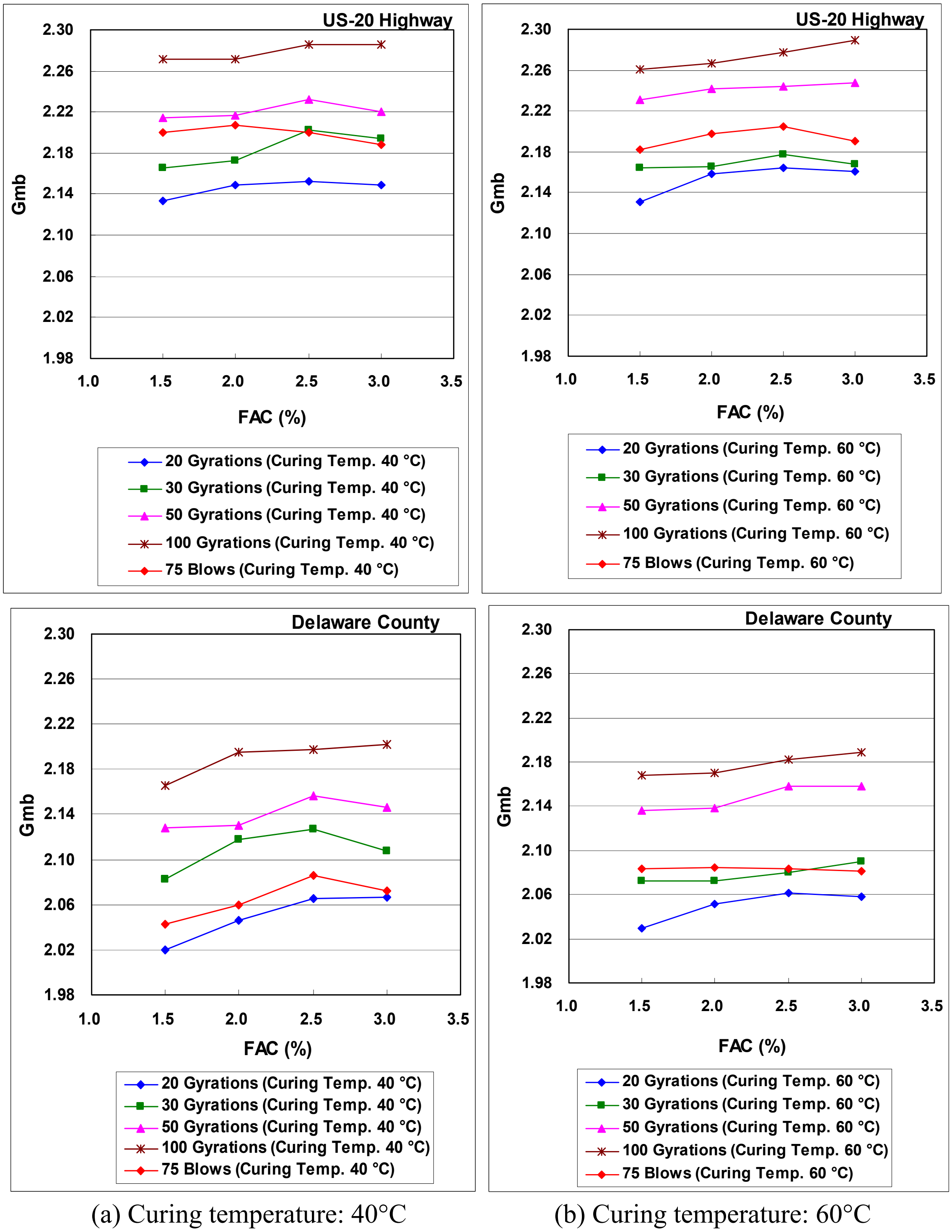
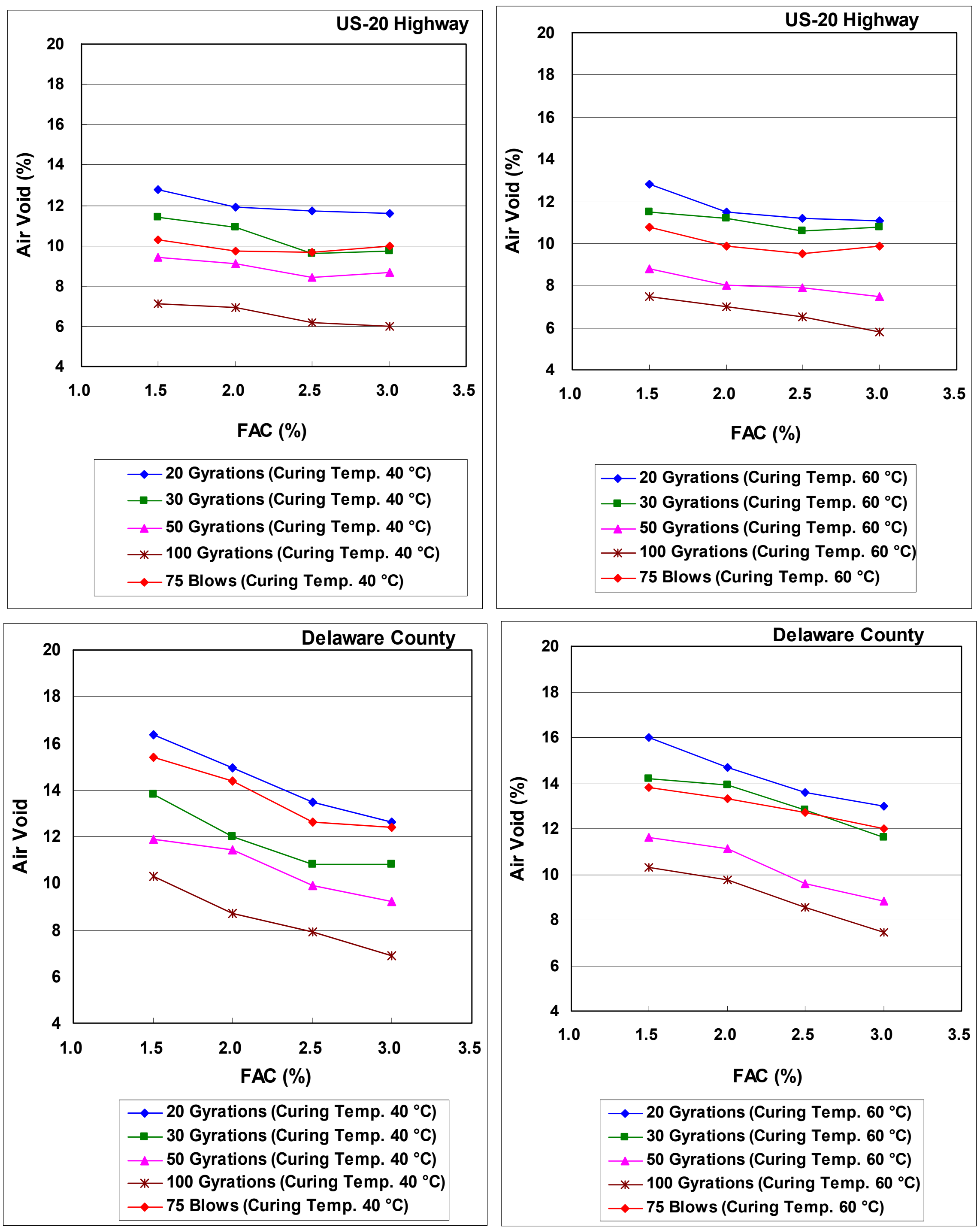


Figure 3-8. Plots of G_{mb} against FAC at five different levels of compaction



(a) Curing temperature: 40°C (b) Curing temperature: 60°C

Figure 3-9. Plots of air void against FAC at five different levels of compaction

3.3.3 Wet Indirect Tensile Strength Test

3.3.3.1 Wet Conditioning of ITS Test

To avoid damaging foamed asphalt specimens by over-vacuuming, the optimum vacuuming duration was determined for wet conditioning. As shown in Table 3-6, three different levels of vacuum procedure were tested to determine the optimum vacuuming duration.

- Procedure A of applying 20 mmHg vacuum for 50 minutes.
- Procedure B: Bubbling stopped after 30 minutes of vacuum saturation at 20 mmHg.
- Procedure C: Bubbling stopped after 30 minutes of vacuum saturation at 25 mmHg. Additional 20 minutes of vacuum at 25 mmHg were applied to the specimen (no bubbling). When vacuum level was increased from 25 to 20 mmHg bubbling started again for 20 minutes.
- Procedure D: Bubbling stopped after 20 minutes of vacuum saturation at 30 mmHg. Additional 30 minutes of vacuum at 30 mmHg were applied to the specimen (no bubbling). When vacuum level was increased from 30 to 20 mmHg bubbling started again for 20 minutes.

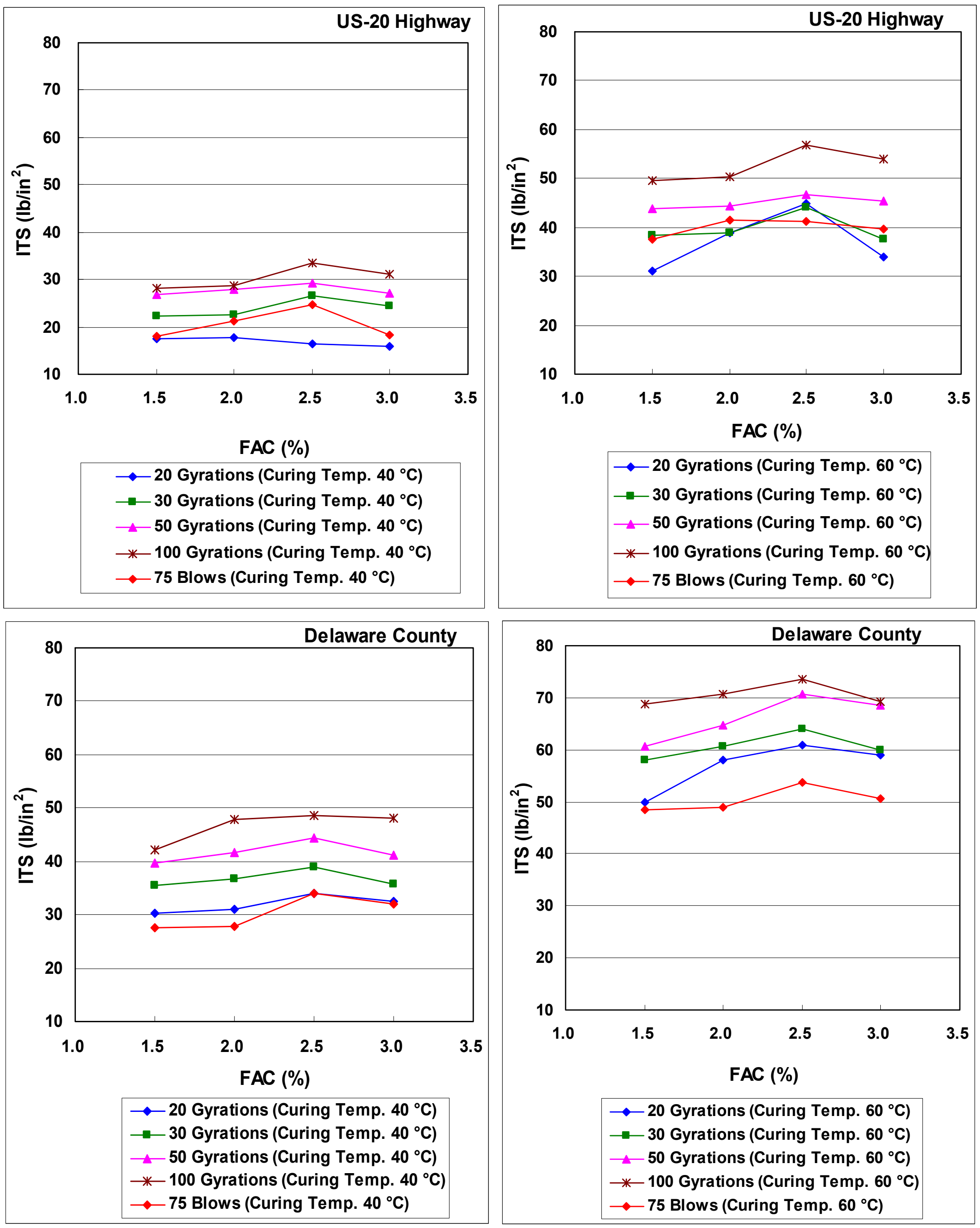
Based on the experiment, procedure B (30 min at 20 mmHg) was chosen as the optimum vacuuming level and duration for producing “wet” specimens.

Table 3-6. Wet conditioning process

Pressure \ Procedure		Step 1: Soaked	Step 2: Vacuum Saturation	Step 3: Soaked
Procedure A	20 mmHg (PHASE I)	20 min	50 min	10 min
Procedure B	20 mmHg (PHASE II)	20 min	30 min	30 min
Procedure C	25 mmHg	20 min	30 min	30 min
Procedure D	30 mmHg	20 min	30 min	30 min

3.3.3.2 Indirect Tensile Strength Test

Foamed asphalt mixtures were compacted at room temperature (23˚C) and cured in the oven at 40˚C for 68 hours or 60˚C for 46 hours. After oven curing, the specimens were allowed to cool down to the room temperature, which normally takes about 2 hours but were reduced to 15 minutes when a fan was used. Specimens for testing at wet condition were placed in 25˚C water bath for 20 minutes, and vacuumed saturated at 20 mmHg for 30 minutes. The saturated wet specimens were left under the water bath for additional 30 minutes. The indirect tensile strength test was performed on wet CIR-foam specimens. As shown in Figure 3-10, indirect tensile strength results are plotted against foamed asphalt contents at 40˚C and 60˚C. Indirect tensile strength exhibited the highest value at 2.5% FAC. Although G_{mb} of Marshall compacted specimens was higher than that of gyratory compacted specimens, indirect tensile strength of Marshall compacted specimens was less than that of gyratory compacted specimens. Although G_{mb} of CIR-foam specimen using RAP materials from US-20 Highway was higher than the specimen using RAP materials from Delaware County, its indirect tensile strength was less than that of Delaware County for all three different foamed asphalt contents. Indirect tensile strength of the foamed asphalt specimens cured in the oven at 60˚C is significantly higher than that of the foamed asphalt specimens cured in the oven at 40˚C. Indirect tensile strength of the CIR-foam specimens using RAP materials collected from Delaware County exhibited a peak at 2.5% FAC whereas that of the mixtures using RAP materials from US-20 Highway was relatively constant over the range of FAC from 2.0% to 3.0%.



(a) Curing temperature: 40°C (b) Curing temperature: 60°C

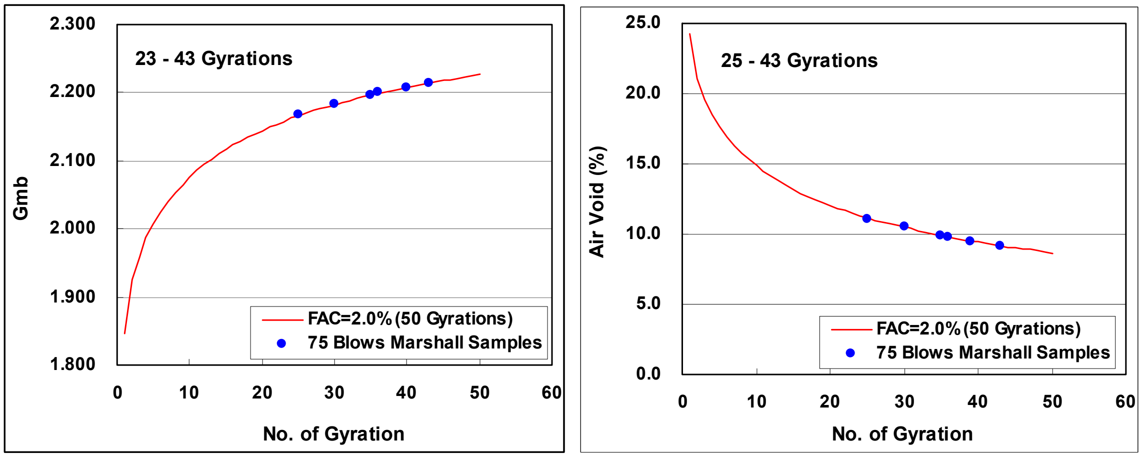
Figure 3-10. Plots of indirect tensile strength against FAC at five different levels of compaction

3.3.4 Correlation between Bulk Specific Gravities by Gyratory and Marshall Compactions

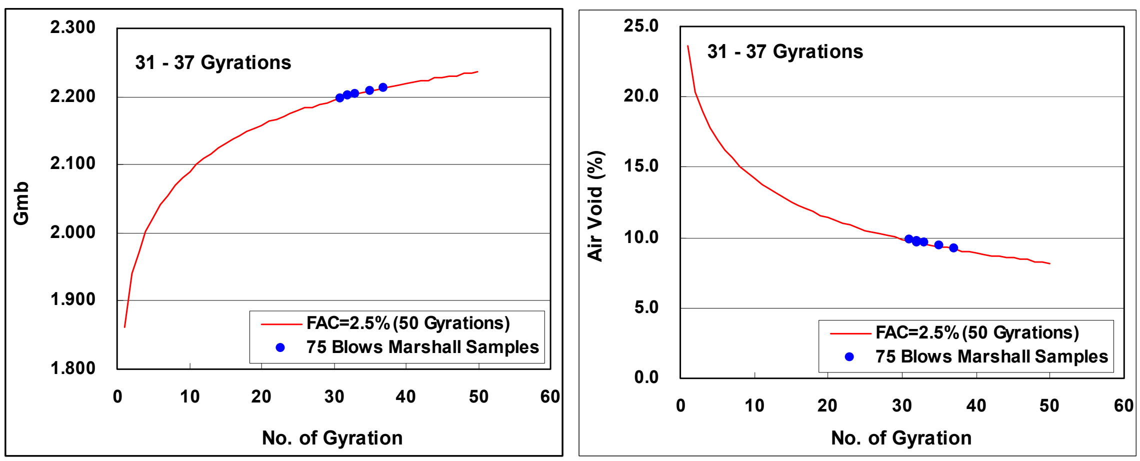
Bulk specific gravities of the 75-blow Marshall compacted foamed asphalt specimens were correlated with those of the gyratory compacted foamed asphalt specimens. Specific gravities by gyratory compactor and Marshall hammer are plotted against the number of gyrations at each foamed asphalt content are plotted in Figure 3-11 and Figure 3-12, respectively. Table 3-7 summarizes the equivalent number of gyrations, which was identified in order to achieve the same density of the 75-blow Marshall compacted foamed asphalt specimens. The equivalent of number of gyrations is derived through correlation between specific gravities by gyratory compactor and Marshall hammer. As show in Table 3-7 and Figure 3-11, 23 to 43 gyrations were needed to achieve the same density obtained using Marshall hammer at 75 blows using RAP materials collected from US-20 Highway. As show in Table 3-7 and Figure 3-12, 15 to 28 gyrations were needed to achieve the same density obtained using Marshall hammer at 75 blows using RAP materials collected from Delaware County.

Table 3-7. Equivalent number of gyrations at three different FAC contents

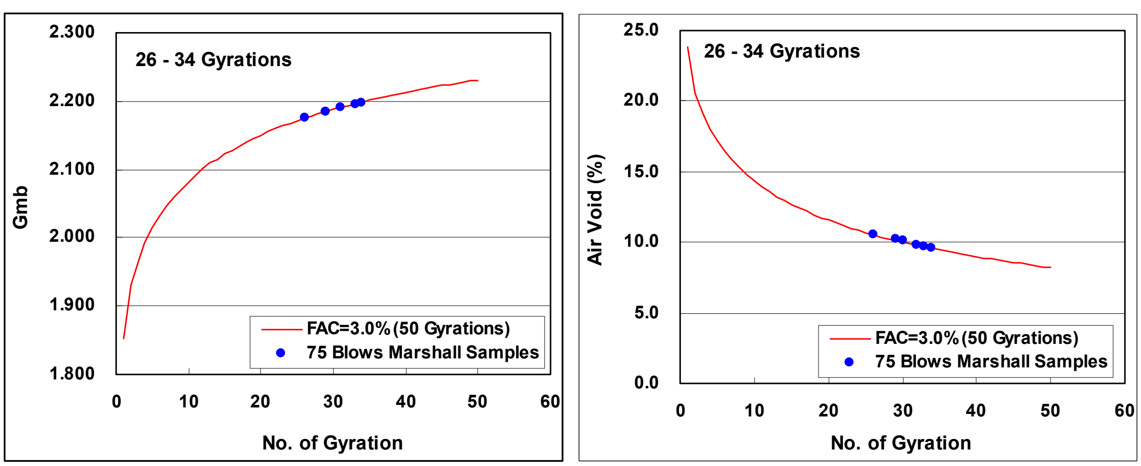
FAC (%)	RAP Source			
	US-20 Highway		Delaware County	
	G_{mb}	Air Void	G_{mb}	Air Void
2.0 %	23-43 gyrations =75 blows	25-43 gyrations =75 blows	16-28 gyrations =75 blows	15-28 gyrations =75 blows
2.5 %	31-37 gyrations =75 blows	31-37 gyrations =75 blows	20-25 gyrations =75 blows	20-25 gyrations =75 blows
3.0 %	26-34 gyrations =75 blows	26-34 gyrations =75 blows	19-25 gyrations =75 blows	19-24 gyrations =75 blows



(a) FAC = 2.0%

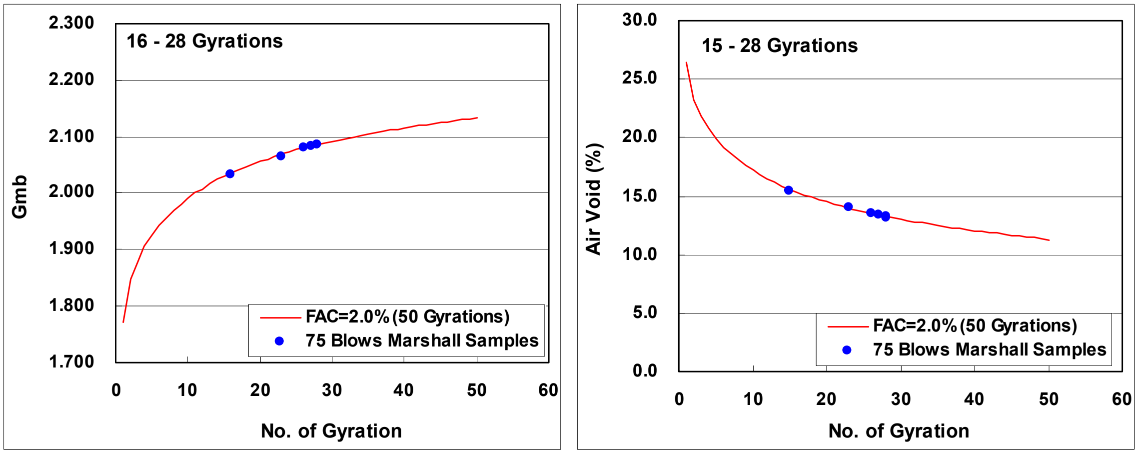


(b) FAC = 2.5%

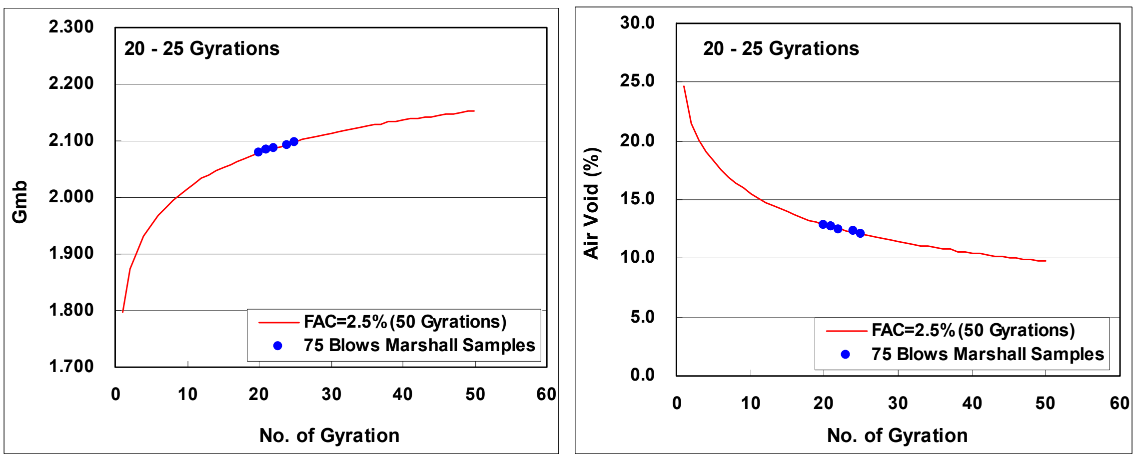


(c) FAC = 3.0%

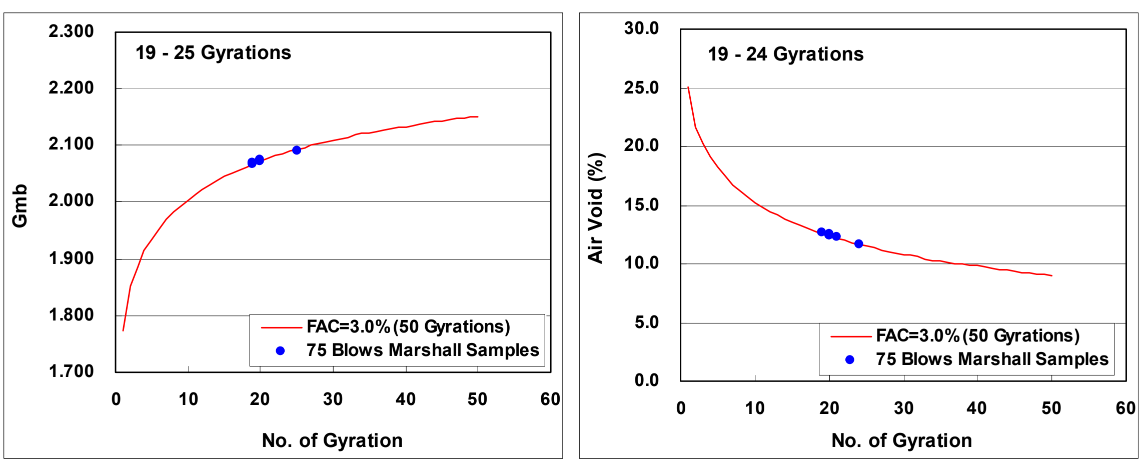
Figure 3-11. Correlation of G_{mb} and air void between gyratory and Marshall compacted foamed asphalt specimens (US-20 Highway)



(a) FAC = 2.0%



(b) FAC = 2.5%



(c) FAC = 3.0%

Figure 3-12. Correlation of G_{mb} and air void between gyratory and Marshall compacted foamed asphalt specimens (Delaware County)

3.3.5 Correlation between Indirect Tensile Strength and G_{mb} (and Air Voids)

CIR-foam mix design was developed based on the modified Marshall mix design procedure using Marshall hammer compacted specimens during the previous phase I study (Lee and Kim 2003). For each of three gradations (“Fine”, “Field”, and “Coarse”) of RAP materials from US-20 Highway, total 120 Marshall compacted specimens at 75 blows were cured at 40°C. Figure 3-13 and Figure 3-14 show the correlation between bulk specific densities and their Marshall stability and the correlation between bulk specific densities and their indirect tensile strength, respectively. No correlation was observed between either of these test results and the bulk specific gravity.

For this phase II study, total 68 Gyratory compacted specimens were prepared to identify the correlation between indirect tensile strength and G_{mb} (and air voids). Figure 3-15 and Figure 3-16 show a significant correlation between indirect tensile strength and G_{mb} (and air voids). This indicates that gyratory compacting equipment produces the more consistent laboratory specimens for the indirect tensile test than Marshall hammer.

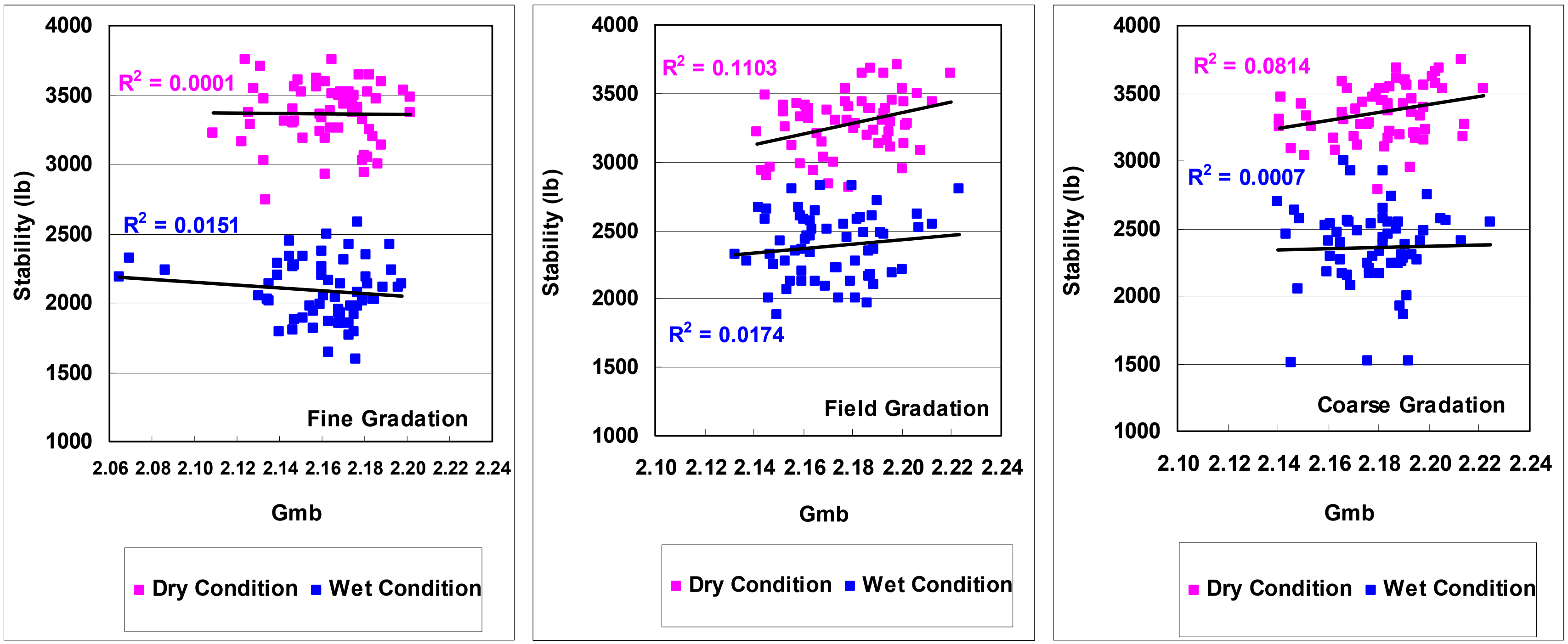


Figure 3-13. Correlation between Marshall stability and G_{mb} for dry and wet specimens compacted using Marshall hammer

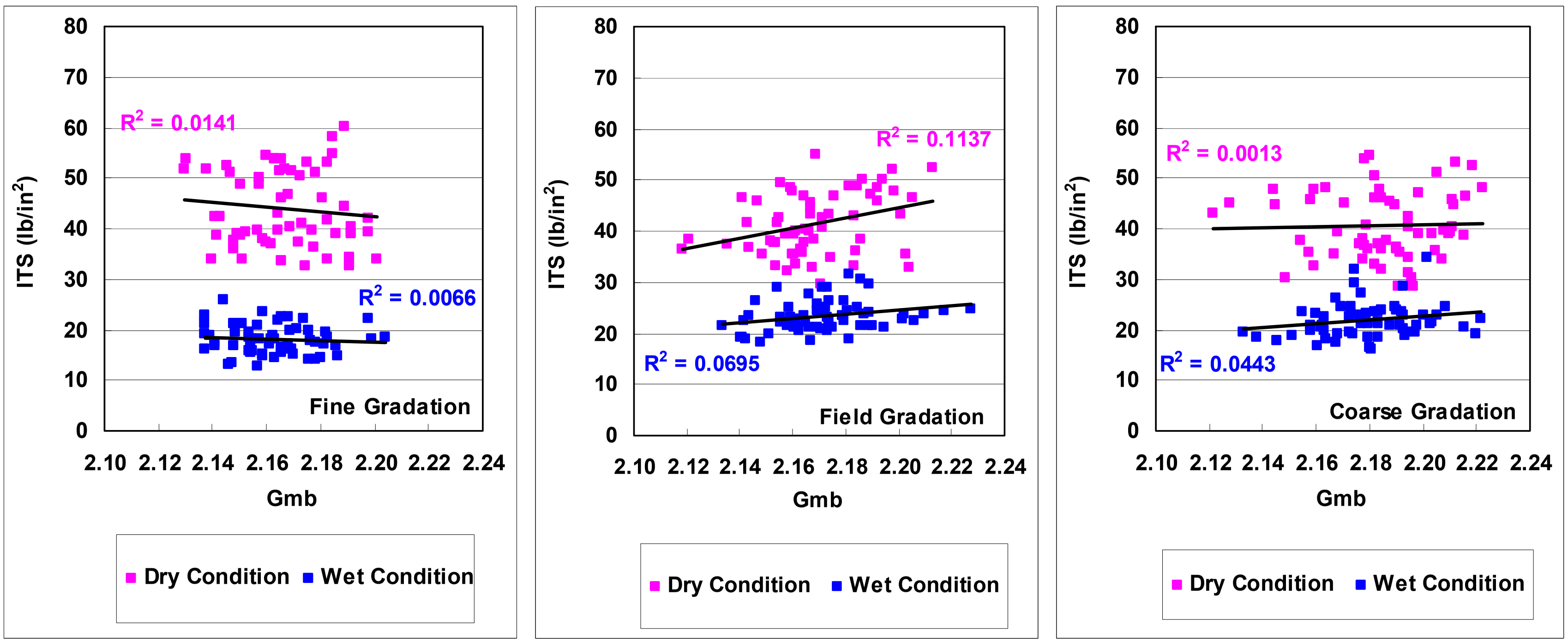


Figure 3-14. Correlation between indirect tensile strength and G_{mb} for dry and wet specimens compacted using Marshall hammer

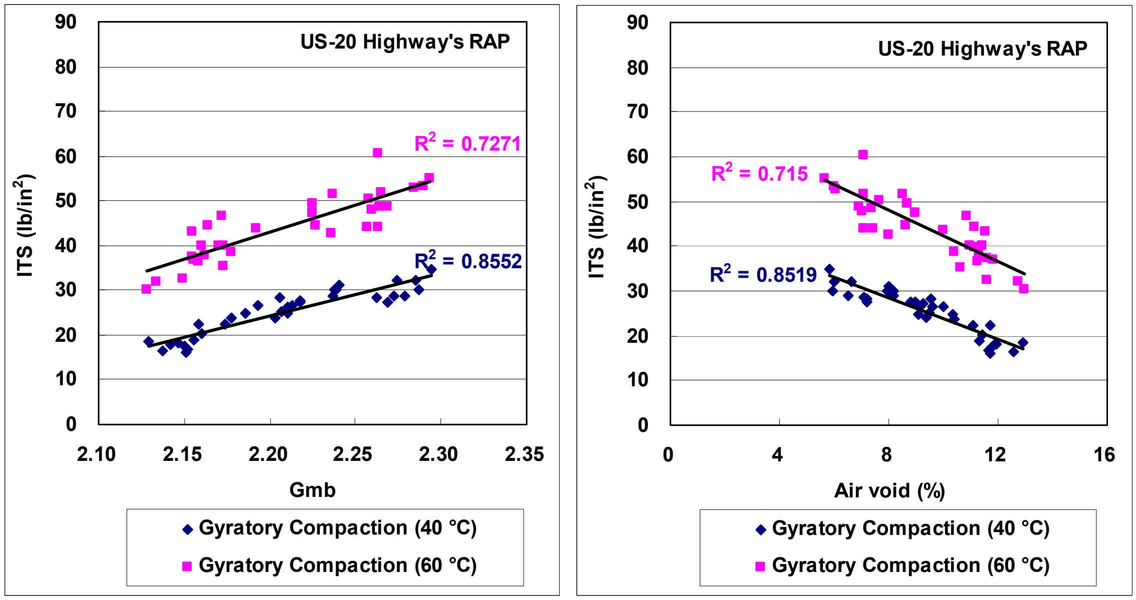


Figure 3-15. Plots of correlation between ITS and G_{mb} (and air void) of specimens at two different curing temperatures (US Highway)

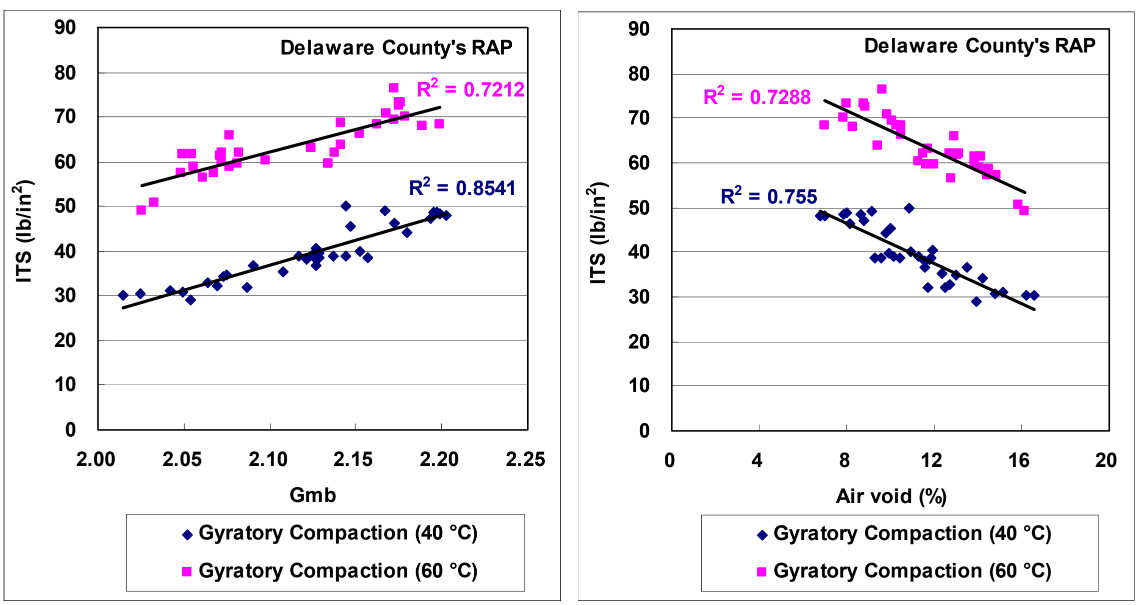


Figure 3-16. Plots of correlation between ITS and G_{mb} (and air void) at two different curing temperatures (Delaware County)

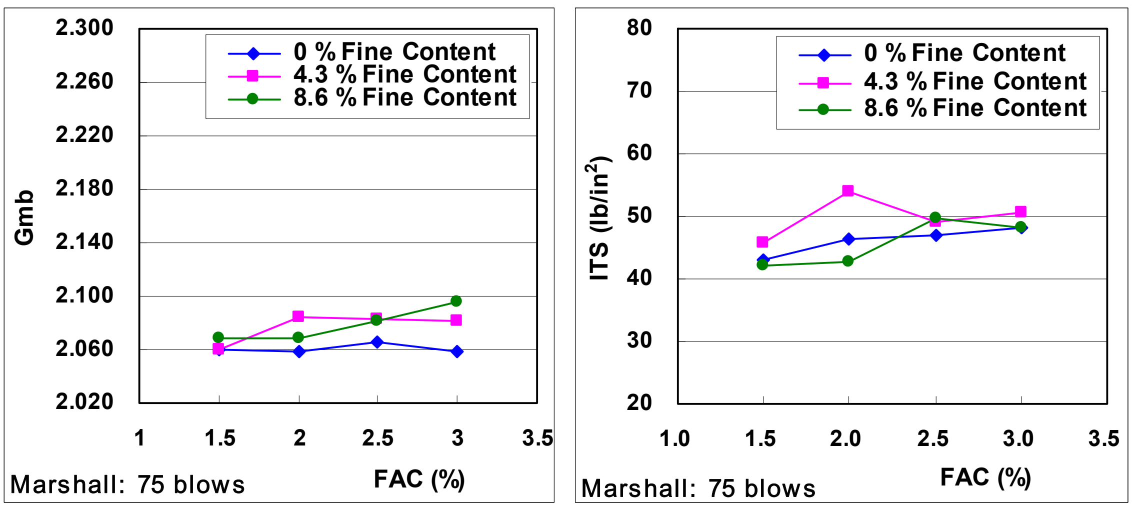
3.4 Effects of Fine Contents

Indirect tensile strength of foamed asphalt mixtures using RAP materials from Delaware County was generally higher than that of foamed asphalt mixtures using RAP materials from US-20 Highway although the Delaware County's RAP were more flat and elongated than US-20 Highway's RAP. It was noted that RAP materials from Delaware County included more fines between No. 100 and No. 200 (4.3 %) than those from US-20 Highway (1.0 %).

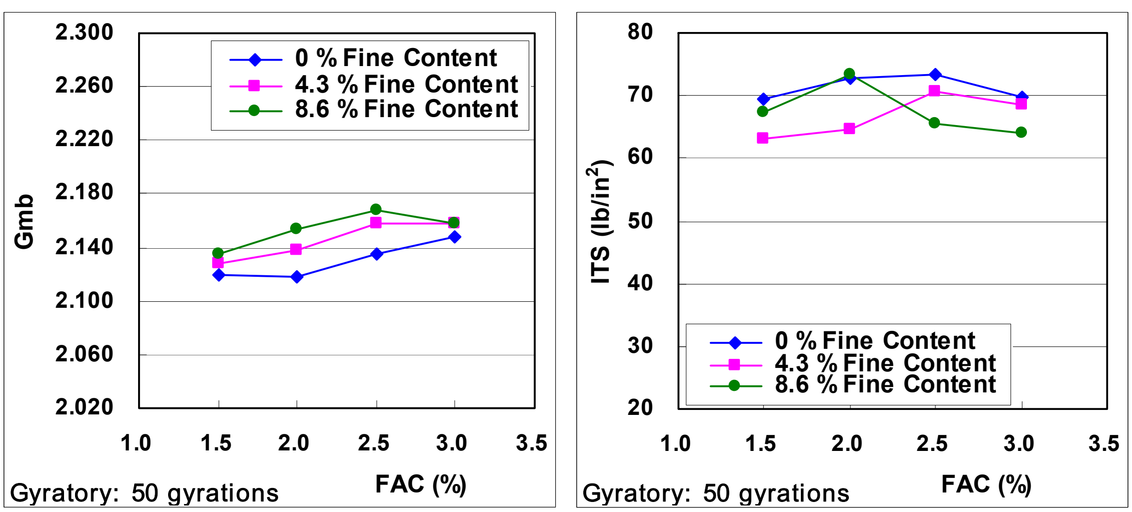
As shown in Table 3-8, to determine the effect of fine content on the indirect tensile strength, three types of RAP gradations were prepared using RAP materials from Delaware County, with fine contents of 0%, 4.3% and 8.6%. Foamed asphalt mixtures containing three different fine contents were prepared at four different foamed asphalt contents and 4.0% water content. Foamed asphalt specimens were compacted by gyratory compactor at 50 gyrations and Marshall hammer at 75 blows. As shown in Figure 3-17, bulk specific gravities and indirect tensile strengths are plotted against the foamed asphalt content for three different fine contents and two different compaction methods. For Marshall compacted specimens, fine content of 4.3% showed the highest indirect tensile strength at 2.0% FAC. For gyratory compacted specimens, fine content of 8.6% showed the highest indirect tensile strength at 2.0% FAC. Fine content of 0% did not affect the indirect tensile strength significantly for both gyratory and Marshall compacted specimens. It can be concluded that fine content of CIR-foam mixtures do not affect the wet indirect tensile strength significantly.

Table 3-8. Proportion of three different fine contents

Fine Content (%) / Proportion	Delaware County		
	0 %	4.3 %	8.6 %
25 mm ~ 0.3 mm (No.50)	100 %	95.7 %	91.4
0.3 mm ~ 0.15 mm (No. 50) (No.100)	0 %	3.0 %	6.0 %
0.15 mm ~ 0.075 mm (No.100) (No. 200)	0 %	1.3 %	2.6 %
Total	100%	100%	100%



(a) Marshall compacted specimens

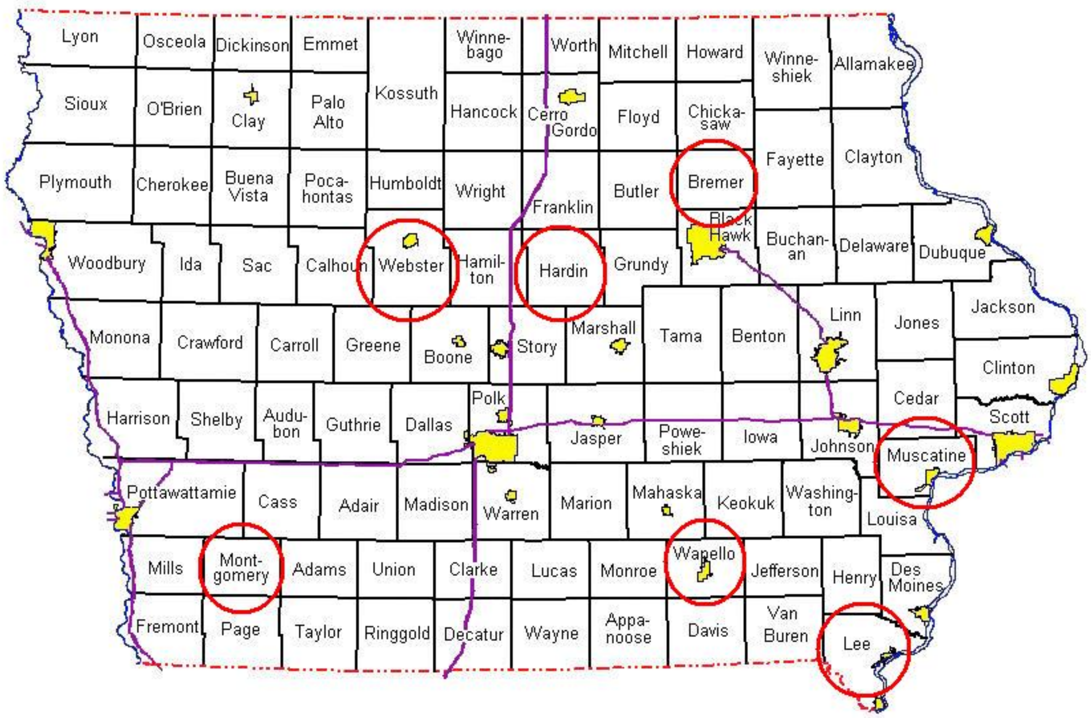


(b) Gyratory compacted specimens

Figure 3-17. Plots of G_{mb} and ITS against FAC at three different fine contents

4. COLLECTION OF RAP MATERIALS FROM VARIOUS SOURCES IN IOWA

During the summer of 2004, in order to validate the mix design process developed during the phase I study, RAP materials were collected from seven different Cold In-Place Recycling (CIR) project sites: three CIR-foam and four CIR-ReFlex sites. As shown in Figure 4-1, CIR project sites were selected across the state of the Iowa, which include Muscatine County, Webster County, Hardin County, Montgomery County, Bremer County, Lee County, and Wapello County.



County	Road Name	Rehabilitation Method
Muscatine	State Highway 22	CIR-foam
Webster	County Road P 33	CIR-ReFlex
Hardin	County Road 175	CIR-foam
Montgomery	State Highway 48	CIR-ReFlex
Bremer	County Road V 56	CIR-ReFlex
Lee	County Road W 62	CIR-ReFlex
Wapello	County Road V 37	CIR-foam

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

4.1 Description of Project Sites

The milled RAP materials were collected from the seven CIR job sites between June 11 and September 1, 2004. The basic and CIR design information are summarized in Table 4-1 and Table 4-2, respectively.

Table 4-1.Basic information for seven project sites

Item \ County	Muscatine County	Webster County	Hardin County	Montgomery County	Bremer County	Lee County	Wapello County
CIR Project Site	State Highway 22	County Road P 33	County Road 175	State Highway 48	County Road V 56	County Road W 62	County Road V 37
Sampling Date	June 11, 2004	June 14, 2004	June 15, 2004	June 17, 2004	June 22, 2004	August 20, 2004	September 1, 2004
RAP Sampling Time	10:00 a.m.– 10:30 a.m.	9:00 a.m. – 10:00 a.m.	12:00 p.m. – 1:00 p.m.	2:00 p.m.– 2:30 p.m.	1:30 p.m.– 2:00 p.m.	11:00a.m. – 12:00p.m.	10:00a.m.– 12:00 p.m.
Pavement Surface Temperature	9:00 a.m. – 11:00 a.m. (25.2°C – 30.9°C)	9:00 a.m. – 1:00 p.m. (27.5°C – 41.5°C)	10:00 a.m. – 2:00 p.m. (26.2°C – 36.5°C)	11:00 a.m. – 3:00 p.m. (36.1°C – 43.1°C)	1:00 p.m. – 2:00 p.m. (36.6°C – 39.5°C)	11:00 a.m. – 1:00 p.m. (27°C – 35°C)	10:00 a.m. – 1:00 p.m. (32°C – 40°C)
Milling Machine	CMI PR-1000	CMI PR-1000	CMI PR-1000	CMI PR-1000	CMI PR-1000	CMI PR-1000	CMI PR-1000
CIR Method	CIR-foam	CIR-ReFlex	CIR-foam	CIR-ReFlex	CIR-ReFlex	CIR-ReFlex	CIR-foam
Construction Company	W.K Construction	Koss Construction	Koss Construction	MidState Reclamation & Trucking	MATHY Construction	Koss Construction	W.K Construction

Table 4-2. CIR design information for seven project sites

Categories / Sources	CIR Length (mile)	CIR Layer Thickness (in.)	HMA Overlay (in.)	AADT	Job Mix Formula	Repairing History
Muscatine County	3.0	3.0	3.5	3036	FAC=2.0% WC=2.0%	No
Webster County	10.0	4.0	3.0	1,040 ~ 1,640	N/A	Seal coat surface
Hardin County	11.5	4.0	3.0	1770 ~ 2080	N/A	No
Montgomery County	18.8	4.0	4.0	1390 ~ 2150	RAC= 2.5 ~ 3.0% WC=2.0%	Seal coat surface, Patching
Bremer County	5.0	4.0	3.0	1160	N/A	Patching
Lee County	9.45	4.0	3.0	170 ~ 1090	RAC=2.2% WC=4.3%	Seal coat surface
Wapello County	7.3	4.0	6.0	1400	N/A	No

(1) Muscatine County Project (State Highway 22) – CIR-foam

The milled RAP materials were collected from the CIR-foam project site in State Highway 22. As shown in Figure 4-2, the project site is located about 2 miles from the intersection of Highway 22 and Highway 70 near the city of Nickles, Iowa. Both RAP materials and foamed asphalt mixtures were collected between 10:00 a.m. and 10:30 a.m. on June 11, 2004. The pavement surface was wet due to rain prior to the sample collection and the pavement surface temperature was 26.3°C. Figure 4-3 shows the CIR-foam construction process and the foamed asphalt mixture collection process.

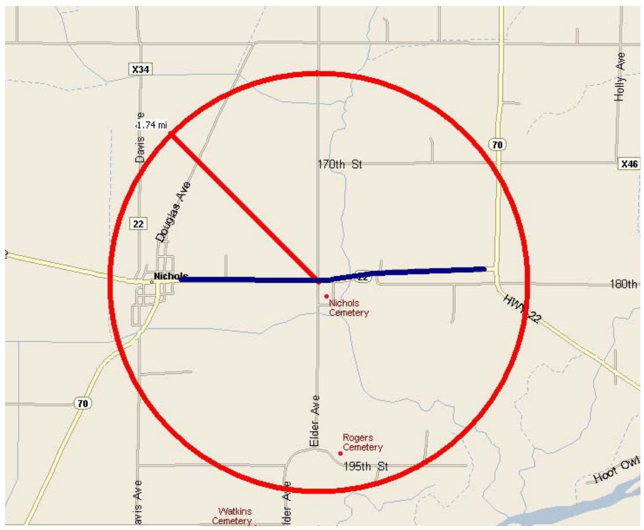


Figure 4-2. Location of the CIR-foam construction site in Muscatine County

(a) CIR-foam process (b) Collection of foamed asphalt mixtures

Figure 4-3. Pictures of job site in Muscatine County

(2) Webster County Project (County Road P 33) – CIR-ReFlex

The milled RAP materials were collected from the CIR-Reflex project site in County Road P33. As shown in Figure 4-4, the project site is located near the intersection of County Road P33 and Highway 20, southwest of city of Fort Dodge, Iowa. RAP materials were collected between 9:00 a.m. and 10:00 a.m. on June 14, 2004. The pavement surface was dry and the pavement surface temperature was 28°C. Figure 4-5 shows the CIR-Reflex construction process and the RAP material collection process.

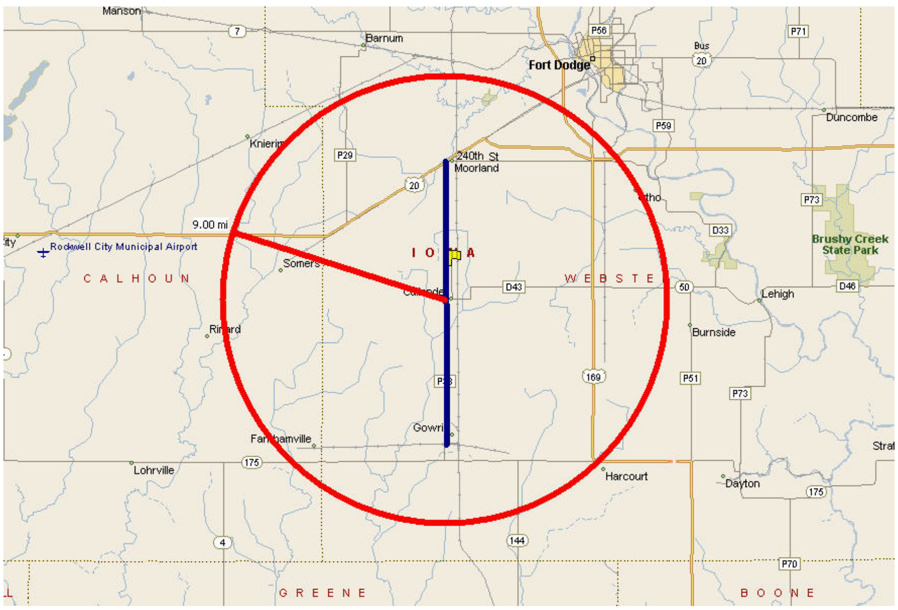
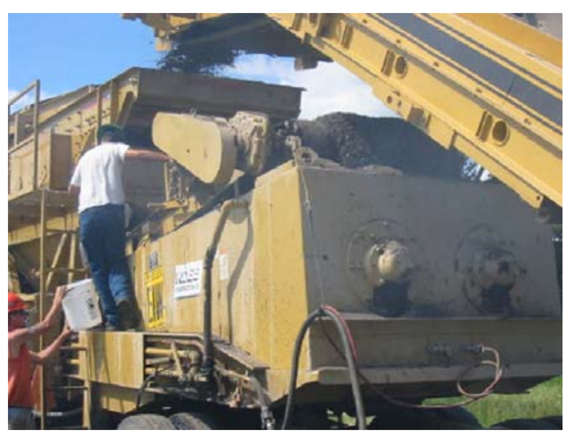


Figure 4-4. Location of the CIR-Reflex construction site in Webster County

(a) CIR-ReFlex process



(b) Collection of milled RAP materials

Figure 4-5. Pictures of CIR-ReFlex job site in Webster County

(3) Hardin County Project (County Road 175) – CIR-foam

The milled RAP materials were collected from the CIR-foam project site in County Road 175. As shown in Figure 4-6, the project site is located near the intersection of County Road 175 and Interstate Highway 35. Both RAP materials and foamed asphalt mixtures were collected between 12:00 p.m. to 1:00 p.m. on June 15, 2004. The pavement surface was dry and the pavement surface temperature was 30.2°C. Figure 4-7 shows the CIR-foam construction process and the RAP material collection process.

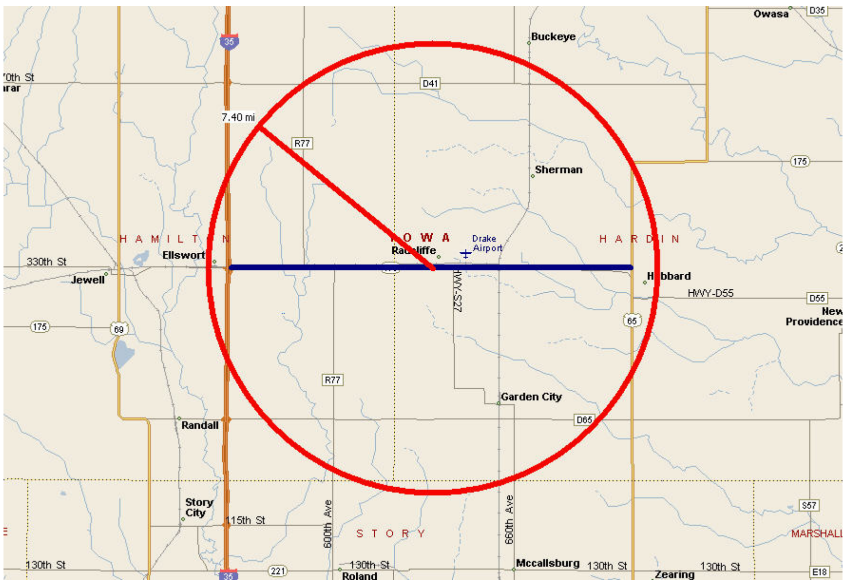


Figure 4-6. Location of the CIR-foam construction site in Hardin County

(a) CIR-foam process (b) Collection of milled RAP materials

Figure 4-7. Pictures of CIR-foam job site in Hardin County

(4) Montgomery County Project (State Highway 48) – CIR-ReFlex

The milled RAP materials were collected from the CIR-Reflex project site in a State Road Highway 48. As shown in Figure 4-8, the project site is located near the intersection of State Highway 48 and State Highway 92. RAP materials were collected between 2:00 p.m. to 2:30 p.m. on June 17, 2004. The pavement surface was dry and the pavement surface temperature was 41.8°C. Figure 4-9 shows the CIR-Reflex construction process and the RAP material collection process.

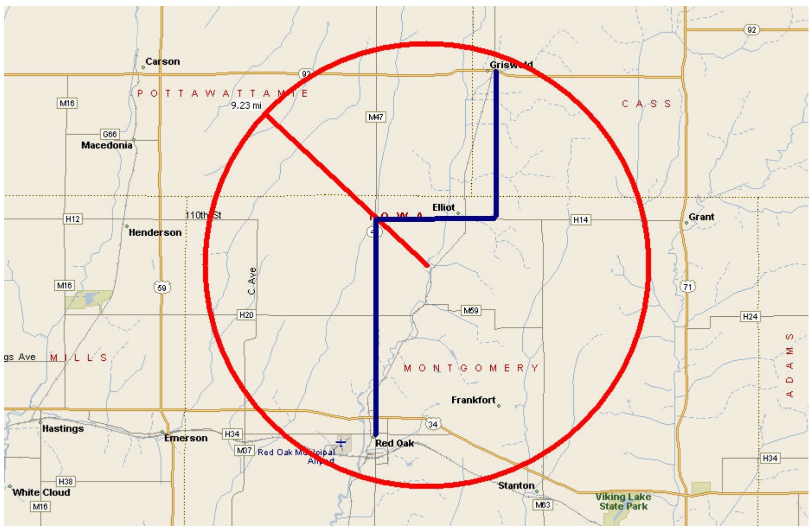


Figure 4-8. Location of the CIR-Reflex construction site in Montgomery County

(a) CIR-ReFlex process (b) Collection of milled RAP materials

Figure 4-9. Pictures of CIR-ReFlex job site in Montgomery County

(5) Bremer County Project (County Road V 56) – CIR-ReFlex

The milled RAP materials were collected from the CIR-Reflex project site in County Road V56. As shown in Figure 4-10, the project site is located near the intersection of County Road V56 and Iowa Highway 93. RAP materials were collected between 1:30 p.m. to 2:00 p.m. on June 22, 2004. The pavement surface was dry and the pavement surface temperature was 38.8°C. Figure 4-11 shows the CIR-Reflex construction process and the RAP material collection process.

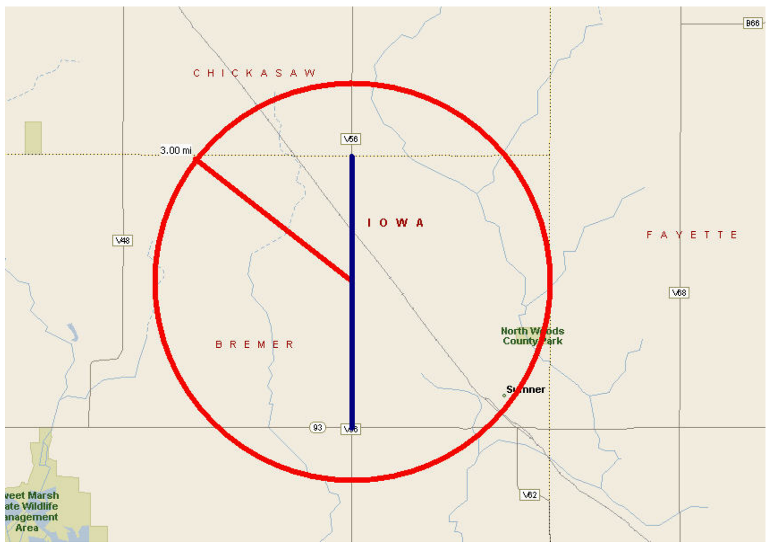


Figure 4-10. Location of the CIR-Reflex construction site in Bremer County

(a) CIR-ReFlex process (b) Collection of milled RAP materials

Figure 4-11. Pictures of CIR-ReFlex job site in Bremer County

(6) Lee County Project (County Road W 62) – CIR-ReFlex

The milled RAP materials were collected from the CIR-ReFlex project site in County Road W 62. As shown in Figure 4-12, the project site is located near the intersection of County Road W 62 and US Highway 61. RAP materials were collected between 11:00 p.m. to 12:00 p.m. on August 20, 2004. The pavement surface was dry and the pavement surface temperature was 33.1°C. Figure 4-13 shows the CIR-ReFlex construction process and the RAP material collection process.

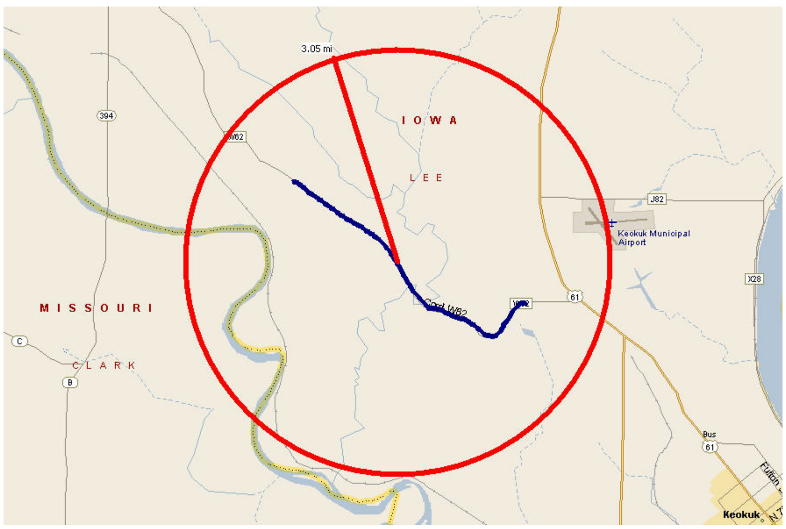


Figure 4-12. Location of the CIR-ReFlex construction site in Lee County

(a) CIR-ReFlex process (b) Collection of milled RAP materials

Figure 4-13. Pictures of CIR-ReFlex Job Site in Lee County

(7) Wapello County Project (County Road V 37) – CIR-foam

The milled RAP materials were collected from the CIR-foam project site in County Road V 37. As shown in Figure 4-14, the project site is located near the intersection of County Road V 37 and US Highway 34 near the city of Agency, Iowa. Both RAP and foamed asphalt materials were collected between 10:00 a.m. to 12:00 p.m. on September 1, 2004. The pavement surface was dry and the pavement surface temperature ranged between 32 to 37.4 °C. Figure 4-15 shows the CIR-foam construction process and the RAP material collection process.

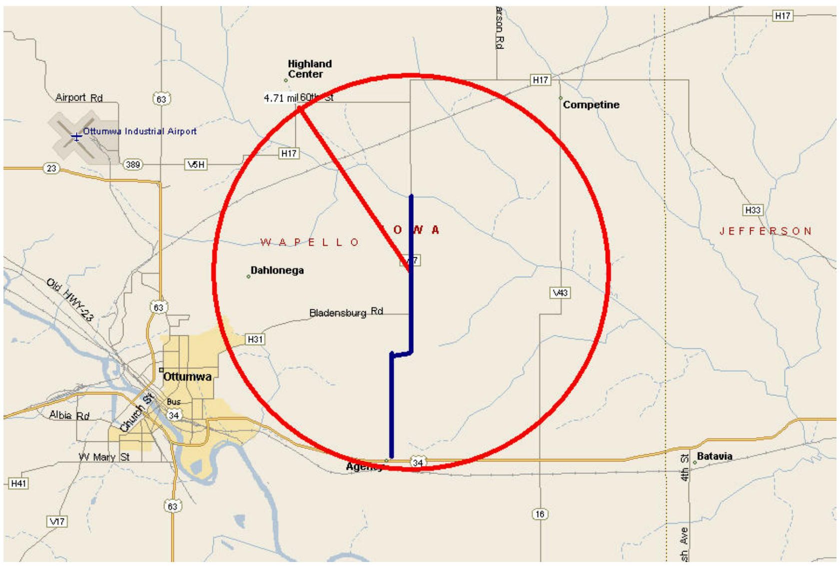


Figure 4-14. Location of the CIR-foam construction site in Wapello County

(a) CIR-foam process

(b) Collection of milled RAP materials

Figure 4-15. Pictures of CIR-foam job site in Wapello County

4.2 Visual Condition Survey of the Existing Pavement

As listed in Table 4-3, the surface conditions of the existing pavement were surveyed by visual observation before the pavement was milled and summarized in Table 4-3. Three 100-ft sections were selected for visual evaluation and pictures of typical conditions are shown in Figure 4-16. An overall condition was determined subjectively and summarized at the bottom of Table 4-3. As shown in Table 4-3 and Figure 4-16, the CIR project site in Muscatine County exhibited a least amount of distress where as CIR project sites in Hardin, Bremer and Lee Counties exhibited a largest amount of pavement distresses.

Table 4-3. Summary of surface conditions from the existing pavement

Sources	Muscatine County	Webster County	Hardin County	Montgomery County	Bremer County	Lee County	Wapello County
Cracking							
Alligator	No	No	Yes	Yes	Yes	Yes	Yes
Block	No	No	Yes	No	Yes	Yes	No
Edge	No	Yes	Yes	Yes	Yes	Yes	Yes
Longitudinal	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transverse	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reflective	No	Yes	Yes	Yes	Yes	Yes	Yes
Patching /Potholes							
Patch	No	No	No	Yes	No	No	No
Potholes	No	Yes	Yes	Yes	No	No	Yes
Surface Deformation							
Rutting	No	No	No	No	No	No	No
Shoving	No	No	No	No	No	No	No
Surface Defects							
Bleeding	No	No	No	No	No	No	No
Polishing Aggregate	No	Yes	Yes	No	No	No	Yes
Raveling	No	No	No	No	No	No	No
Overall Condition	Very Good	Fair	Very Poor	Poor	Very Poor	Very Poor	Good

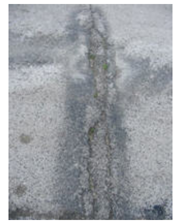
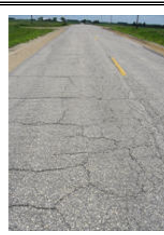
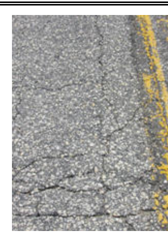
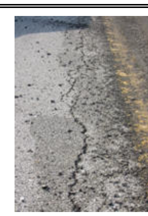
RAP Sources	Pictures of Existing Pavement Surface Conditions			
Muscatine County (Very Good)				
Webster County (Fair)				
Hardin County (Very Poor)				
Montgomery County (Poor)				
Bremer County (Very Poor)				
Lee County (Very Poor)				
Wapello County (Good)				

Figure 4-16. Pictures of surface conditions on existing pavement

4.3 Evaluation of the Collected CIR-foam Mixtures from Three Job Sites

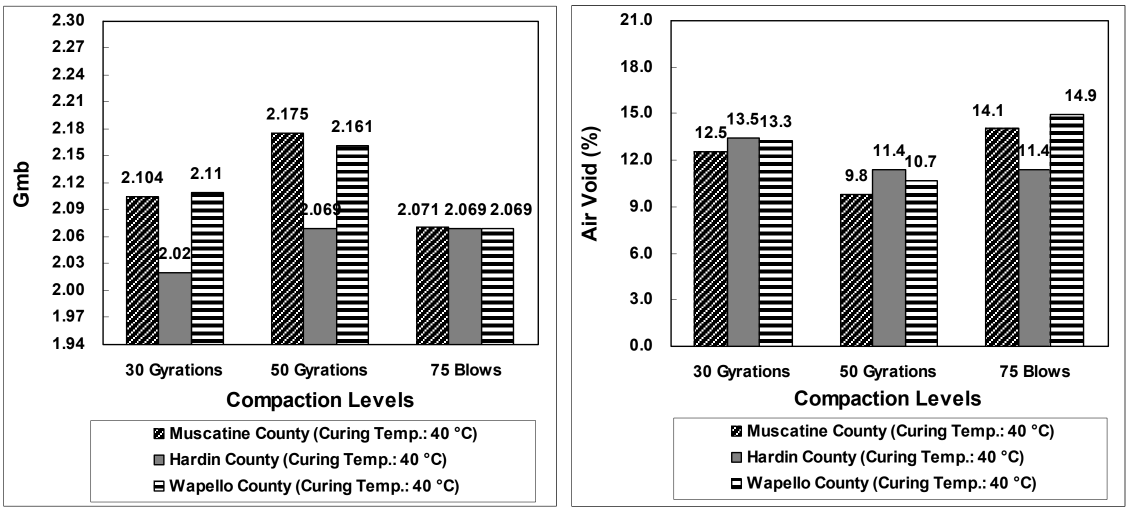
CIR-foam field mixtures were collected from three project sites in Muscatine County, Hardin County, and Wapello County. They were compacted at the laboratory using a Marshall hammer and a gyratory compactor without adding additional water and cured in the oven at 40°C for three days or at 60°C for two days. The foamed asphalt specimens were saturated under vacuum and tested to determine their "wet" indirect tensile strengths. As shown in Table 4-4, six 75-blow Marshall compacted specimens were prepared and a set of three specimens was cured in the oven at 40°C or 60°C. Four 30-gyration compacted specimens and four 50-gyration compacted specimens were also prepared. Out of four specimens made at each gyration level, two specimens were cured in the oven at 40°C for three days and the other two specimens were cured in the oven at 60°C for two days. The cured foamed asphalt specimens were placed in 25˚C water bath for a total of 1.5 hours, 30 minutes without vacuum, 30 minutes with 20mmHg vacuum, and 30 minutes without vacuum.

Table 4-4. Number of specimens for evaluating field CIR-foam mixtures

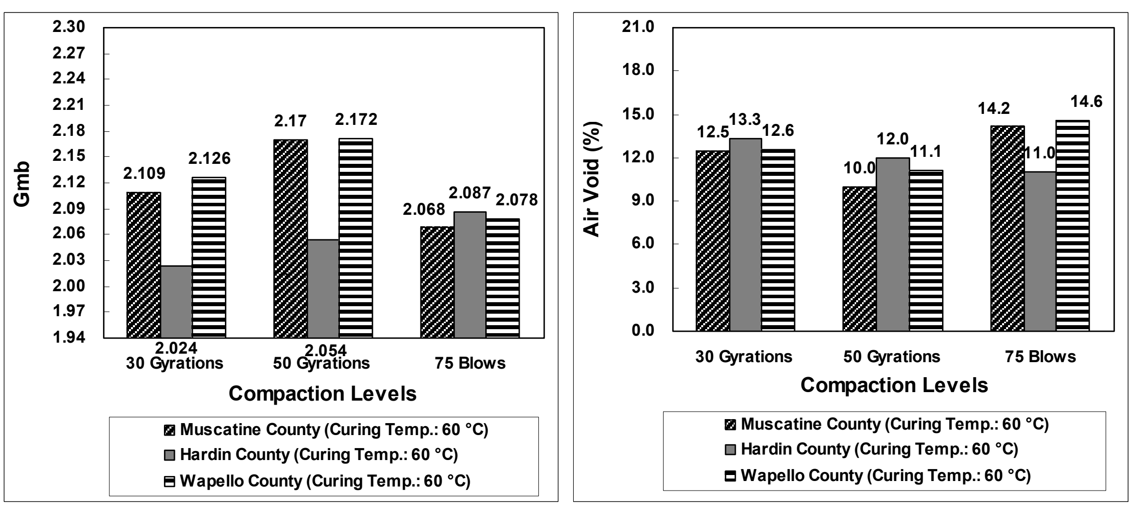
Compaction Method		75 blows	30 gyrations	50 gyrations
Curing Condition	Specimen Condition	No. of specimens		
40°C for 3 days	Vacuum-saturated	3	2	2
60°C for 2 days	Vacuum-saturated	3	2	2

4.3.1 Bulk Specific Gravity and Air Void

The estimated bulk specific gravities (G_{mb}) of the foamed asphalt mixtures were estimated by measuring volume of the compacted specimens. The maximum specific gravities were measured by the Rice test method. Figure 4-17 shows the estimated bulk specific gravities and air void for three different compaction levels and two different curing temperatures. Bulk specific gravities of gyratory compacted specimens from Hardin County were significantly lower than other specimens. As shown in Figure 4-17, air voids of those specimens from Hardin County were also higher than others. However, it is interesting to note that bulk specific gravities of Marshall hammer compacted specimens of Hardin county were about the same or slightly higher than those of Muscatine and Wapello Counties.



(a) Curing condition: 40°C for 3 days

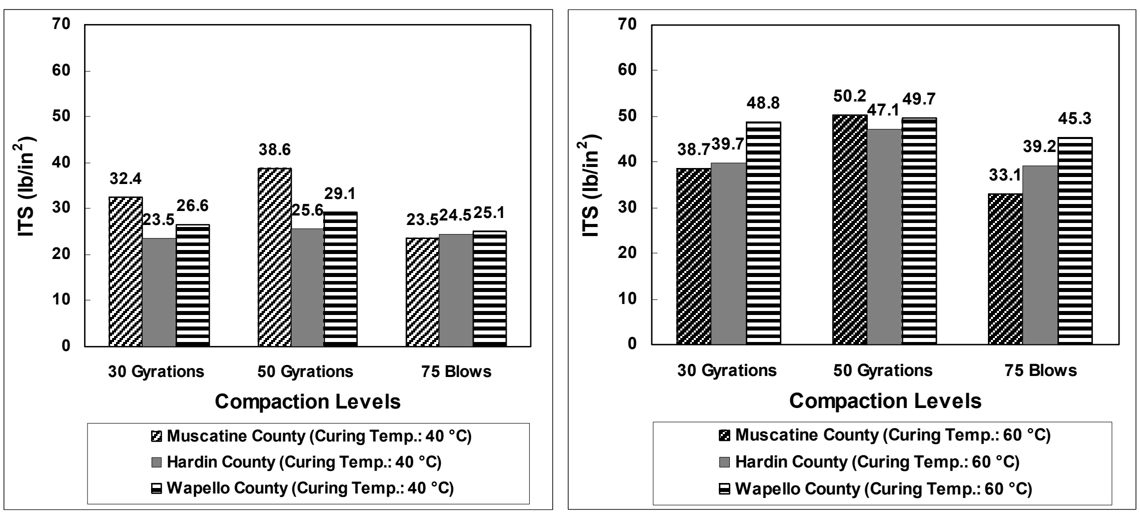


(b) Curing condition: 60°C for 2 days

Figure 4-17. Estimated G_{mb} and air void against compaction levels at two different curing temperatures

4.3.2 Wet Indirect Tensile Strength

Indirect tensile strength was determined from the field mixtures obtained from three different CIR-foam project sites. Figure 4-18 shows wet indirect tensile test results of field CIR-foam mixtures. As illustrated in Figure 4-18, the gyratory compacted specimens of Hardin County with curing temperature of 40°C exhibited significantly lower wet indirect tensile strength than those of Muscatine and Wapello County possible due to its lower bulk specific gravity. However, the gyratory compacted specimens of Hardin County with curing temperature of 60°C exhibited the similar wet indirect tensile strength to those of Muscatine and Wapello Counties.



(a) Curing condition: 40°C for 3 days (b) Curing condition: 60°C for 2 days

Figure 4-18. Indirect tensile strength against compaction levels at two different curing temperatures

5. EVALUATION OF RAP MATERIALS

As part of the phase I study, the effect of gradation on the mix design was evaluated but our test results indicated that the gradation has little effect on the optimum asphalt content moisture contents. However, it can be postulated that different RAP materials with different asphalt contents and penetration indexes may have an effect on the mix design and performance of CIR mixtures. The fundamental characteristics of RAP materials were evaluated, which include RAP gradation, elongation and flatness ratio, residual asphalt content, penetration index, dynamic shear modulus and extracted aggregate gradation. Milled RAP materials were collected from the conveyor belt of the milling machine before foamed asphalt (or ReFlex) is added except two CIR-foam project sites in Muscatine and Wapello Counties. At these two sites, milled RAP materials were collected from the ground before a paver finishes the surface by spraying foamed asphalt on them. The RAP materials were brought to laboratory and they were dried in the air (25°C~27°C) for 10 days. The moisture contents of the dried RAP materials were between 0.2% and 0.3%. Figure 5-1 shows RAP materials being dried on the floor of the laboratory and their storage in the carts.

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

5.1 RAP Gradation Analysis

First, dried RAP materials were divided into six stockpiles that were retained on the following sieves: 25mm, 19mm, 9.5mm, 4.75mm, 1.18mm and below 1.18mm. As shown in Figure 5-2, sorted RAP materials were stored in 5-gallon buckets holding about 50 lbs of RAP materials. The sorted RAP materials were then weighed and their relative proportions were computed. The more detailed gradations of the RAP materials are plotted in Figure 5-3, where all RAP materials ranges from dense to coarse with very small amount of fine aggregates passing 0.075mm sieve. All RAP materials passed 38.1 mm sieve and less than 1% was retained on 25mm sieve except Muscatine (2.6%), Hardin (6.0%), and Wapello Counties (1.3%). After discarding RAP materials bigger than 25mm, gradations for our mix design are plotted on a 0.45 power chart in Figure 5-4. To allow the comparison among seven RAP material sources side by side, their relative proportions are graphed in Figure 5-5. Overall, RAP materials from Muscatine County are the most coarse, those from Montgomery, Webster and Wapello Counties are coarse, and those from Hardin, Bremer and Lee Counties are dense.

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

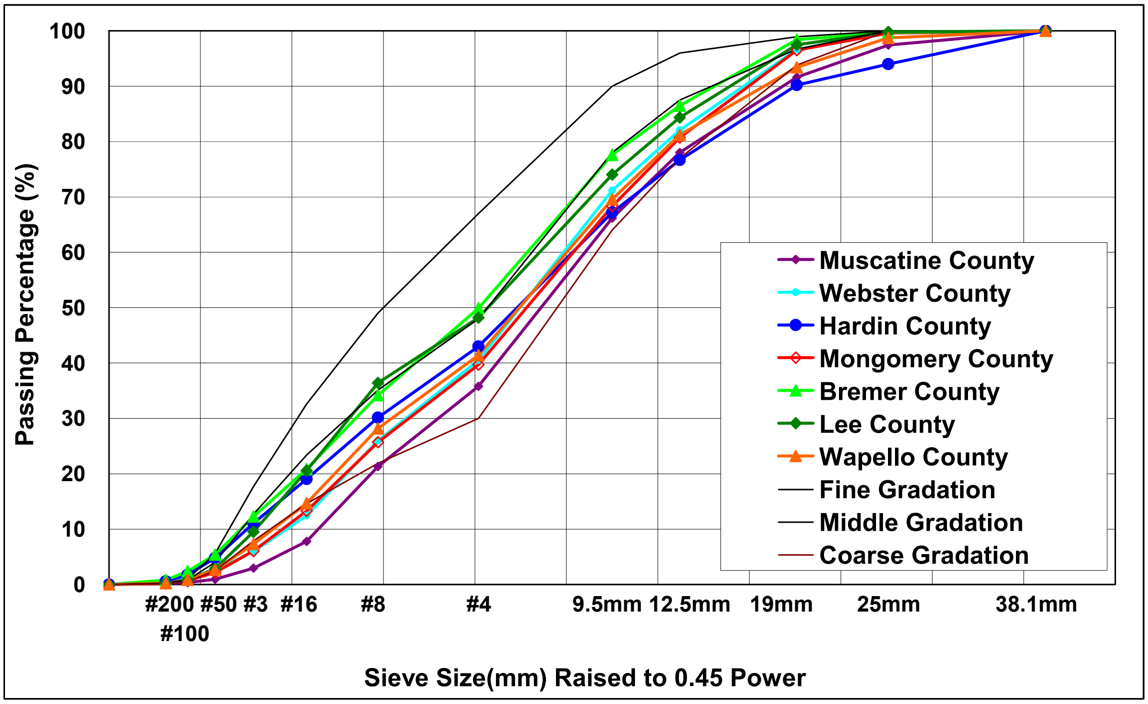


Figure 5-3. Gradation plots of seven different RAP materials

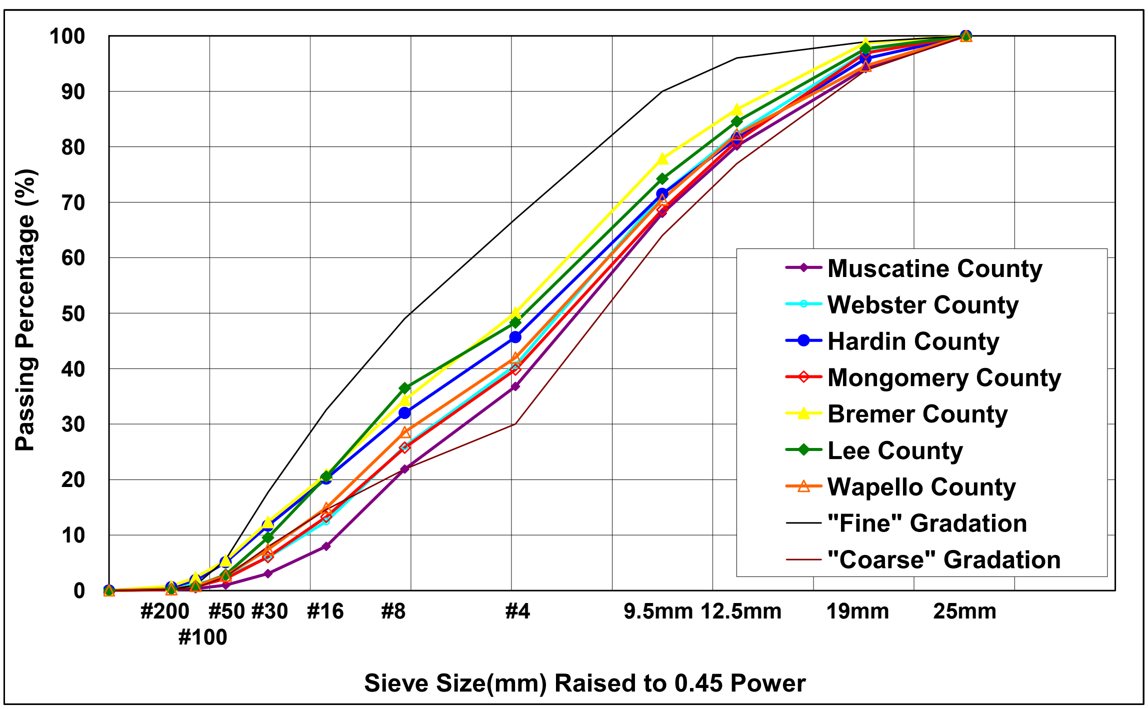


Figure 5-4. Gradation plots of seven different RAP materials passing 25mm sieve

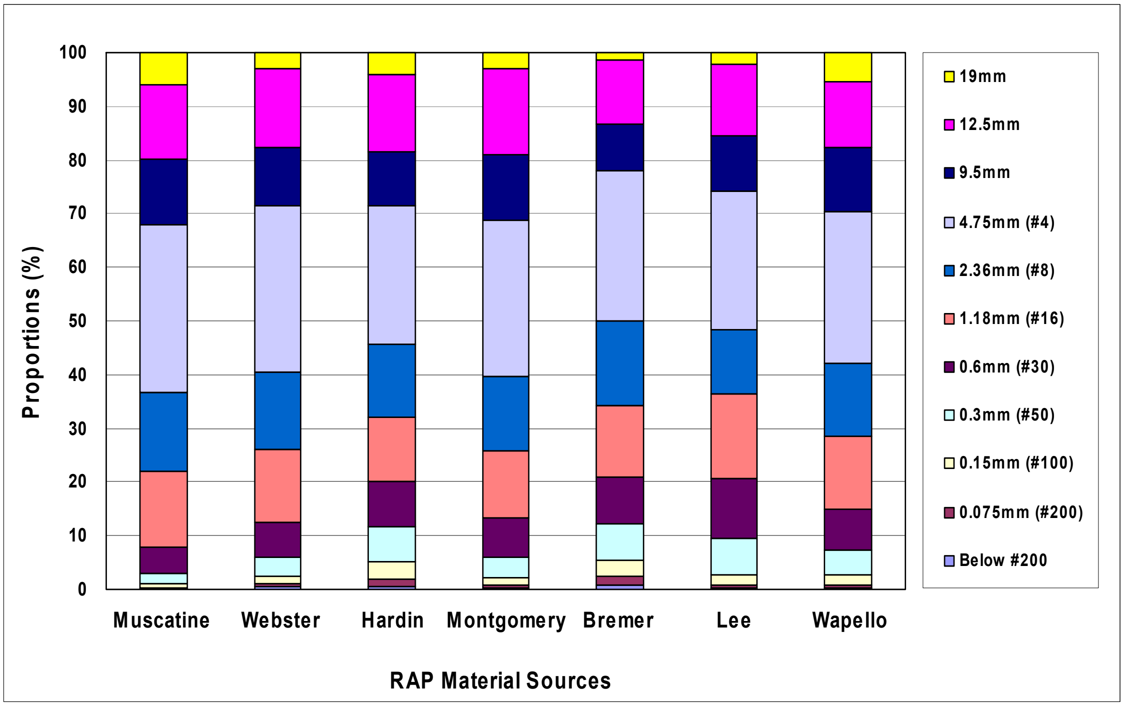


Figure 5-5. Cumulated gradation bar charts of seven different RAP materials passing 25mm sieve

5.2 Characteristics of Extracted RAP

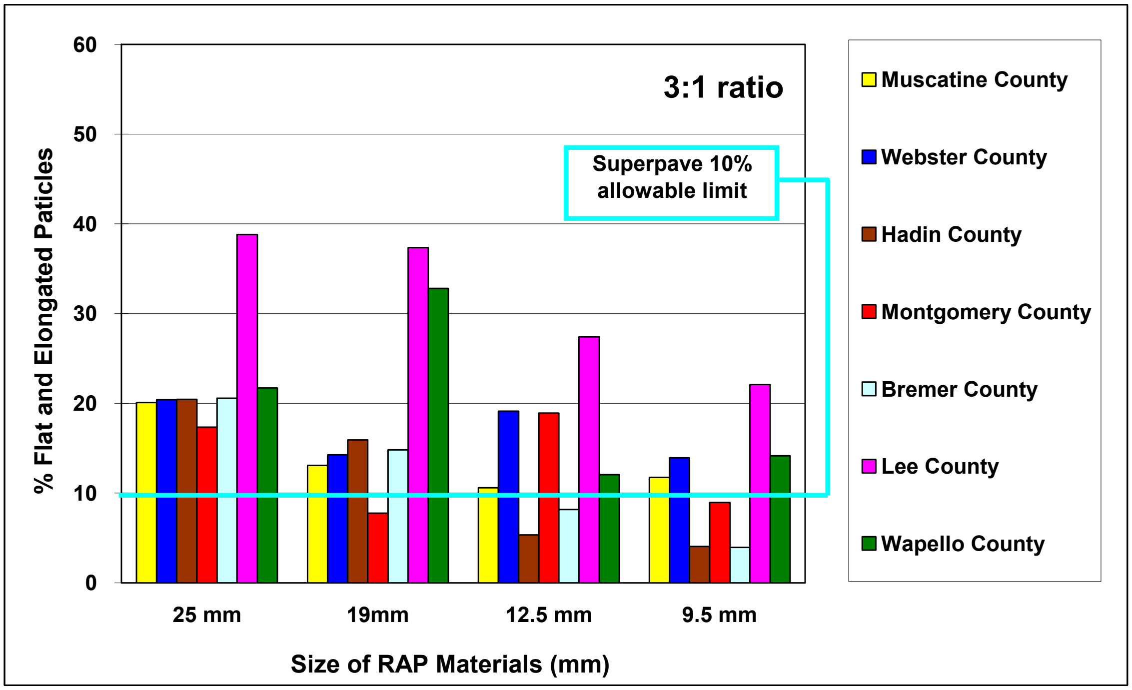
Collected RAP materials from seven different RAP sources were provided to Iowa DOT for the extracted asphalt content, penetration, dynamic shear modulus, phase angle and extracted aggregate gradation. As summarized in Table 5-1, the extracted asphalt contents ranged from 4.59% for RAP materials collected from Wapello County to 6.06% from Hardin County. The Dynamic Shear Rheometer (DSR) test was performed at the highest temperature that would produce a G*/sin δ value greater than 1.0 kPa. The extracted asphalt of RAP material from Montgomery County exhibited the highest penetration of 28 and a small G*/sin δ value of 1.08 at the lowest temperature of 76°C whereas that of Lee County showed the lowest penetration of 15 and G*/sin δ value of 1.06 at the highest temperature of 94°C. Overall, gradations of extracted aggregates were finer than those of RAP materials with a high amount of fines passing No. 200 sieve.

Table 5-1. Properties of extracted asphalt and extracted aggregates

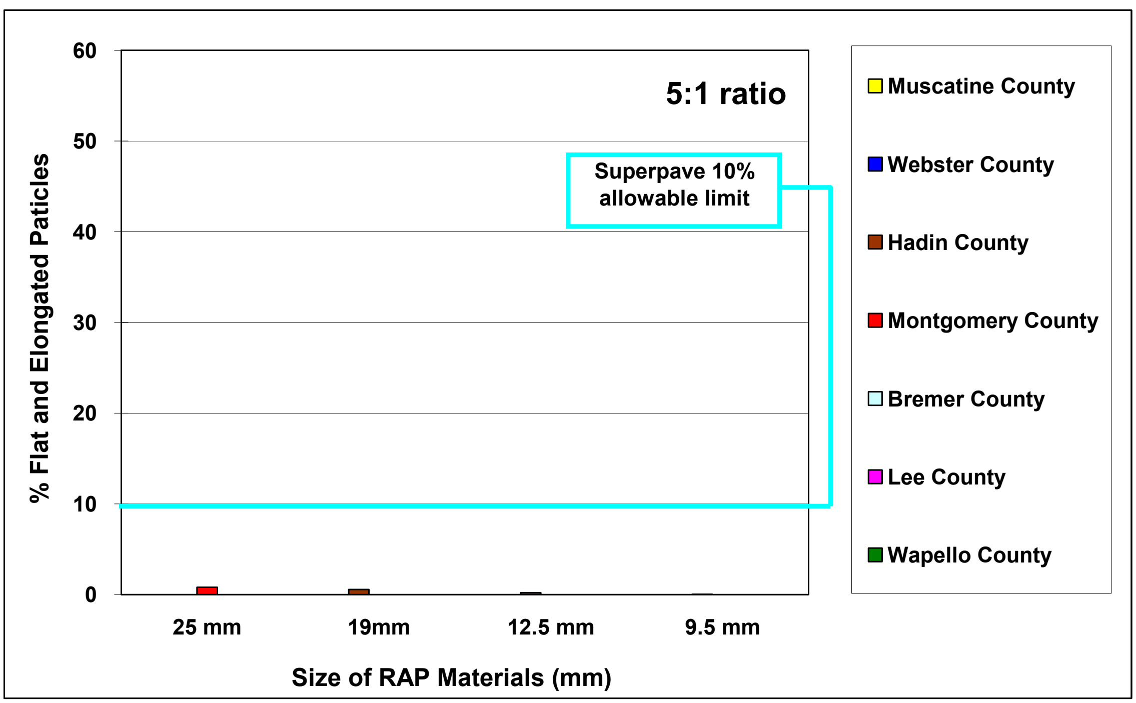
Characteristic \ County	Muscatine	Webster	Hardin	Montgomery	Bremer	Lee	Wapello
Extracted AC Content (%)	4.72	5.95	6.06	5.69	4.98	5.39	4.59
Penetration at 25°C	19	17	15	28	17	15	21
G*/sin δ (kPa)	1.05 at 82°C	1.93 at 76°C	1.19 at 88°C	1.08 at 76°C	1.44 at 76°C	1.06 at 94°C	1.11 at 76°C
Gradation of Extracted Aggregates							
25 mm	100	100	100	100	100	100	100
19.0 mm	100	100	100	100	99	100	100
12.5 mm	98	99	98	99	95	97	98
9.5 mm	93	96	93	96	88	92	91
No. 4	68	80	75	80	69	77	69
No. 8	47	63	62	61	54	64	50
No. 16	35	47	50	47	44	52	39
No. 30	25	32	37	35	34	36	29
No. 50	16	22	21	22	21	19	18
No. 100	12	16	12	15	15	13	14
No. 200	10.4	12.6	9.7	12.7	11.5	11.2	11.2

5.3 Flatness and Elongation of RAP

To evaluate the morphological characteristic of RAP materials, the flat and elongation ratio test was performed in accordance with ASTM D 4791. RAP materials retained on each of the following four sieves were analyzed individually: 9.5mm, 12.5mm, 19mm and 25.0mm. Percentages of RAP materials exceeding 3:1 or 5:1 ratios were identified as flat and elongated RAP materials. Currently, SuperPave specification requires that hot mix asphalt mixtures should have less than 10% of the aggregates that exceed 3:1 ratio. The flat and elongation test results are plotted against different RAP material sizes in Figure 5-6. As shown in Figure 5-6 (a), all RAP materials exceeded the 10% limit of 3:1 ratio but, as can be seen from Figure 5-6 (b), very little amount of RAP materials were elongated higher than the 5:1 ratio. As shown in Figure 5-6 (a), RAP materials from Lee County were most elongated followed by Wapello County. The least elongated materials were from Hardin, Montgomery and Bremer Counties.



(a) 3:1 ratio



(b) 5:1 ratio

Figure 5-6. Plots of percent flat and elongation of RAP materials from seven counties

6. Compaction Characteristics of RAP Materials

To investigate compaction characteristics of RAP materials, as a reference point, RAP materials were compacted using a gyratory compactor without adding water or foamed asphalt. As shown in Table 6-1, RAP materials were also compacted with 4.0% water added and dried in the oven at 40°C for 3 days. Two specimens were compacted up to 200 gyrations for each case.

Table 6-1. Test condition for gyratory compaction of RAP materials

RAP Condition	Number of Specimens	Compaction Level	Curing Condition
RAP only	2	200 Gyrations	Not necessary
RAP + 4.0% WC	2	200 Gyrations	40°C oven for 3 days

6.1 Sample Observation

Figure 6-1 (a), (b), and (c) show the pictures of the compacted RAP materials from Wapello County with (a) no water or foamed asphalt (b) 4.0% water and (c) 2.5% foamed asphalt and 4.0% water. Without water or foamed asphalt, RAP materials did not compact evenly as can be seen from the irregular surface in Figure 6-1 (a). With 4.0% water and 2.5% foamed asphalt, RAP materials seemed to have been over-compacted as can be seen from thick and dark asphalt spots on the surface in Figure 6-1 (c). RAP materials from Wapello County produced the highest G_{mb}.

Figure 6-2 (a), (b), and (c) show the pictures of the compacted RAP materials from Hardin County with (a) no water or foamed asphalt (b) 4.0% water and (c) 2.5% foamed asphalt and 4.0% water. Without water or foamed asphalt, RAP materials seemed to have been compacted better than those from Wapello County as shown in Figure 6-2 (c). With 4.0% water and 2.5% foamed asphalt, RAP materials seemed to have been well compacted as can be seen from well distributed asphalt spots on the surface as shown in Figure 6-2 (c). RAP materials from Hardin County produced the lowest G_{mb}.

(a) RAP specimens without foamed asphalt and water

(b) RAP specimens with 4.0% water

(c) Foamed asphalt specimens with 2.5% FAC and 4.0% water

Figure 6-1. Pictures of compacted specimens at three different RAP conditions (Wapello County)

(a) RAP specimens without foamed asphalt and water

(b) RAP specimens with 4.0% water

(c) Foamed asphalt specimens with 2.5% FAC and 4.0% water

Figure 6-2. Pictures of compacted specimens at three different RAP conditions (Hardin County)

6.2 Gyratory Compacted RAP Specimens without Water or Foamed Asphalt

Bulk specific gravities of compacted RAP specimens without water were measured and summarized in Table 6-2 and plotted against the number of gyrations in Figure 6-3. It should be noted that the specific gravity of RAP materials are not known at this time and the bulk specific gravity of compacted specimens would be significantly affected by it. As shown in Figure 6-3, at the end of 200 gyrations, RAP materials from Wapello, Bremer, and Muscatine Counties achieved the highest bulk specific gravity followed by those from Lee County. RAP materials from Webster and Montgomery Counties achieved the next highest bulk specify gravity followed by those from Hardin County.

To investigate the compaction level up to 30 gyrations, bulk specific gravities are plotted against 30 gyrations in Figure 6-4. At 30th gyration, it is interesting to note that bulk specific gravity of RAP materials from Wapello was lower than those of Bremer, which indicates that the compaction rate of RAP materials from Wapello County is higher than other RAP materials. Again, although the initial bulk specific gravity of RAP materials from Hardin County was similar Webster and Montgomery Counties it became significantly lower than others as the gyration increases. It confirms that the compaction rate of RAP materials from Hardin County is the lowest.

Table 6-2. G_{mb} of gyratory compacted RAP specimens without water adding any additional material

No. of Gyrations.	Muscatine County	Webster County	Hardin County	Montgomery County	Bremer County	Lee County	Wapello County
1	**1.613**	**1.557**	**1.590**	**1.572**	**1.735**	**1.648**	**1.656**
3	1.693	1.649	1.666	1.658	1.806	1.732	1.739
5	1.731	1.689	1.702	1.699	1.836	1.769	1.778
7	1.759	1.718	1.725	1.727	1.859	1.796	1.804
9	1.781	1.741	1.744	1.751	1.878	1.815	1.827
11	1.799	1.761	1.760	1.769	1.892	1.832	1.842
13	1.813	1.777	1.774	1.784	1.904	1.846	1.858
15	1.828	1.790	1.785	1.798	1.914	1.857	1.872
17	1.840	1.803	1.794	1.811	1.923	1.868	1.885
19	1.852	1.815	1.805	1.820	1.931	1.878	1.895
21	1.862	1.824	1.812	1.831	1.939	1.886	1.904
23	1.870	1.834	1.821	1.839	1.945	1.895	1.913
25	1.879	1.841	1.828	1.848	1.951	1.901	1.921
27	1.887	1.851	1.834	1.855	1.957	1.908	1.927
29	1.894	1.858	1.840	1.863	1.962	1.914	1.934
30	**1.898**	**1.861**	**1.844**	**1.867**	**1.965**	**1.917**	**1.937**
40	1.927	1.891	1.869	1.896	1.985	1.942	1.964
50	1.950	1.914	1.890	1.920	2.002	1.961	1.982
60	1.968	1.933	1.906	1.938	2.015	1.975	1.999
70	1.983	1.949	1.919	1.953	2.026	1.988	2.013
80	1.997	1.962	1.931	1.965	2.035	1.998	2.025
90	2.009	1.975	1.943	1.978	2.044	2.009	2.034
100	2.020	1.986	1.951	1.986	2.050	2.016	2.043
110	2.030	1.995	1.959	1.995	2.058	2.024	2.052
120	2.038	2.003	1.967	2.003	2.064	2.031	2.058
130	2.047	2.012	1.973	2.012	2.067	2.037	2.064
140	2.054	2.019	1.978	2.018	2.073	2.043	2.070
150	2.060	2.026	1.985	2.025	2.079	2.047	2.076
160	2.068	2.032	1.991	2.029	2.082	2.052	2.082
170	2.074	2.038	1.995	2.035	2.085	2.058	2.087
180	2.080	2.044	2.000	2.041	2.090	2.062	2.091
190	2.083	2.049	2.004	2.046	2.094	2.065	2.096
200	**2.090**	**2.053**	**2.008**	**2.050**	**2.098**	**2.070**	**2.101**

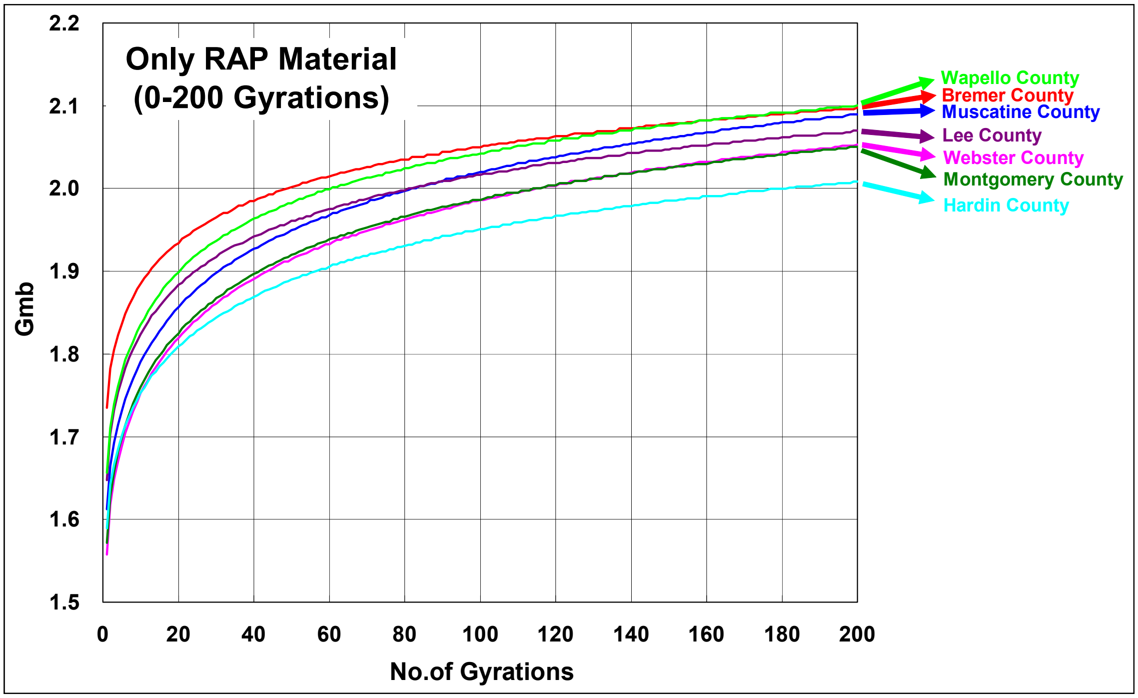


Figure 6-3. Plots of G_{mb} of RAP materials against the number of gyrations up to 200

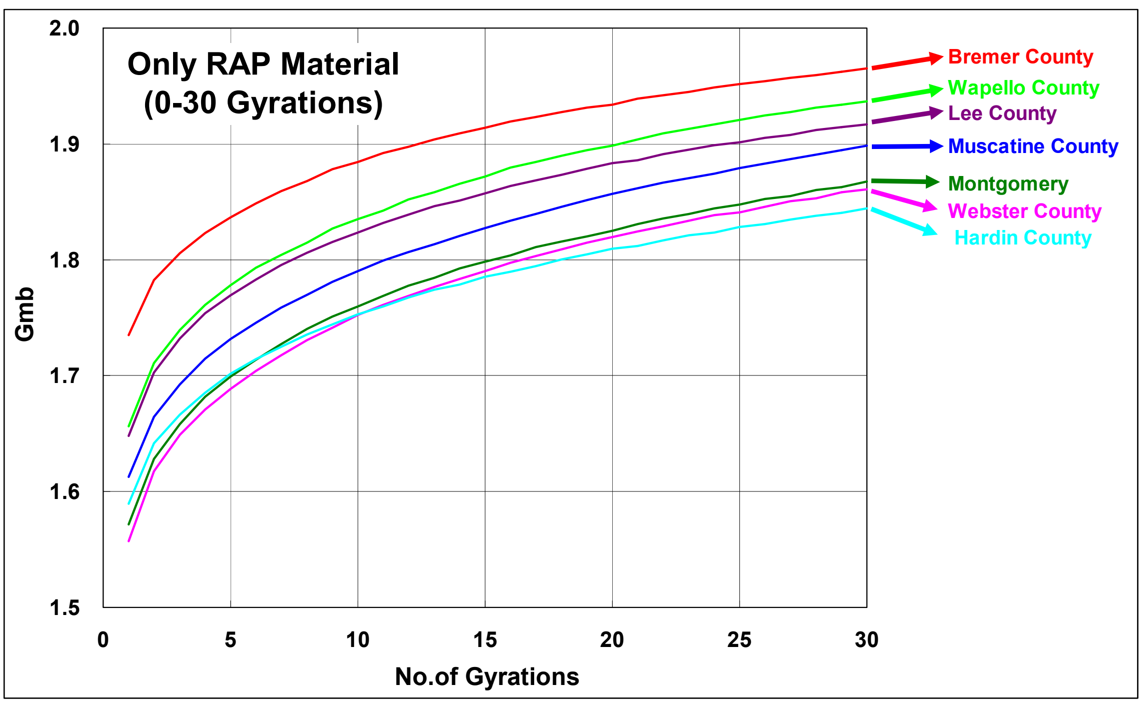


Figure 6-4. Plots of G_{mb} of RAP materials against the number of gyrations up to 30

6.3 Gyratory Compacted RAP Specimens with 4.0% Water

Bulk specific gravities of compacted RAP specimens with 4.0% water were measured and summarized in Table 6-3 and plotted against the number of gyrations in Figure 6-5. As shown in Figure 6-5, at the end of 200 gyrations, RAP materials from Wapello County achieved the highest bulk specific gravity followed by those from Bremer County. RAP materials from Muscatine, Lee, Webster and Montgomery Counties achieved the next highest bulk specify gravity followed by those from Hardin County. Although the bulk specific gravities have significantly increased due to water, it did not significantly affect the relative compactability of RAP materials.

To investigate the compaction characteristic up to 30 gyrations, bulk specific gravities are plotted against 30 gyrations in Figure 6-6. At 30th gyrations, it is interesting to note that bulk specific gravity of RAP materials from Wapello was lower than those of Bremer, which indicates that the compaction rate of RAP materials from Wapello County is higher than other RAP materials. Again, although the initial bulk specific gravity of RAP materials from Hardin County was similar Webster, Muscatine and Montgomery Counties it became significantly lower than others as the gyration increases. It confirms that the compaction rate of RAP materials from Hardin County is the lowest.

Table 6-3. G_{mb} of gyratory compacted RAP specimens without 4.0% water

No. of Gyrations.	Muscatine County	Webster County	Hardin County	Montgomery County	Bremer County	Lee County	Wapello County
1	**1.632**	**1.650**	**1.638**	**1.605**	**1.761**	**1.727**	**1.722**
3	1.719	1.751	1.729	1.707	1.854	1.823	1.822
5	1.762	1.796	1.770	1.754	1.893	1.864	1.868
7	1.793	1.828	1.798	1.788	1.921	1.892	1.900
9	1.818	1.853	1.820	1.814	1.943	1.915	1.925
11	1.838	1.874	1.838	1.836	1.959	1.934	1.943
13	1.857	1.893	1.852	1.855	1.974	1.949	1.960
15	1.871	1.906	1.866	1.870	1.985	1.959	1.975
17	1.887	1.919	1.877	1.885	1.997	1.970	1.986
19	1.899	1.932	1.887	1.898	2.007	1.982	1.997
21	1.910	1.941	1.896	1.908	2.015	1.990	2.008
23	1.920	1.951	1.905	1.919	2.023	1.999	2.016
25	1.930	1.959	1.913	1.927	2.030	2.006	2.023
27	1.938	1.969	1.920	1.935	2.037	2.011	2.031
29	1.947	1.976	1.927	1.943	2.043	2.019	2.038
30	**1.951**	**1.980**	**1.930**	**1.947**	**2.046**	**2.022**	**2.041**
40	1.985	2.011	1.959	1.979	2.069	2.048	2.068
50	2.012	2.034	1.979	2.004	2.089	2.066	2.089
60	2.034	2.052	1.995	2.026	2.105	2.082	2.109
70	2.052	2.071	2.009	2.044	2.118	2.096	2.122
80	2.068	2.083	2.022	2.059	2.127	2.105	2.135
90	2.084	2.095	2.034	2.071	2.139	2.116	2.148
100	2.096	2.106	2.043	2.085	2.145	2.123	2.158
110	2.109	2.116	2.053	2.096	2.154	2.131	2.166
120	2.119	2.126	2.059	2.105	2.162	2.137	2.175
130	2.128	2.132	2.067	2.113	2.169	2.144	2.181
140	2.138	2.140	2.073	2.123	2.174	2.150	2.188
150	2.146	2.148	2.079	2.130	2.179	2.157	2.195
160	2.155	2.152	2.086	2.138	2.184	2.160	2.200
170	2.163	2.158	2.090	2.144	2.191	2.165	2.206
180	2.170	2.165	2.095	2.151	2.194	2.169	2.213
190	2.175	2.168	2.100	2.156	2.198	2.174	2.216
200	**2.182**	**2.175**	**2.104**	**2.162**	**2.201**	**2.179**	**2.220**

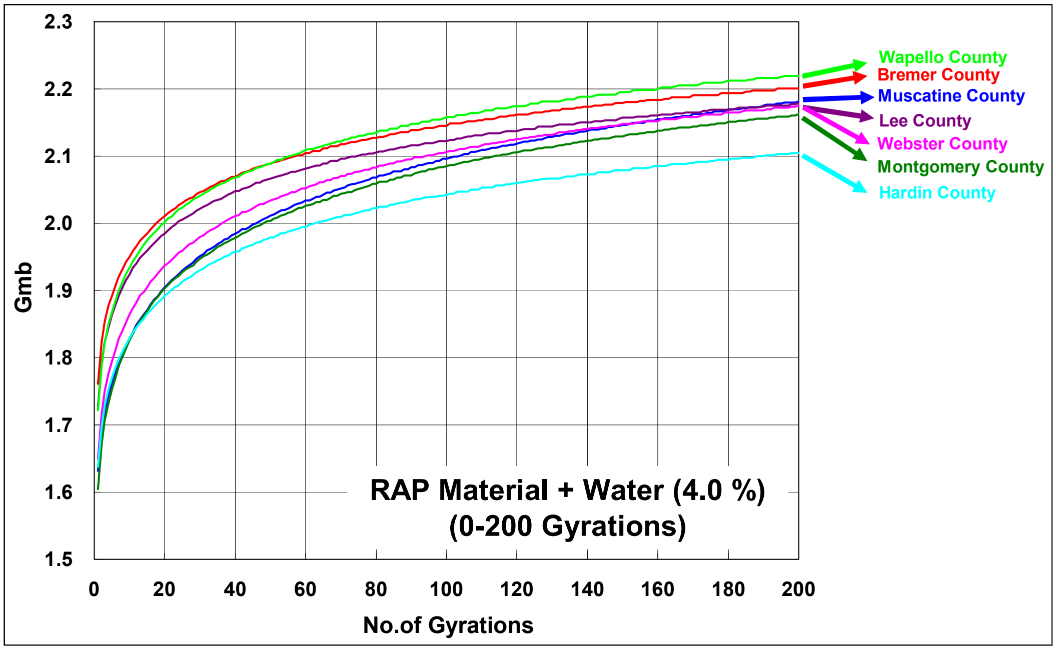


Figure 6-5. Plots of G_{mb} of RAP materials with 4.0% water against the number of gyrations up to 200

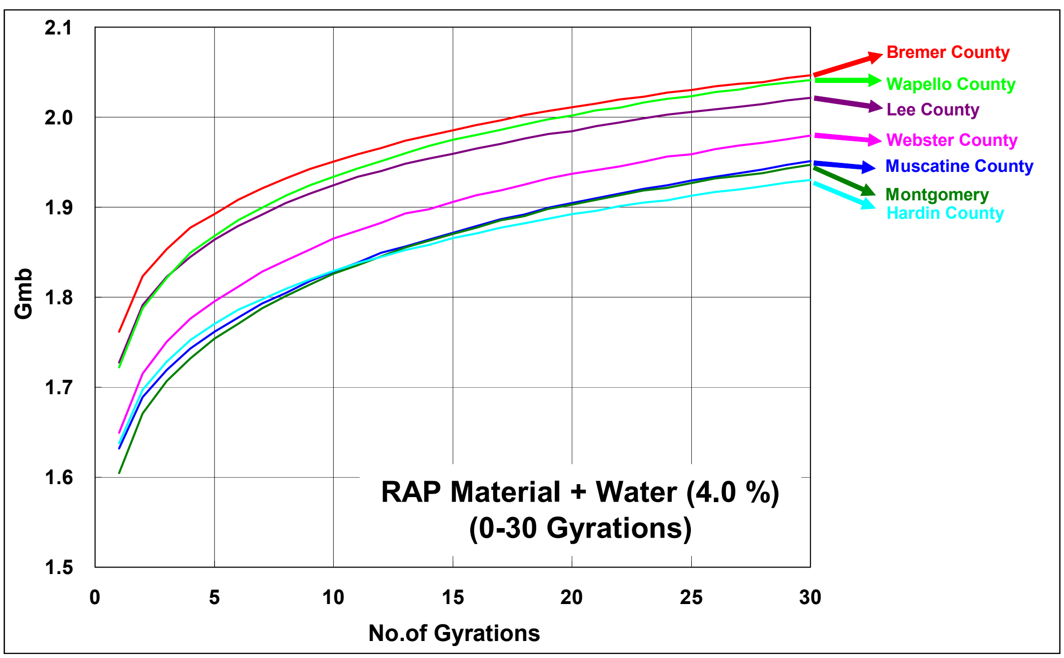


Figure 6-6. Plots of G_{mb} of RAP materials with 4.0% water against the number of gyrations up to 30

6.4 Gyratory Compacted RAP Specimens with 4.0% Water and Foamed Asphalt

To investigate compaction characteristics of RAP materials with foamed asphalt, RAP materials were compacted using a gyratory compactor for five different foamed asphalt contents while fixing the water content to 4.0%. The compacted specimens were dried in the oven at 40°C for 3 days. Two specimens were compacted up to 30 gyrations for each case.

Bulk specific gravities of compacted RAP specimens with foamed asphalt of 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% were measured and plotted against the number of gyrations in Figure 6-7, Figure 6-8, Figure 6-9, Figure 6-10, and Figure 6-11, respectively. As can be seen from these figures, at 30^{th} gyration, RAP materials from Wapello County achieved the highest bulk specific gravity whereas those from Hardin County achieved the lowest bulk specific gravity. It is interesting to note that the initial bulk specific gravity of RAP materials from Hardin County was higher than that of RAP materials from Muscatine County but it gradually became lower than it. Overall, the variation among specific gravities of different RAP materials decreased as the foamed asphalt contents increased. For example, at the highest foamed asphalt content of 3.0%, RAP materials from Bremer, Montgomery, Muscatine, Webster and Lee Counties produced very similar bulk specific gravity values.

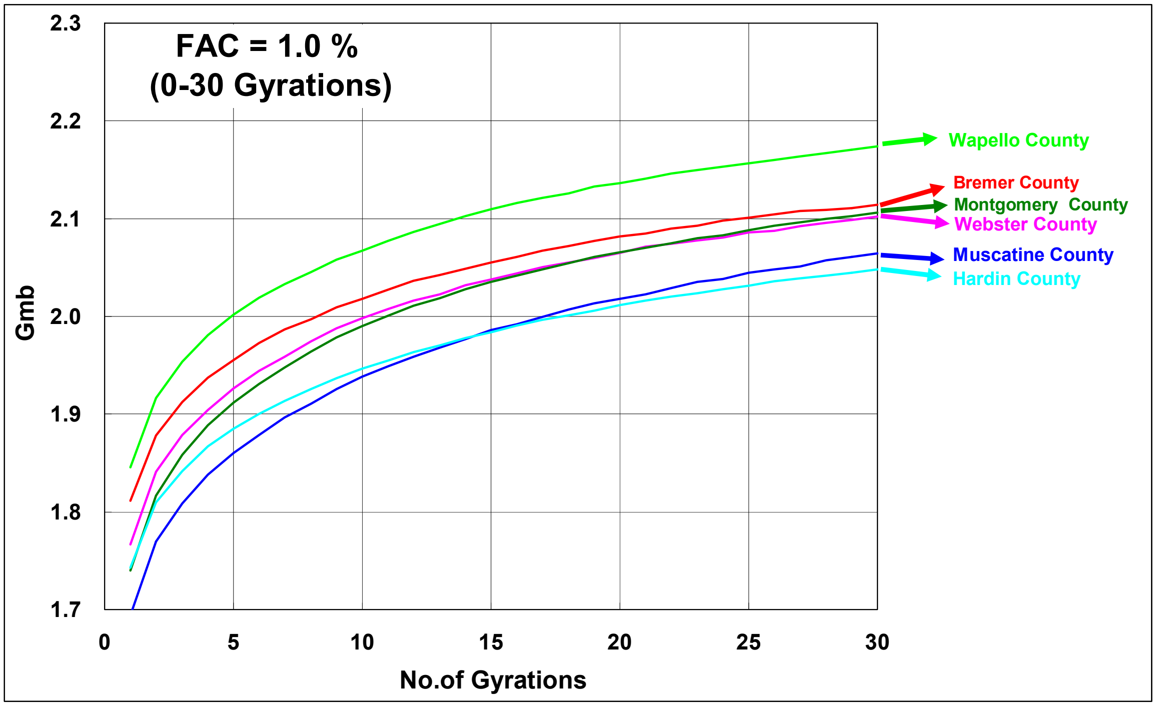


Figure 6-7. Plots of G_{mb} of RAP materials with 1.0% FAC against the number of gyrations up to 30

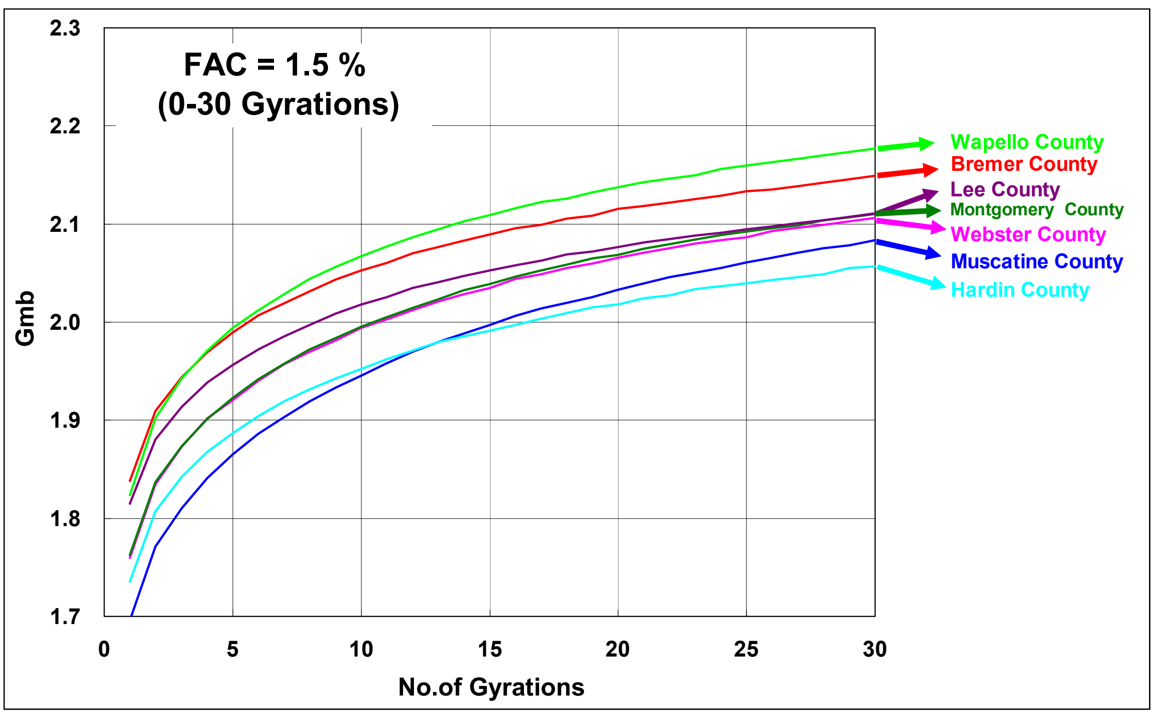


Figure 6-8. Plots of G_{mb} of RAP materials with 1.5% FAC against the number of gyrations up to 30

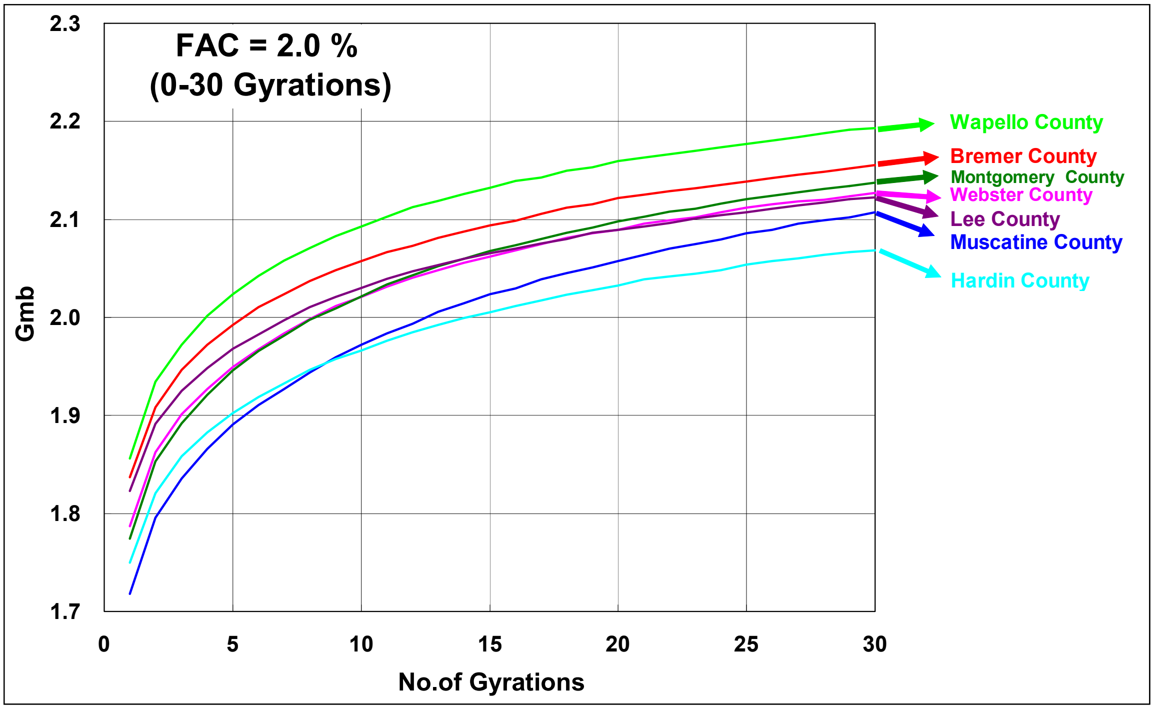


Figure 6-9. Plots of G_{mb} of RAP materials with 2.0% FAC against the number of gyrations up to 30

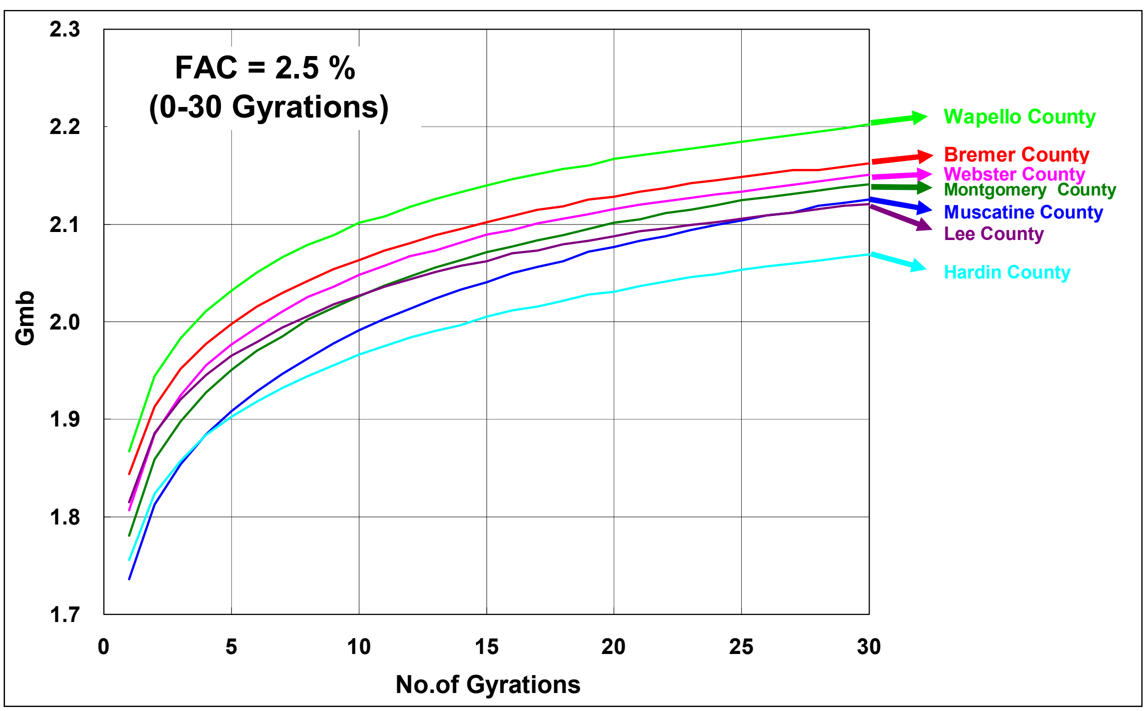


Figure 6-10. Plots of G_{mb} of RAP materials with 2.5% FAC against the number of gyrations up to 30

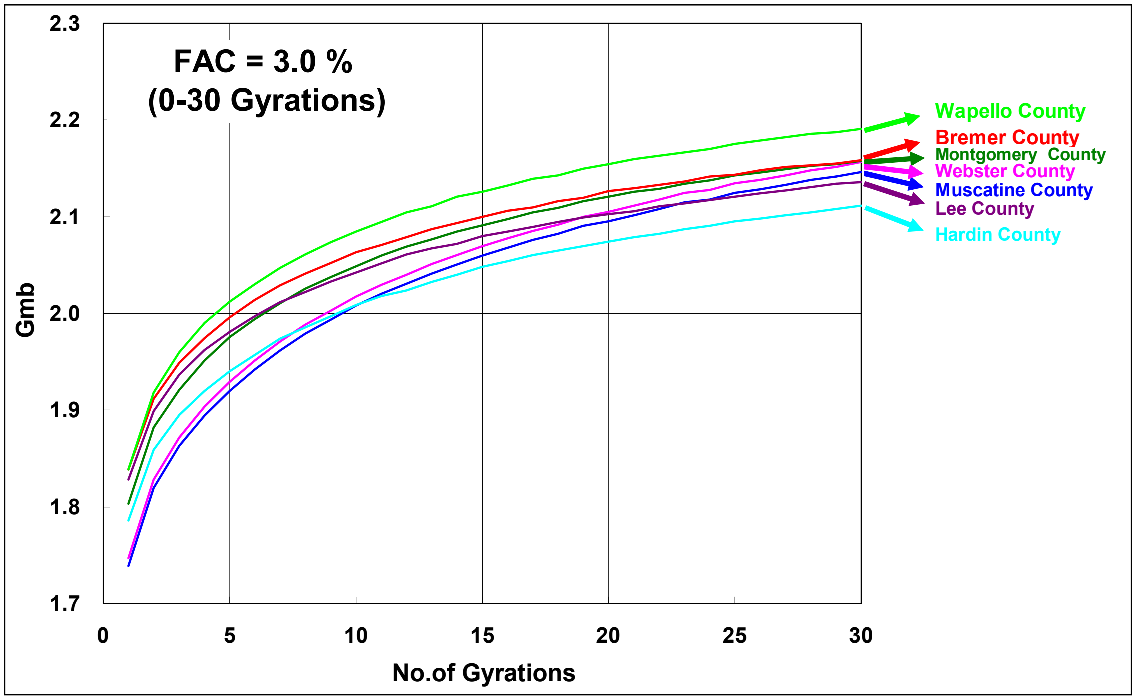
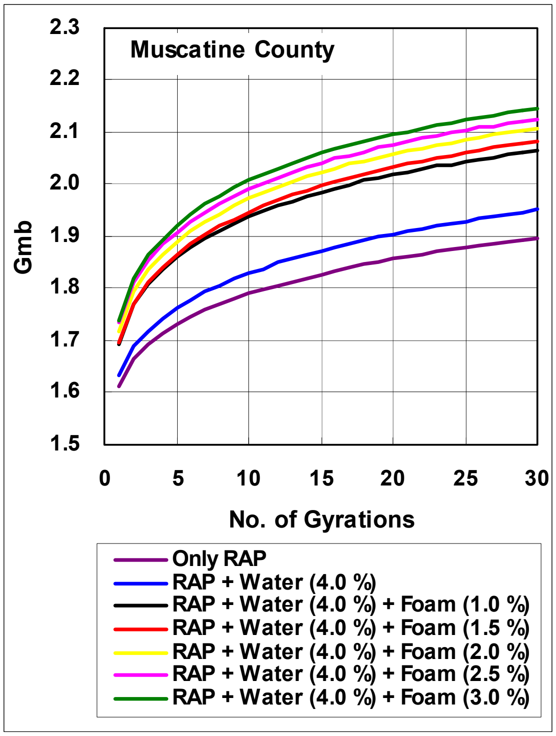
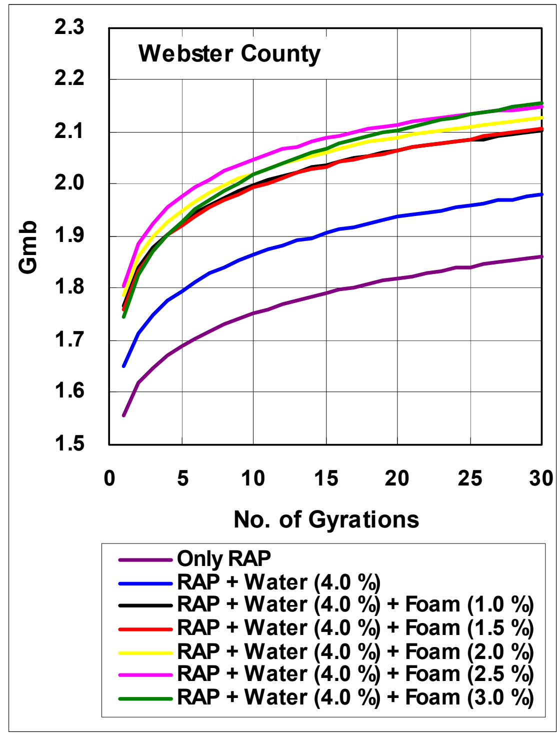


Figure 6-11. Plots of G_{mb} of RAP materials with 3.0% FAC against the number of gyrations up to 30

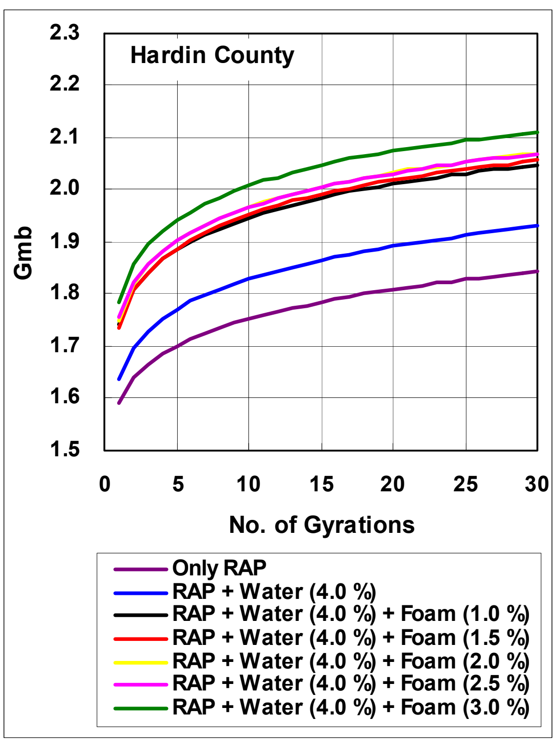
Bulk specific gravities of seven different RAP specimens compacted without water or foamed asphalt, with 4.0% water, and with 4.0% water and foamed asphalt of 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% are plotted in Figure 6-12. As can be seen from Figure 6-12, there is a significant increase in bulk specific gravity by adding foamed asphalt compared to the mixtures without foamed asphalt. It is interesting to note that the bulk specific gravities of RAP materials from Bremer, Wapello, and Lee Counties did not change very much as the foamed asphalt content increased from 1.0 % to 3.0 %.



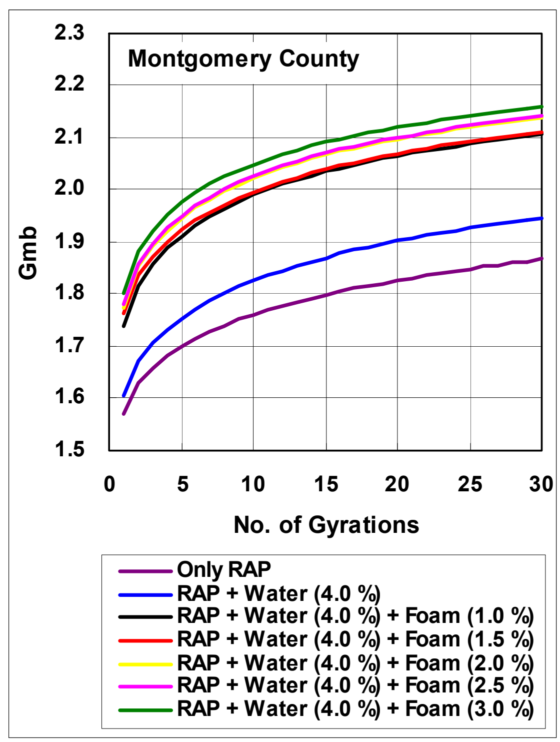
(a) Muscatine County



(b) Webster County

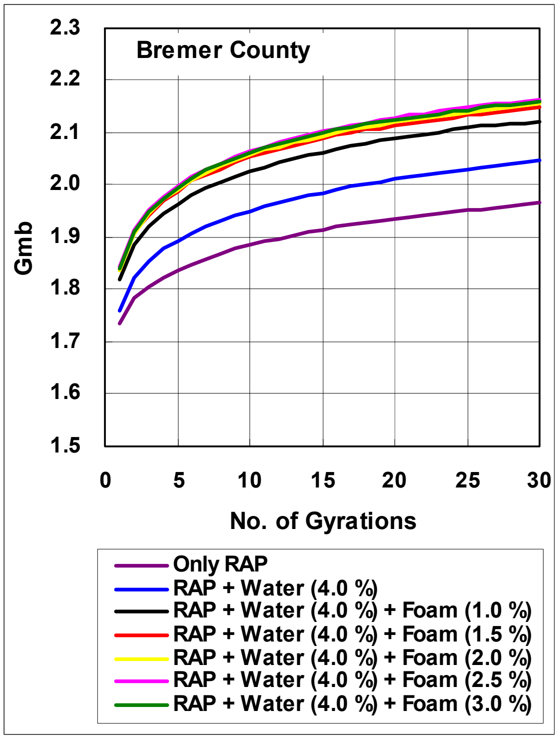


(a) Hardin County

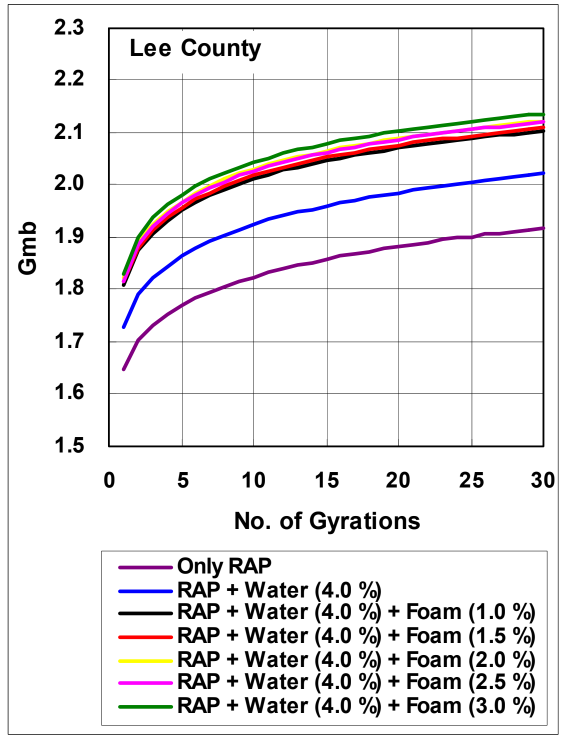


(b) Montgomery County

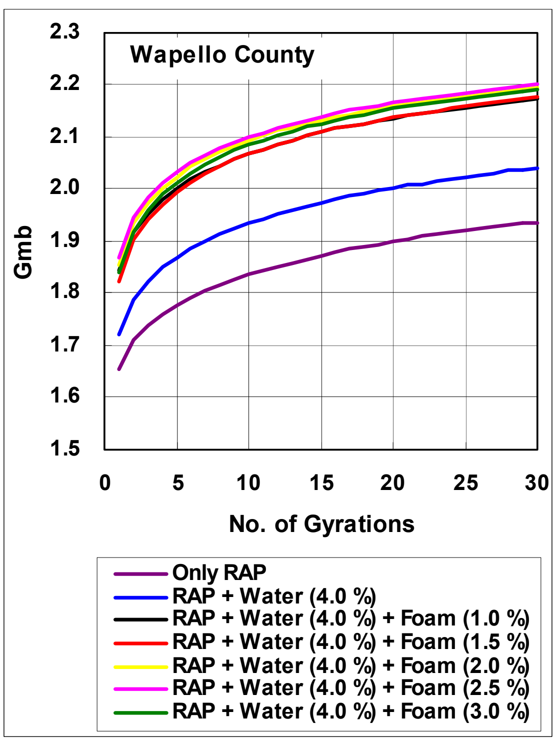
Figure 6-12. Plots of bulk specific gravities against the number of gyrations (1)



(e) Bremer County



(f) Lee County



(g) Wapello County

Figure 6-13. Plots of bulk specific gravities against the number of gyrations (2)

7. VALIDATION OF MIX DESIGN AGAINST VARIOUS RAP MATERIALS

During the phase I, a mix design was performed based on both Marshall and indirect tensile tests on both dry and wet test specimens. Based on the results obtained from the phase I study, the indirect tensile test on wet gyratory compacted test specimen was recommended as the most appropriate mix design test procedure (rather than Marshall mix design). The developed mix design process should be validated if it is applicable for different RAP materials. Therefore, indirect tensile test was performed on wet specimens from seven different RAP sources at five different foamed asphalt contents.

As shown in Table 7-1, the mix design parameters identified from phase 1 study were adopted for five different foamed asphalts (1.0%, 1.5%, 2.0%. 2.5%, and 3.0%) and one fixed water content (4.0%).

Table 7-1. Design parameters for validation of laboratory mix design

Asphalt Binder	PG 52-34
Foaming Temperature (°C)	170 °C
Foaming Water Content (%)	1.3 %
Foamed Asphalt Content (%)	1.0 %, 1.5 %, 2.0 %. 2.5 %, and 3.0 %
Water Content of RAP (%)	4.0 %

7.1 Sample Preparation

First, the number of gyrations, which would produce the same density as the one compacted using Marshall hammer with 75 blows should be determined. Table 7-2 shows the number of test specimens prepared for a combination of five foamed asphalt contents, two compaction methods (Marshall at 75 below and gyratory compactor at 30 gyrations), and two curing temperatures (40°C and 60°C) using seven different sources of RAP materials. Each test specimen was used to measure the bulk specific gravity and the indirect tensile strength at wet condition.

Table 7-2. Number of specimens prepared for each design parameter

FAC (%)	1.0 %				1.5 %				2.0 %				2.5 %				3.0 %			
Compaction Method	Marshall Hammer (75 blows)		Gyratory Compactor (30 Gyrations)		Marshall Hammer (75 blows)		Gyratory Compactor (30 Gyrations)		Marshall Hammer (75 blows)		Gyratory Compactor (30 Gyrations)		Marshall Hammer (75 blows)		Gyratory Compactor (30 Gyrations)		Marshall Hammer (75 blows)		Gyratory Compactor (30 Gyrations)	
Curing Temperature (°C)	40	60	40	60	40	60	40	60	40	60	40	60	40	60	40	60	40	60	40	60
RAP Sources	Number of Specimens																			
Muscatine County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2
Webster County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2
Hardin County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2
Montgomery County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2
Bremer County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2
Lee County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2
Wapello County	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3	2	2

7.2 Visual Observation

Generally, gyratory compacted specimens exhibited black color on the surface as shown in Figure 7-1 (a) whereas Marshall hammer compacted specimens exhibited brown color as shown in Figure 7-1 (b). As shown in Figure 7-2, specimens cured at 60°C exhibited darker color on the surface than those cured at 40 °C.

(a) Gyratory compacted specimens (b) Marshall compacted specimens

Figure 7-1. Pictures of gyratory and Marshall compacted specimens (FAC=2.5%)

(a) Gyratory compacted specimens (40°C)

(b) Gyratory compacted specimens (60°C)

(c) Marshall compacted specimens (40°C)

(d) Marshall compacted specimens (60°C)

Figure 7-2. Pictures of compacted and cured foamed asphalt specimens (Webster County)

7.3 Volumetric Characteristics

7.3.1 Bulk Specific Gravities

Tables 7-3 and 7-4 summarize bulk specific gravities of foamed asphalt specimens compacted by Marshall hammer and gyratory compactor, respectively. The test specimens were prepared using RAP materials from seven sources at five different foamed asphalt contents (1.0 %, 1.5 %, 2.0 %, 2.5 % and 3.0 %), cured at two different temperatures (40°C and 60°C).

Bulk specific gravities are plotted against foamed asphalt contents for Marshall hammer compaction at 40°C in Figure 7-3, gyratory compaction at 40°C in Figure 7-4, Marshall hammer compaction at 60°C in Figure 7-5, and gyratory compaction at 60°C in Figure 7-6. As shown in these figures, the bulk specific gravity of specimens compacted by gyratory compactor at 30 gyrations seemed to be close to that of specimens compacted by Marshall hammer at 75 blow. Overall, the bulk specific gravities seemed to increase as the foamed asphalt content increased. RAP materials from Hardin County showed the lowest value where as those from Wapello County showed highest value.

Table 7-3. Estimated G_{mb} of Marshall compacted foamed asphalt specimens for seven different sources of RAP materials

FAC (%)	1.0 %		1.5 %		2.0 %		2.5 %		3.0 %	
Compaction Method	Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)	
Curing Temperature (°C)	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
RAP Sources	Bulk Specific Gravity (G_{mb})									
Muscatine County	2.039	2.054	2.040	2.076	2.086	2.084	2.082	2.108	2.083	2.080
Webster County	2.140	2.131	2.144	2.148	2.149	2.162	2.152	2.162	2.150	2.157
Hardin County	2.046	2.044	2.053	2.055	2.055	2.057	2.066	2.062	2.072	2.067
Montgomery County	2.117	2.103	2.117	2.115	2.124	2.104	2.107	2.118	2.108	2.122
Bremer County	2.133	2.137	2.136	2.139	2.139	2.144	2.151	2.137	2.130	2.135
Lee County	2.124	2.129	2.134	2.142	2.135	2.132	2.143	2.130	2.149	2.125
Wapello County	2.209	2.185	2.224	2.217	2.212	2.209	2.210	2.208	2.211	2.214

Table 7-4. Estimated G_{mb} of gyratory compacted foamed asphalt specimens for seven different sources of RAP materials

FAC (%)	1.0 %		1.5 %		2.0 %		2.5 %		3.0 %	
Compaction Method	Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)	
Curing Temperature (°C)	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
RAP Sources	Bulk Specific Gravity (G_{mb})									
Muscatine County	2.064	2.100	2.083	2.125	2.107	2.155	2.125	2.180	2.146	2.178
Webster County	2.102	2.126	2.106	2.138	2.127	2.151	2.151	2.173	2.157	2.178
Hardin County	2.048	2.068	2.057	2.092	2.068	2.093	2.069	2.120	2.111	2.129
Montgomery County	2.106	2.142	2.110	2.142	2.138	2.163	2.141	2.169	2.158	2.175
Bremer County	2.122	2.133	2.149	2.156	2.156	2.176	2.162	2.185	2.158	2.183
Lee County	2.105	2.116	2.111	2.132	2.122	2.138	2.120	2.141	2.136	2.156
Wapello County	2.174	2.196	2.177	2.211	2.193	2.213	2.002	2.227	2.191	2.210

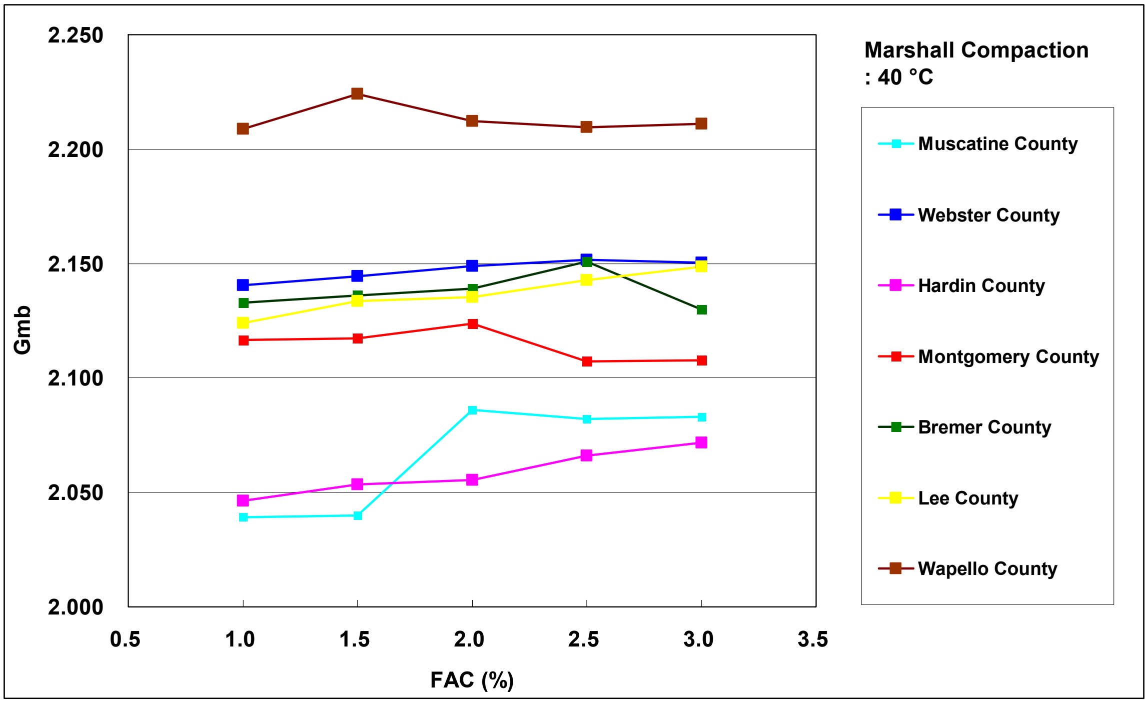


Figure 7-3. G_{mb} of Marshall hammer compacted specimens against FAC (40°C)

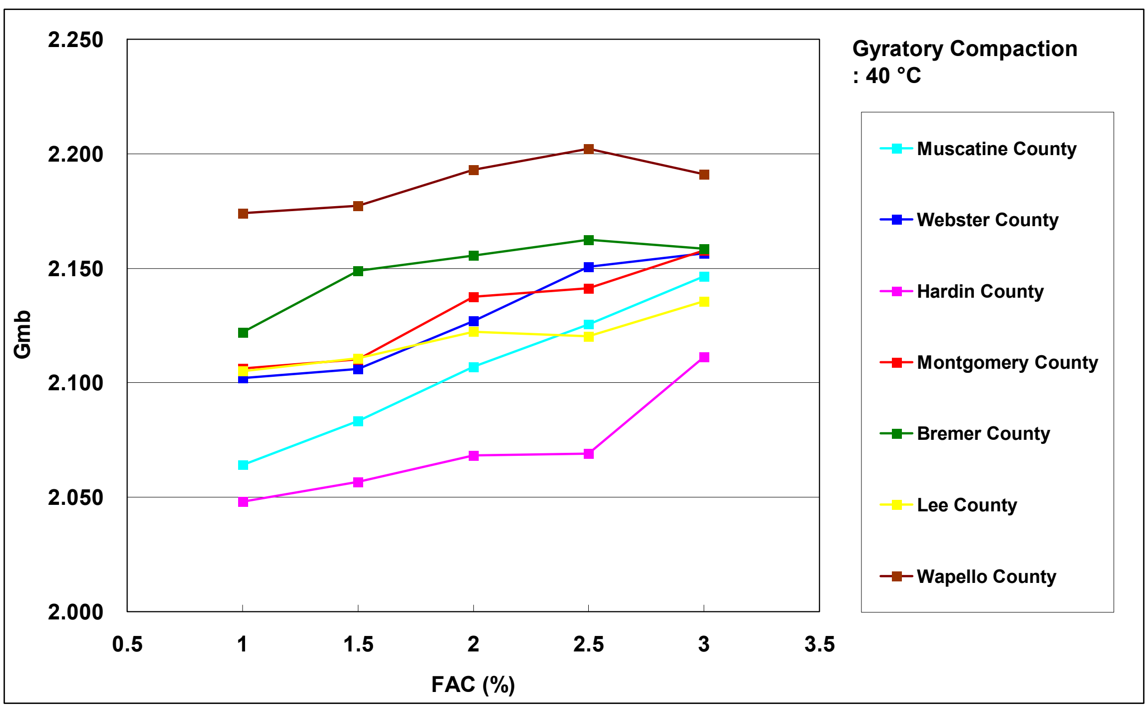


Figure 7-4. G_{mb} of gyratory compacted specimens against FAC (40°C)

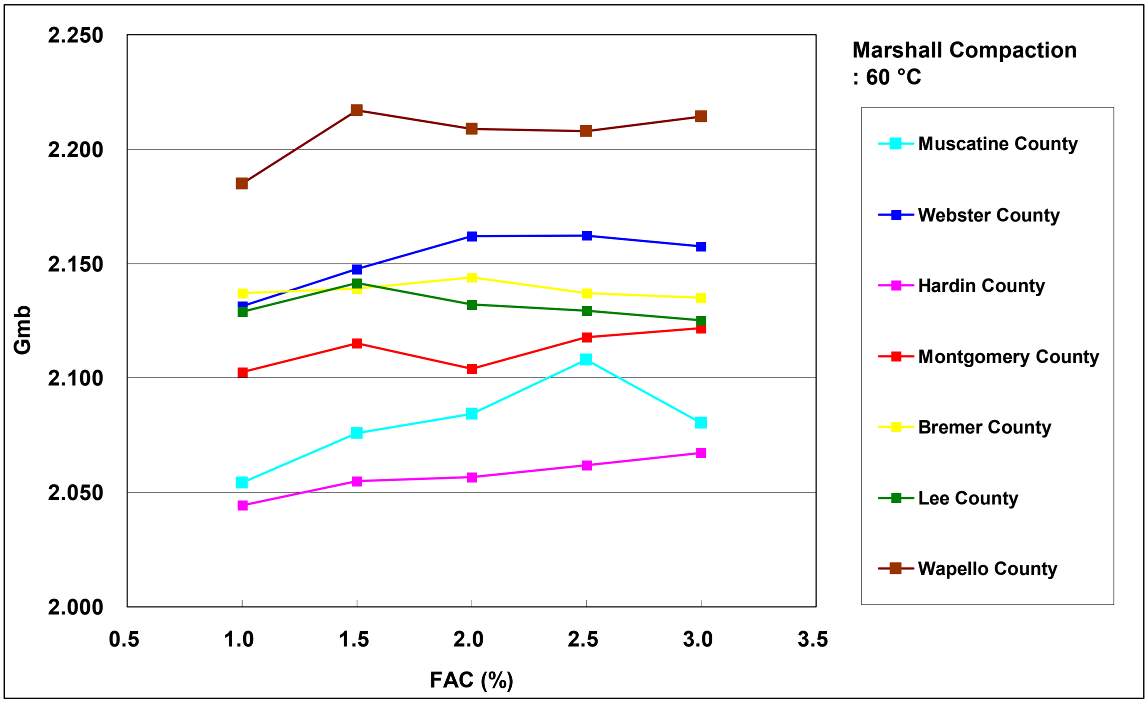


Figure 7-5. G_{mb} of Marshall hammer compacted specimens against FAC (60°C)

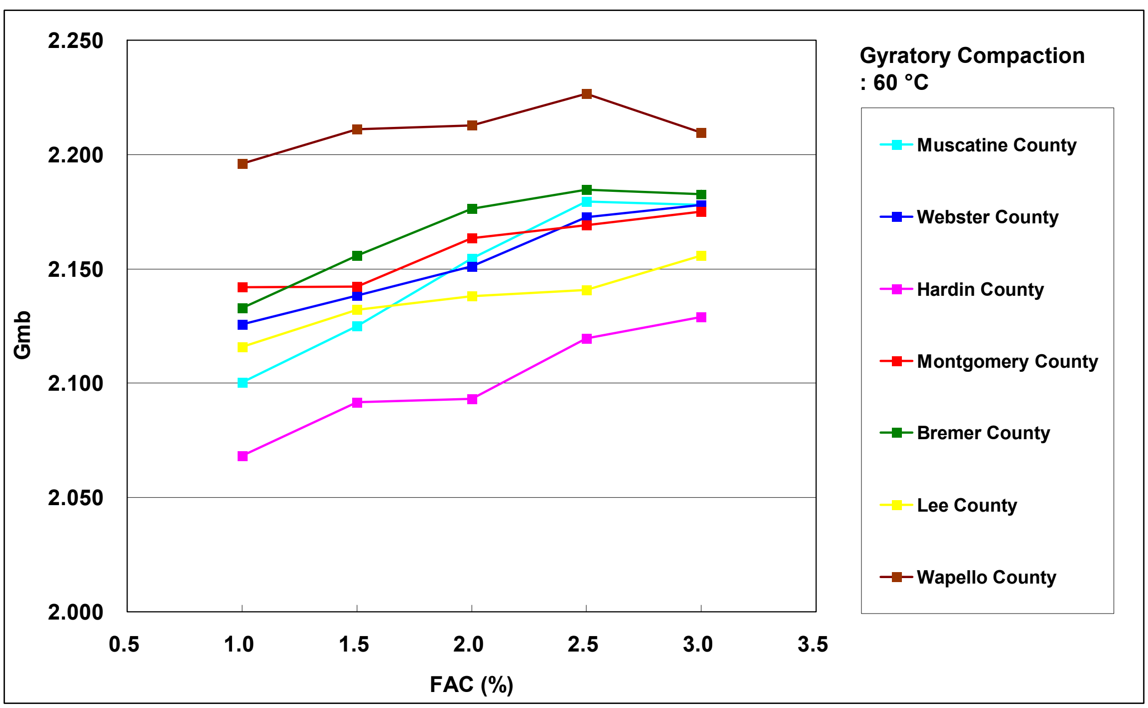


Figure 7-6. G_{mb} of gyratory compacted specimens against FAC (60°C)

7.3.2 Theoretical Maximum Specific Gravities

The theoretical maximum specific gravity was measured at five different foamed asphalt contents for seven different RAP materials. As shown in Figure 7-7, the theoretical maximum specific gravities of the specimens from Muscatine County showed the highest values whereas those of the specimens from Hardin County showed the lowest values

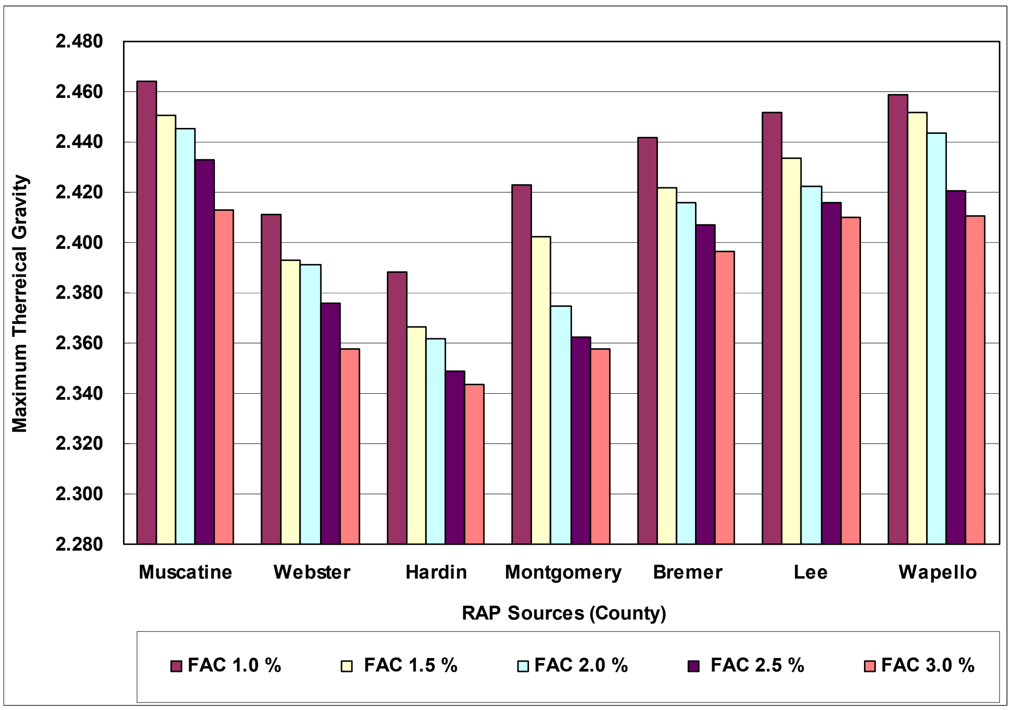


Figure 7-7. Plots of theoretical maximum specific gravities

7.3.3 Air Void

Air voids are calculated by measured bulk specific gravities and the maximum theoretical gravities. Tables 7-5 and 7-6 summarize the computed air voids of foamed asphalt specimens compacted by Marshall hammer and gyratory compactor, respectively. Air voids of the test specimens were computed at five different foamed asphalt contents (1.0%, 1.5%, 2.0%, 2.5% and 3.0%) and two different temperatures (40°C and 60°C). Air voids are plotted against foamed asphalt contents for Marshall hammer compaction at

40°C in Figure 7-8, gyratory compaction at 40°C in Figure 7-9, Marshall hammer compaction at 60°C in Figure 7-10, and gyratory compaction at 60°C in Figure 7-11. As expected, air voids decreased gradually as the foamed asphalt content increased.

Table 7-5. Calculated air void of Marshall compacted foamed asphalt specimens for seven different sources of RAP materials

FAC (%)	1.0 %		1.5 %		2.0 %		2.5 %		3.0 %	
Compaction Method	Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)	
Curing Temperature (°C)	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
RAP Sources	Air Void (%)									
Muscatine County	17.2	16.6	16.8	15.3	14.7	14.8	14.4	13.4	13.7	13.8
Webster County	11.2	11.6	10.4	10.3	10.1	9.6	9.4	9.0	8.8	8.5
Hardin County	14.3	14.4	13.2	13.1	13.0	12.9	12.0	12.2	11.6	11.8
Montgomery County	12.6	13.2	11.9	12.0	10.6	11.4	10.8	10.3	10.6	10.0
Bremer County	12.7	12.5	11.8	11.7	11.5	11.2	10.6	11.2	11.1	10.9
Lee County	13.4	13.2	12.3	12.0	11.8	12.0	11.3	11.9	10.8	11.8
Wapello County	10.2	11.1	9.3	9.6	9.5	9.6	8.7	8.8	8.3	8.2

Table 7-6. Calculated air void of gyratory compacted foamed asphalt specimens for seven different sources of RAP materials

FAC (%)	1.0 %		1.5 %		2.0 %		2.5 %		3.0 %	
Compaction Method	Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)	
Curing Temperature (°C)	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
RAP Sources	Air Void (%)									
Muscatine County	16.2	14.8	15.0	13.3	13.8	11.9	12.6	10.4	11.0	9.7
Webster County	12.8	11.8	12.0	10.6	11.0	10.0	9.5	8.6	8.5	7.6
Hardin County	14.2	13.4	13.1	11.6	12.4	11.4	11.9	9.8	9.9	9.1
Montgomery County	13.1	11.6	12.2	10.9	10.0	8.9	9.3	8.2	8.5	7.8
Bremer County	13.1	12.7	11.3	11.0	10.8	9.9	10.2	9.2	9.9	8.9
Lee County	14.2	13.7	13.2	12.4	12.4	11.7	12.2	11.4	11.4	10.5
Wapello County	11.6	10.7	11.2	9.8	10.3	9.5	9.0	8.0	9.1	8.4

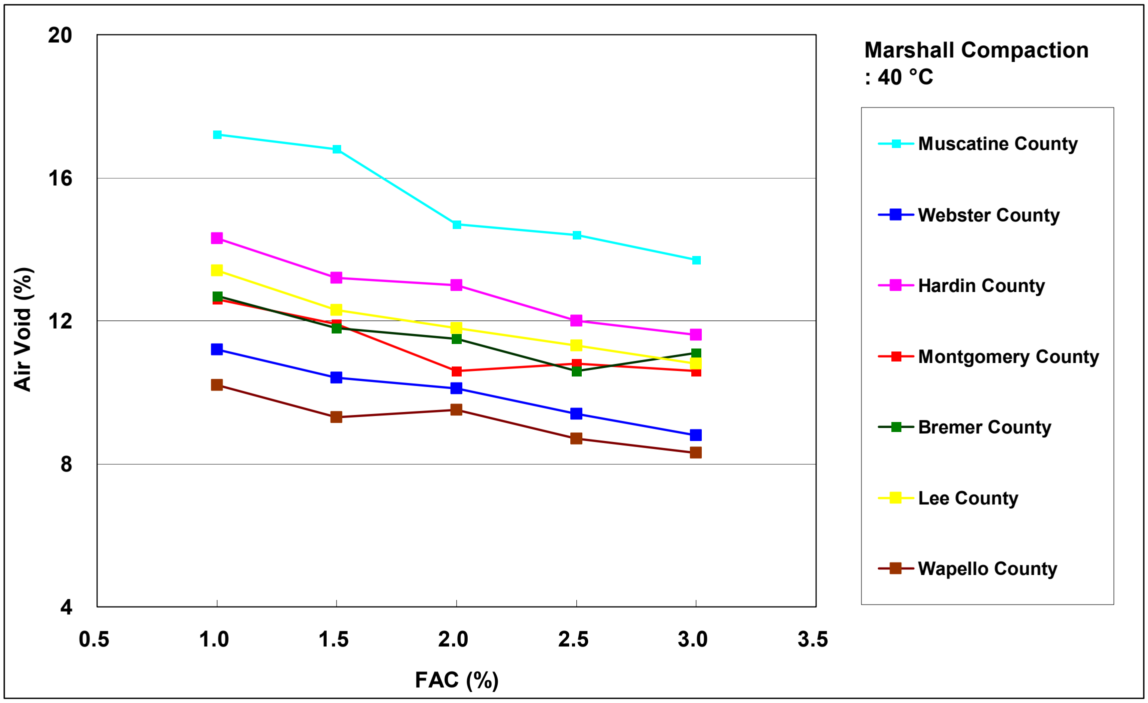


Figure 7-8. Air void of Marshall hammer compacted specimens against FAC (40°C)

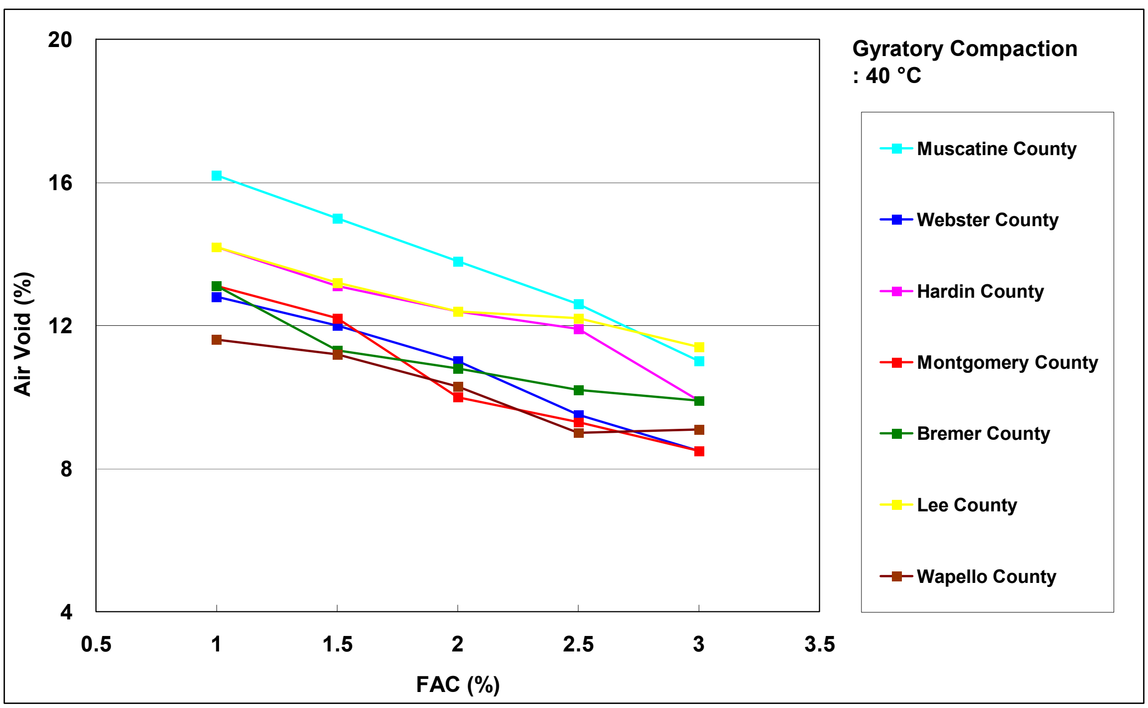


Figure 7-9. Air void of gyratory compacted specimens against FAC (40°C)

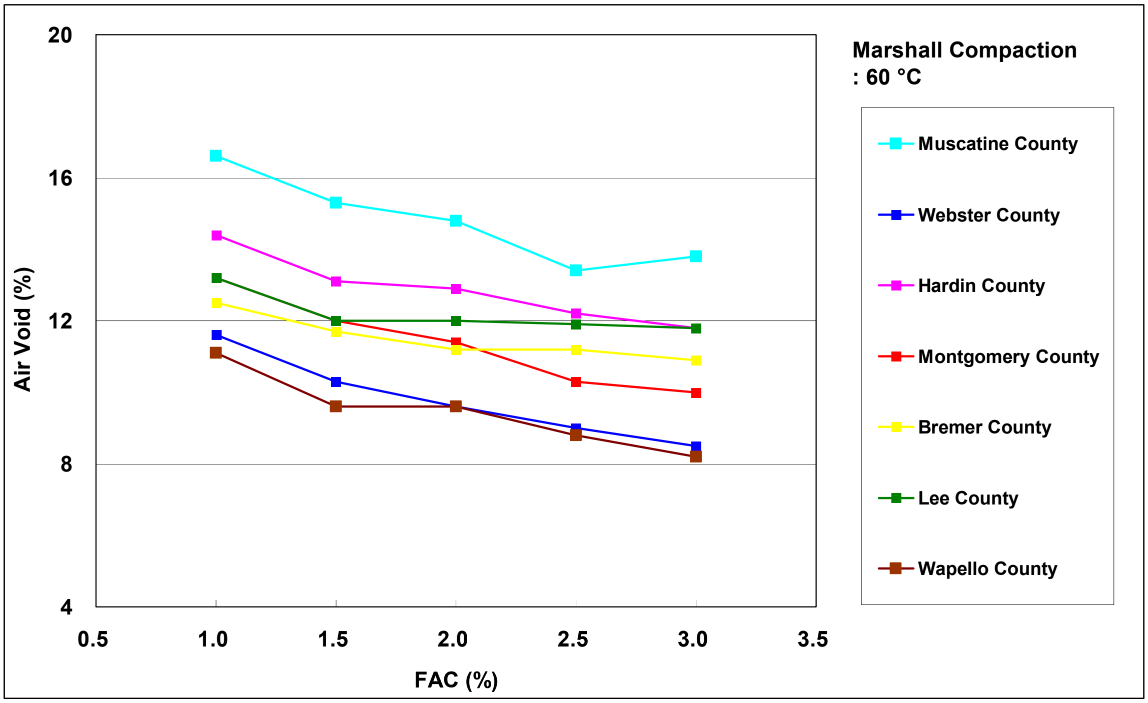


Figure 7-10. Air void of Marshall hammer compacted specimens against FAC (60°C)

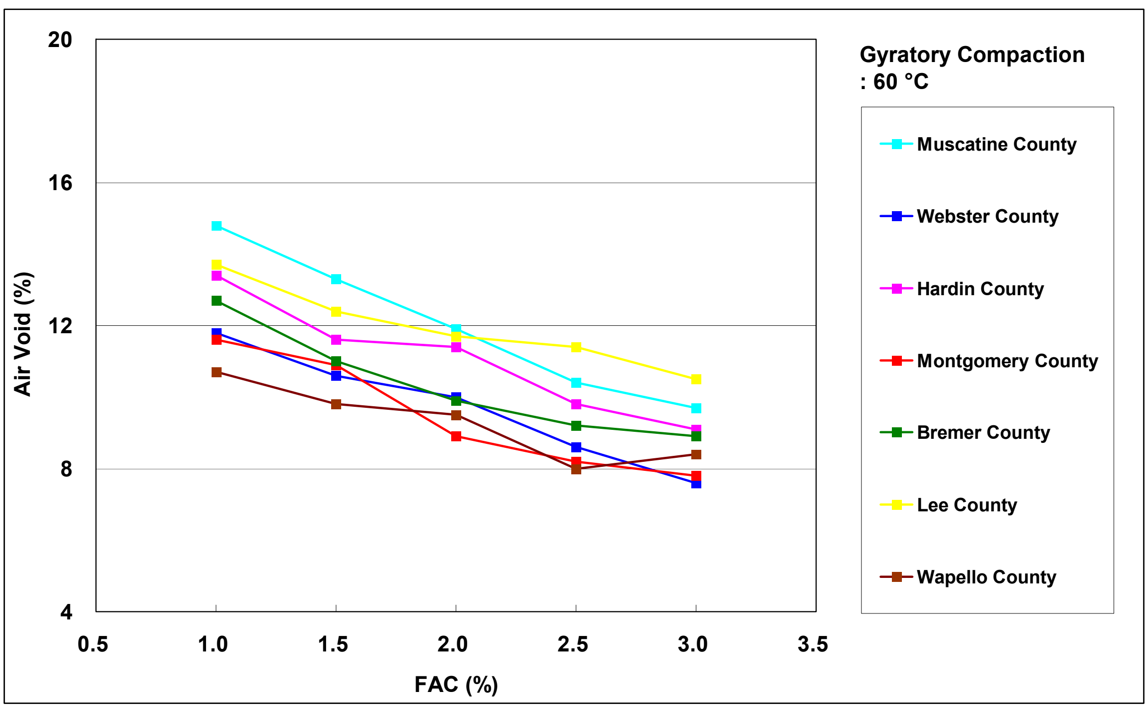


Figure 7-11. Air void of gyratory compacted specimens against FAC (60°C)

7.4 Wet Indirect Tensile Strength

For the Indirect tensile test, a total of 10 specimens were prepared for each RAP source: 1) three for Marshall hammer compacted and cured at 40˚C for three days, 2) three for Marshall hammer compacted and cured at 60˚C for two days, 3) two for gyratory compacted and cured at 40˚C for three days and 4) two for gyratory compacted and cured at 60˚C for two days. After oven curing, the specimens were allowed to cool to room temperature. This normally took about 2 hours, but it was reduced to 15 minutes if a fan was used. Specimens were placed in 25˚C water for 30 minutes as shown in Figure 7-12 (a), vacuumed at 20 mmHg for 30 minutes as shown in Figure 7-12 (b), and remained under water for additional 30 minutes as shown in Figure 7-12 (c).

(a) Soaking **(b) Vacuuming** **(c) Soaking**

Figure 7-12. Vacuum saturation procedure for making wet specimens

Tables 7-7 and 7-8 summarize indirect tensile strengths of foamed asphalt specimens compacted by Marshall hammer and gyratory compactor, respectively. The test specimens were prepared using RAP materials from seven sources at five different foamed asphalt contents (1.0%, 1.5%, 2.0%, 2.5% and 3.0%) and cured at two different temperatures (40°C and 60°C). Indirect tensile strengths are plotted against foamed asphalt contents for Marshall hammer compaction at 40°C in Figure 7-13, gyratory compaction at 40°C in Figure 7-14, Marshall hammer compaction at 60°C in Figure 7-15, and gyratory compaction at 60°C in Figure 7-16. As shown in these figures, the indirect tensile strength of the gyratory compacted specimens is higher than that of Marshall hammer compacted specimens. Indirect tensile strength of foamed asphalt specimens cured at 60°C for two days is significantly higher than that of foamed asphalt specimens cured at 40°C for three days. There is a clear peak in indirect strength test results obtained from gyratory compacted specimens cured at 60°C.

Table 7-7. Indirect tensile strength of Marshall compacted foamed asphalt specimens for seven different RAP materials

FAC (%)	1.0 %		1.5 %		2.0 %		2.5 %		3.0 %	
Compaction Method	Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)		Marshall Hammer (75 blows)	
Curing Temperature (°C)	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
RAP Sources	Indirect Tensile Strength (lb/in^2)									
Muscatine County	26.0	37.7	27.9	40.1	30.9	41.5	28.7	39.4	28.1	29.9
Webster County	25.6	40.8	29.9	43.0	28.0	45.8	27.7	43.5	27.1	42.6
Hardin County	24.4	38.0	25.9	42.5	31.3	44.9	30.3	43.2	28.3	42.2
Montgomery County	27.1	40.7	30.2	44.2	28.0	42.0	27.4	40.5	26.0	35.5
Bremer County	25.5	34.6	26.4	35.5	26.7	39.3	28.6	37.4	26.3	36.9
Lee County	25.7	33.3	26.5	37.0	27.4	37.8	28.7	39.2	27.6	36.9
Wapello County	28.8	40.6	34.5	48.7	31.3	46.7	29.2	40.9	29.2	38.1

Table 7-8. Indirect tensile strength of gyratory compacted foamed asphalt specimens for seven different RAP materials

FAC (%)	1.0 %		1.5 %		2.0 %		2.5 %		3.0 %	
Compaction Method	Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)		Gyratory Compactor (30 Gyrations)	
Curing Temperature (°C)	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
RAP Sources	Indirect Tensile Strength (lb/in^2)									
Muscatine County	29.7	43.0	33.2	51.2	37.6	56.3	36.8	50.6	33.6	48.5
Webster County	28.2	43.1	29.8	46.9	31.2	49.2	32.0	47.3	29.0	44.3
Hardin County	32.2	48.8	40.9	50.6	44.1	52.7	40.2	48.0	39.0	47.5
Montgomery County	31.1	48.2	33.8	55.2	33.3	48.5	32.3	44.4	31.7	42.6
Bremer County	25.6	41.3	26.9	48.7	29.3	52.1	31.0	46.1	28.6	45.1
Lee County	26.3	45.7	30.8	48.8	31.7	52.4	31.4	45.3	31.0	40.2
Wapello County	29.2	41.4	34.9	52.7	35.0	49.0	33.2	45.3	32.8	41.1

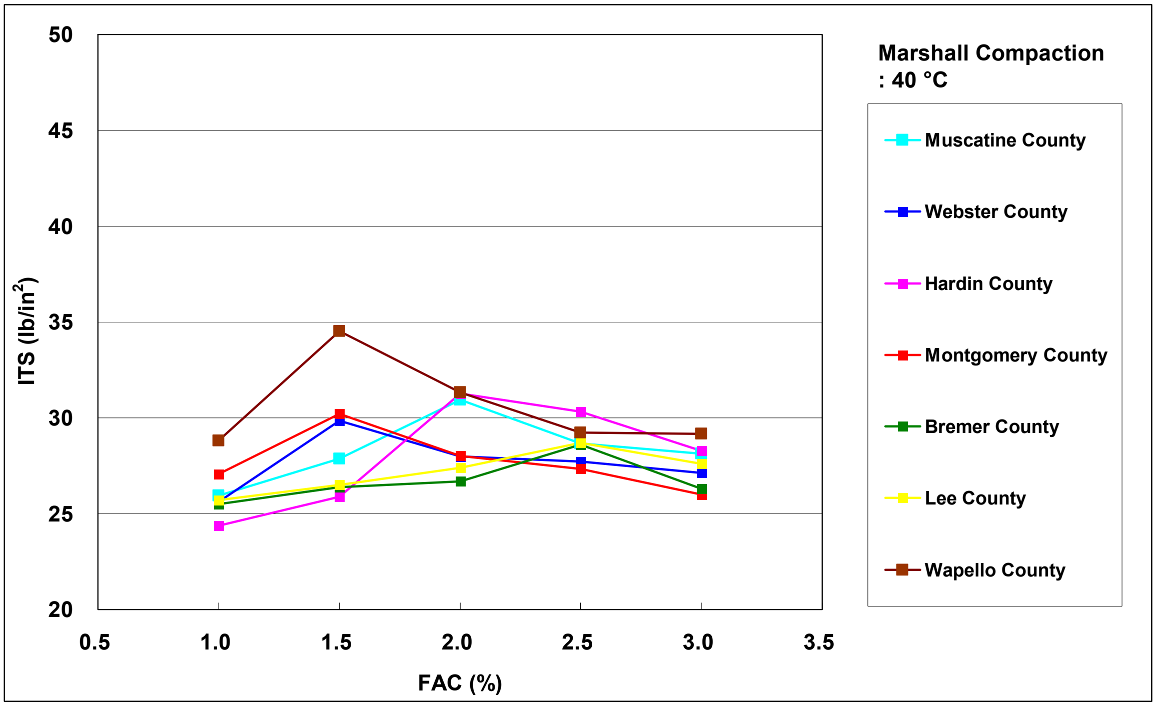


Figure 7-13. ITS of Marshall compacted foamed asphalt specimens (40°C)

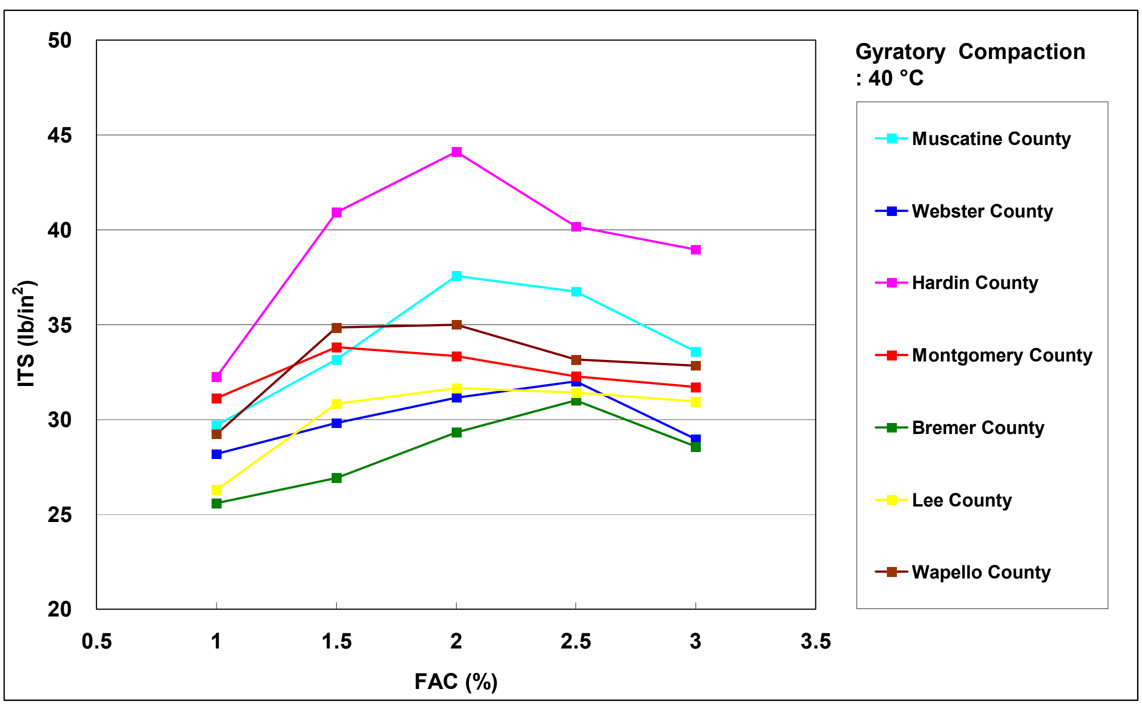


Figure 7-14. ITS of gyratory compacted foamed asphalt specimens (40°C)

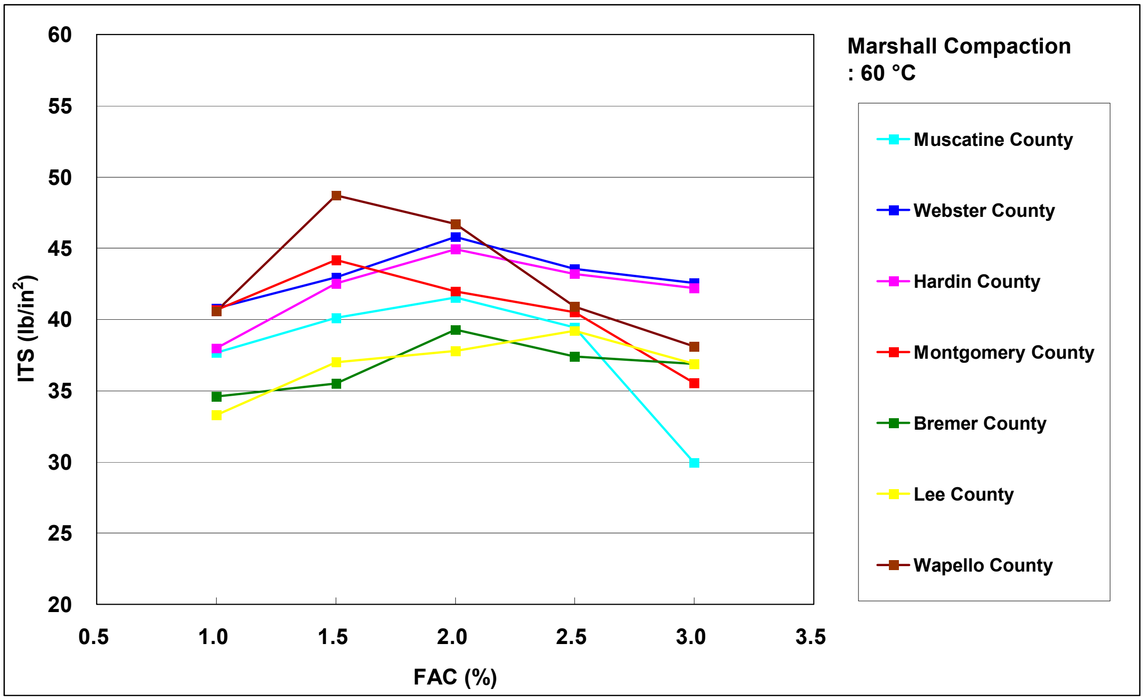


Figure 7-15. ITS of Marshall compacted foamed asphalt specimens (60°C)

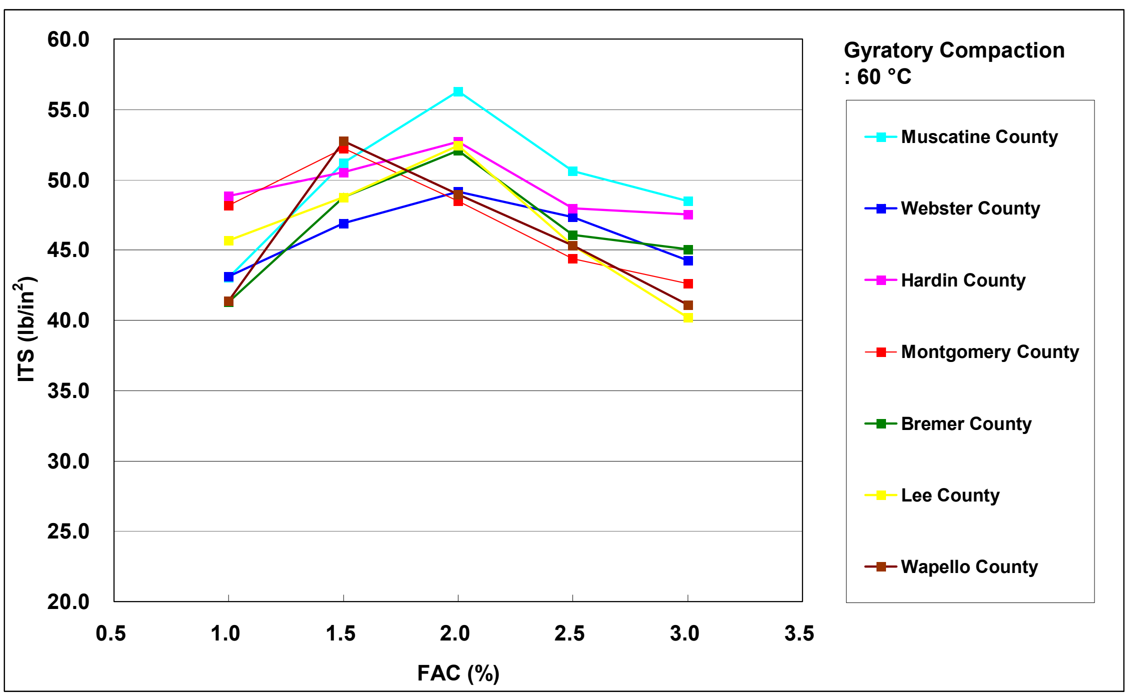


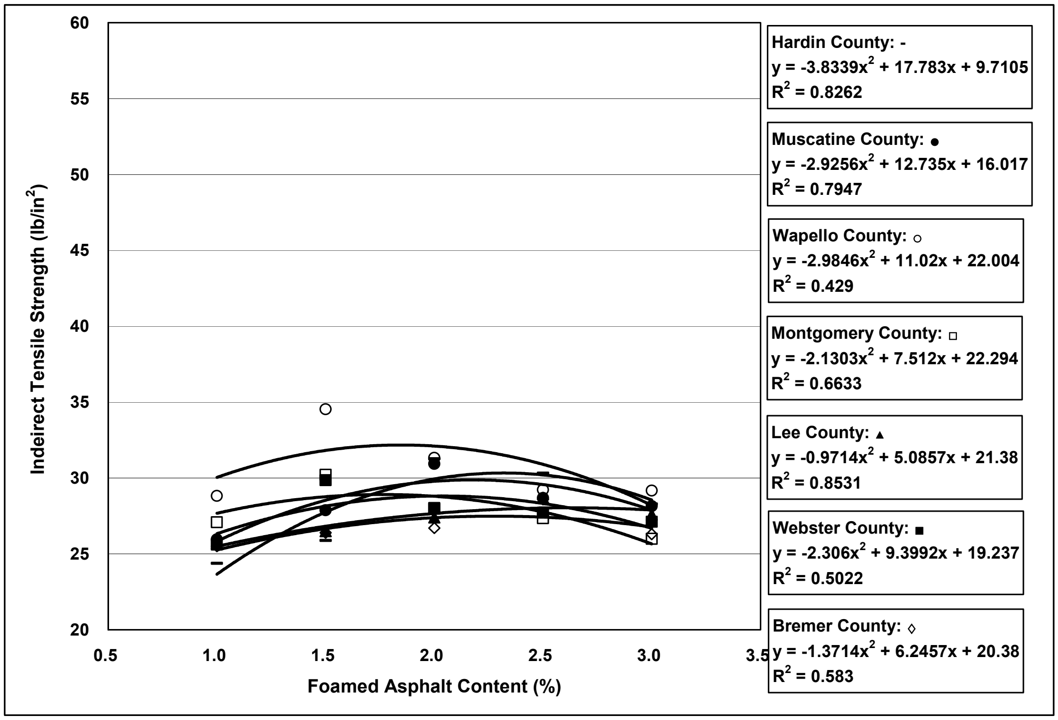
Figure 7-16. ITS of gyratory compacted foamed asphalt specimens (60°C)

7.5 Correlations between OFAC and RAP Characteristics

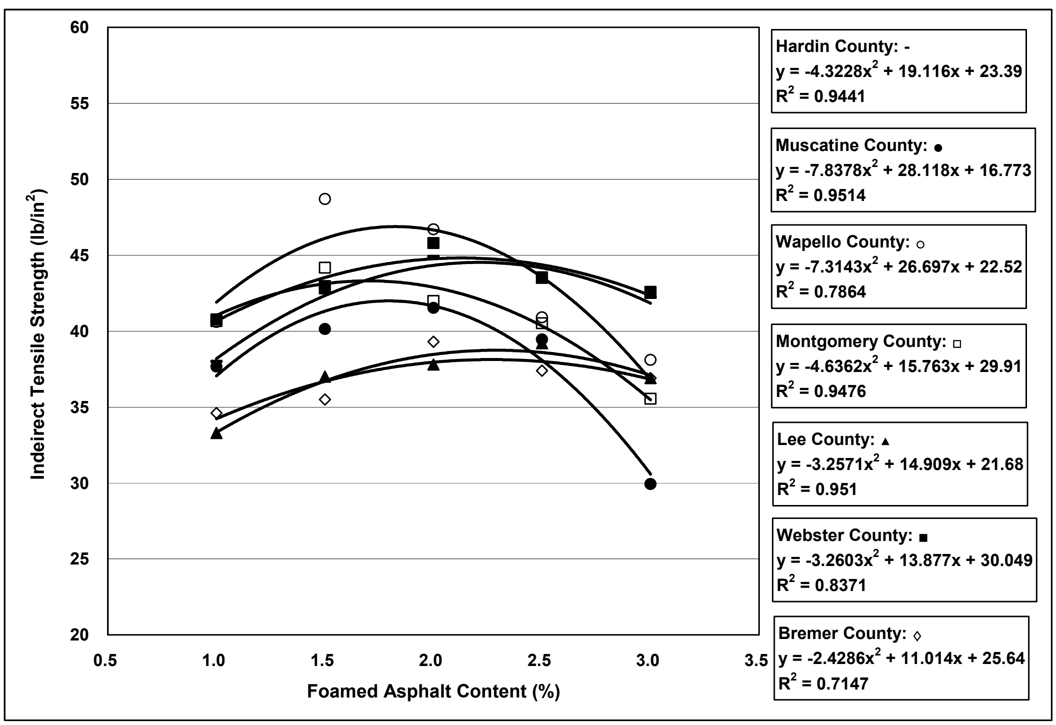
The indirect tensile strength test on vacuum-saturated specimens was conducted using these RAP materials at five foamed asphalt contents, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%, given a fixed moisture content of 4.0%. The specimens compacted by gyratory compactor at 30 gyrations and by Marshall hammer at 75 blows were prepared and they were cured at 40°C oven for three days and 60°C for two days, respectively. The indirect tensile strength of gyratory compacted and vacuum-saturated specimens was more sensitive to foamed asphalt contents than that of Marshall compacted and vacuum-saturated specimens. The indirect tensile strength of CIR-foam specimens cured for two days at 60°C oven was significantly higher than that of CIR-foam specimens cured for three days at 40°C oven.

The optimum foamed asphalt content was determined when the highest indirect tensile strength of vacuum saturated specimens was obtained. Based on the test results, neither air voids nor flat and elongation characteristics of RAP materials affected the indirect tensile strength of the CIR-foam mixtures.

Attempts were made to discover a correlation between foamed asphalt content and RAP characteristics such as residual asphalt stiffness and residual asphalt content. As shown in Figures 7-17 and 7-18, the optimum foamed asphalt content (OFAC) was determined based on a polynomial regression equation and the results are summarized in Table 7-9. A higher OFAC value was obtained from the RAP materials containing large amount of hard residual asphalt. As shown in Figure 7-19 and Figure 7-21, a strong correlation between OFAC and stiffness of residual asphalt exhibits, but no correlation between OFAC and residual asphalt contents.

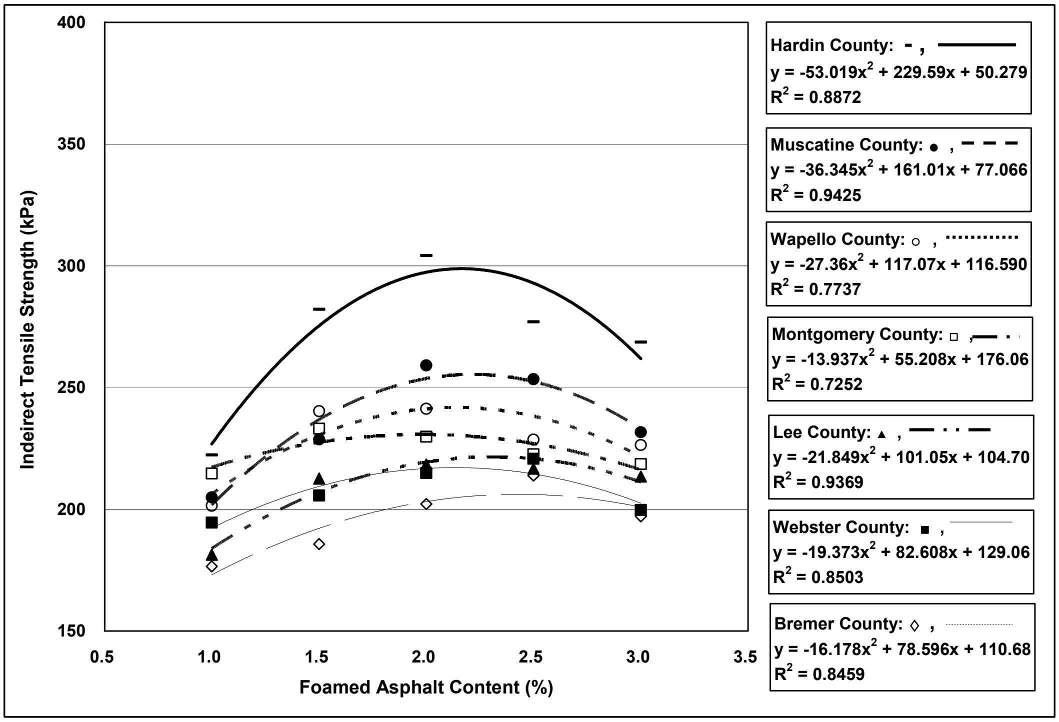


(a) Curing condition: three days at 40°C oven

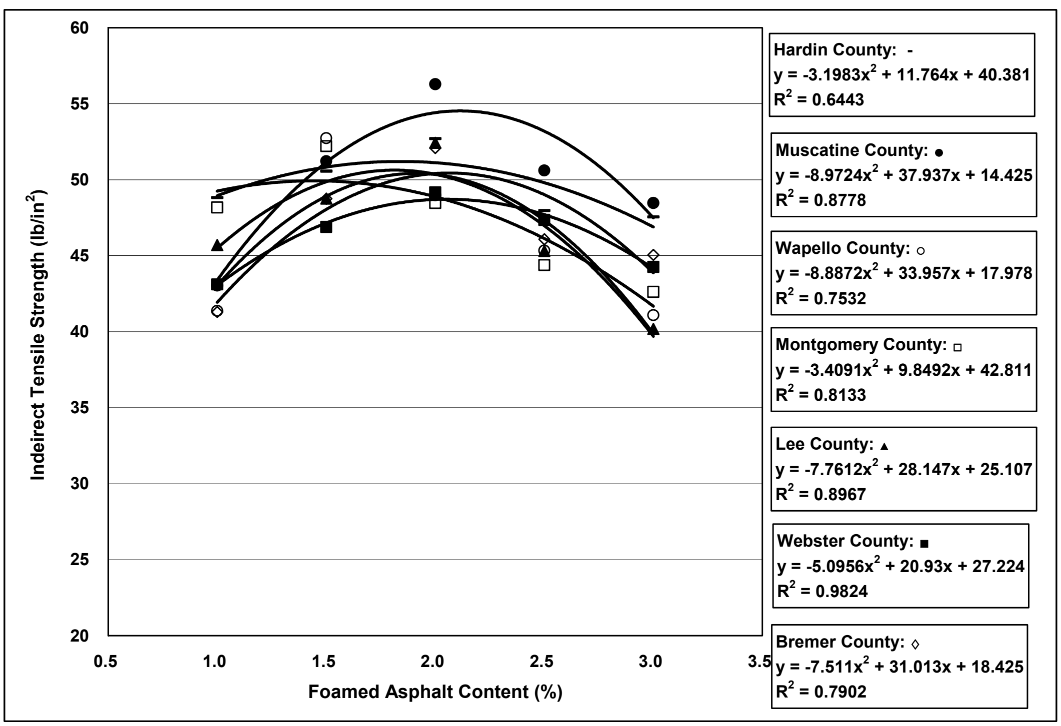


(b) Curing condition: two days at 60°C oven

Figure 7-17. Indirect tensile strength against foamed asphalt content (Marshall hammer compacted specimens)



(a) Curing condition: three days at 40°C oven

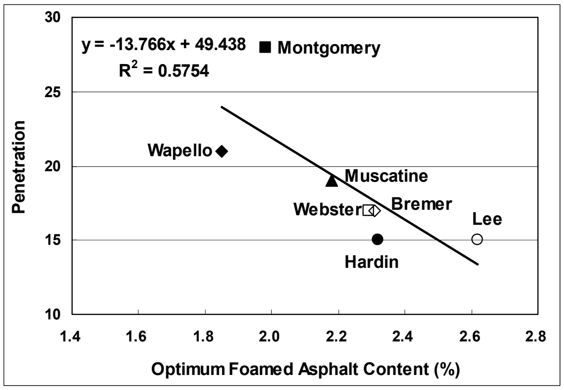


(b) Curing condition: two days at 60°C oven

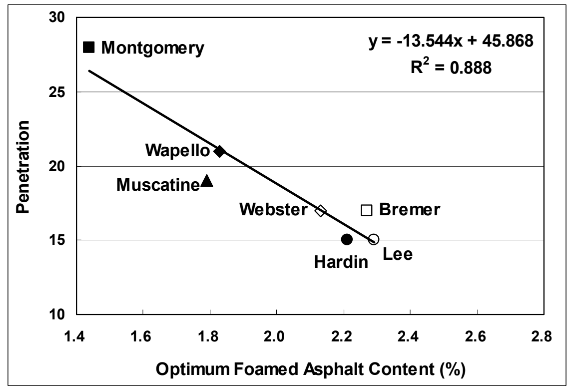
Figure 7-18. Indirect tensile strength against foamed asphalt content (Gyratory compacted specimens)

Table 7-9. Summary of RAP characteristics and optimum foamed asphalt contents

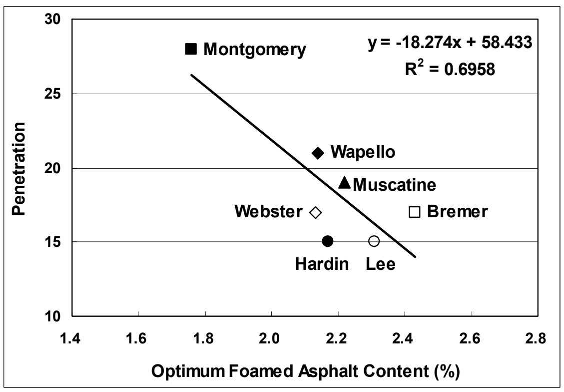
Source	Stiffness (Pen.)	Residual AC (%)	Compaction Method	Curing Temperature (°C)	Maximum ITS (psi)	Optimum FAC (%)
Montgomery	Soft (28)	High (5.7)	Marshall	40	28.9	1.98
				60	43.3	1.44
			Gyratory	40	33.5	1.76
				60	49.9	1.70
Wapello	Soft (21)	Low (4.6)	Marshall	40	32.2	1.85
				60	46.9	1.83
			Gyratory	40	35.1	2.14
				60	50.4	1.91
Muscatine	Soft (19)	Low (4.7)	Marshall	40	29.9	2.18
				60	42.0	1.79
			Gyratory	40	37.0	2.22
				60	54.5	2.11
Webster	Hard (17)	High (6.0)	Marshall	40	30.1	2.31
				60	44.8	2.13
			Gyratory	40	31.5	21.3
				60	48.7	2.05
Bremer	Hard (17)	Low (5.0)	Marshall	40	27.5	2.29
				60	38.1	2.27
			Gyratory	40	29.9	2.43
				60	50.4	2.06
Hardin	Hard (15)	High (6.1)	Marshall	40	30.3	2.32
				60	44.5	2.21
			Gyratory	40	43.3	2.17
				60	51.2	1.84
Lee	Hard (15)	Low (5.4)	Marshall	40	28.0	2.62
				60	38.7	2.29
			Gyratory	40	32.1	2.31
				60	50.6	1.81



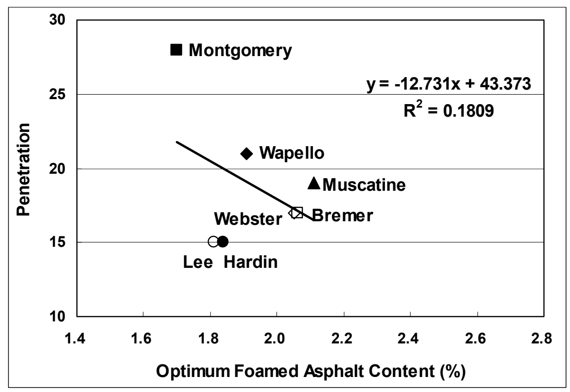
(a) Marshall compaction (40˚C)



(b) Marshall compaction (60˚C)

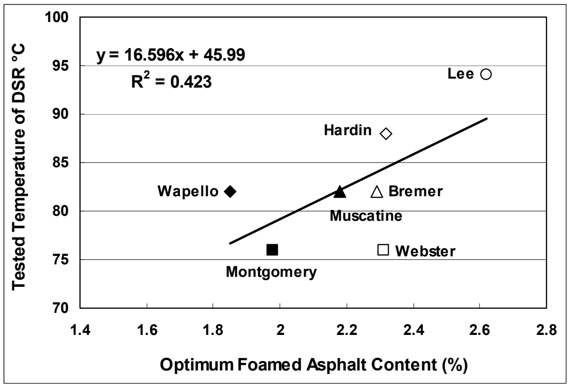


(c) Gyratory compaction (40˚C)

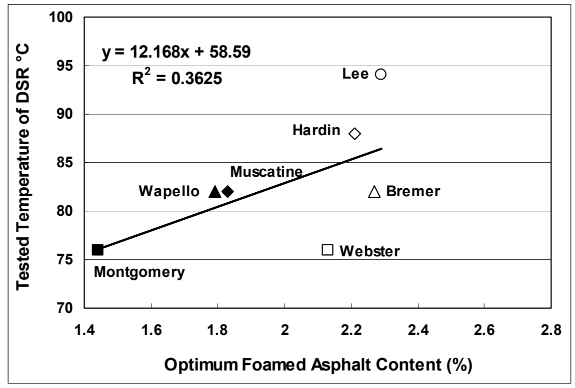


(d) Gyratory compaction (60˚C)

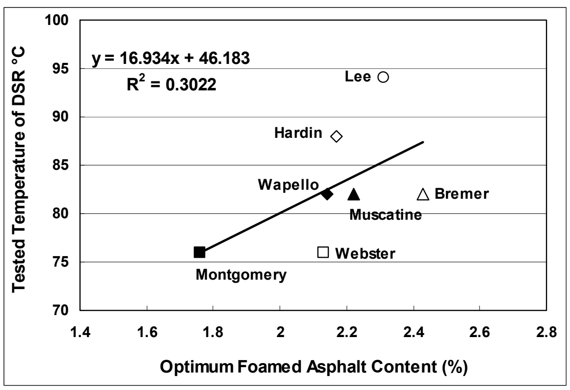
Figure 7-19. Correlations between optimum foamed asphalt content and residual asphalt stiffness



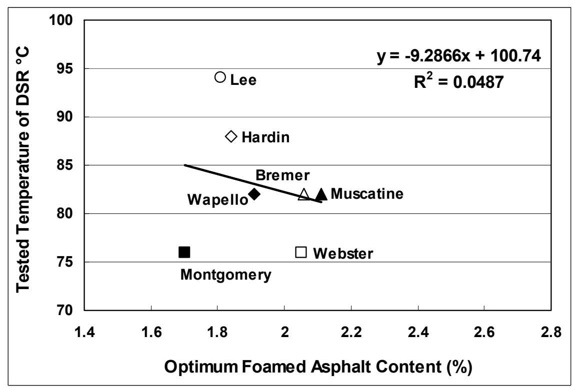
(a) Marshall compaction (40˚C)



(b) Marshall compaction (60˚C)

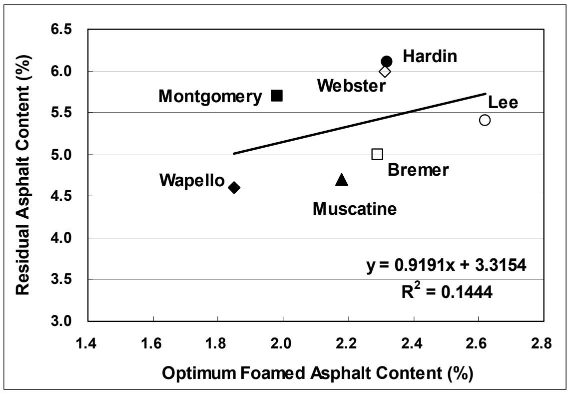


(c) Gyratory compaction (40˚C)

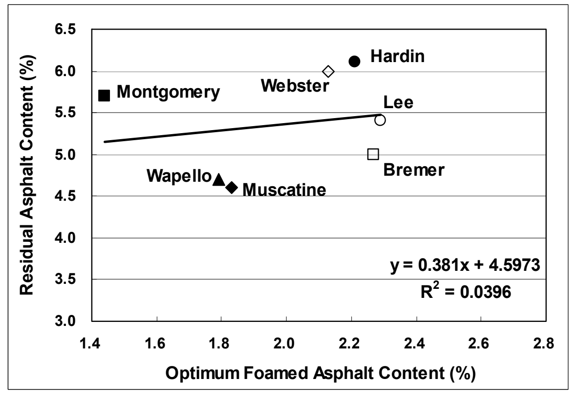


(d) Gyratory compaction (60˚C)

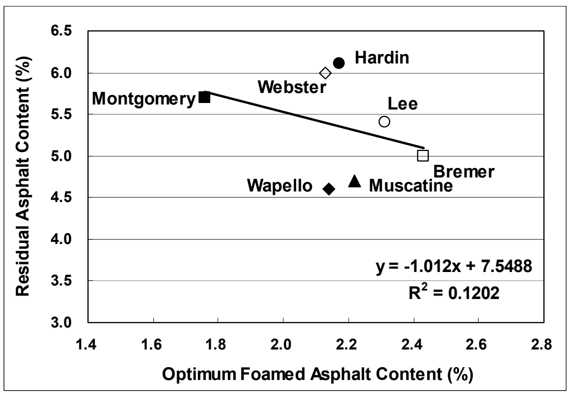
Figure 7-20. Correlations between optimum foamed asphalt content and testing temperature of DSR



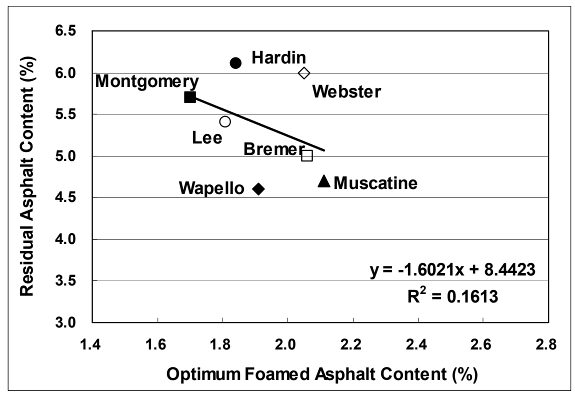
(a) Marshall compaction (40˚C)



(b) Marshall compaction (60˚C)



(c) Gyratory compaction (40˚C)



(d) Gyratory compaction (60˚C)

Figure 7-21. Correlations between optimum FAC content and residual asphalt content

7.6 Equivalent Number of Gyrations for 75-blow Marshall

Bulk specific gravities of the 75-blow Marshall specimens were correlated with those of the gyratory compacted specimens. As shown in Table 7-10, the equivalent number of gyrations was then identified, which would achieve the same specific gravity of the 75-blow Marshall specimens. As shown in Table 7-10**,** the equivalent number gyrations of foamed asphalt specimens cured at 40°C is higher than that of foamed asphalt specimens cured at 60°C. For example, if the curing temperature increases from 40°C to 60°C, the equivalent number of gyration should be lowered from 30 to 25. As shown in Table 7-10, for specimens cured at 40°C, RAP materials from Wapello County required the highest number of gyrations up to 31-49 whereas those from Muscatine

County required the lowest number of gyrations down to 17-26.

Table 7-10. Number of gyrations at three FAC contents and two curing temperatures

RAP Sources / FAC	Muscatine County		Webster County		Hardin County		Montgomery County	
	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
1.0 %	24 gyrations =75 blows	19-20 gyrations =75 blows	42-44 gyration =75 blows	32 gyrations =75 blows	29 gyrations =75 blows	21-23 gyrations =75 blows	33-34 gyrations =75 blows	20 gyrations =75 blows
1.5 %	20-22 gyrations =75 blows	16-22 gyrations =75 blows	42-44 gyrations =75 blows	28-37 gyrations =75 blows	28-30 gyrations =75 blows	18-22 gyrations =75 blows	30-35 gyrations =75 blows	21-23 gyrations =75 blows
2.0 %	22-26 gyrations =75 blows	16-17 gyrations =75 blows	34-44 gyrations =75 blows	31-36 gyrations =75 blows	23-29 gyrations =75 blows	19-20 gyrations =75 blows	25-27 gyrations =75 blows	14-17 gyrations =75 blows
2.5 %	19-23 gyrations =75 blows	15-18 gyrations =75 blows	27-32 gyrations =75 blows	23 -30 gyrations =75 blows	28-30 gyrations =75 blows	21-28 gyrations =75 blows	21-22 gyrations =75 blows	16-18 gyrations =75 blows
3.0 %	17-21 gyrations =75 blows	13 gyrations =75 blows	29 gyrations =75 blows	24-25 gyrations =75 blows	19-20 gyrations =75 blows	21-26 gyrations =75 blows	16-19 gyrations =75 blows	15-18 gyrations =75 blows
Average	17-26 gyrations	13-22 gyrations	27-44 gyrations	23-36 gyrations	23-30 gyrations	18-28 gyrations	16-35 gyrations	14-23 gyrations

RAP Sources / FAC	Bremer County		Lee County		Wapello County	
	40 °C	60 °C	40 °C	60 °C	40 °C	60 °C
1.0 %	33-34 gyrations =75 blows	29-35 gyrations =75 blows	34-38 gyrations =75 blows	31-37 gyrations =75 blows	39-43 gyrations =75 blows	26-28 gyrations =75 blows
1.5 %	23-30 gyrations =75 blows	23-26 gyrations =75 blows	36-39 gyrations =75 blows	30-36 gyrations =75 blows	41-49 gyrations =75 blows	28-35 gyrations =75 blows
2.0 %	24-26 gyrations =75 blows	18-23 gyrations =75 blows	32-36 gyrations =75 blows	25-30 gyrations =75 blows	32-40 gyrations =75 blows	28-31 gyrations =75 blows
2.5 %	21-34 gyrations =75 blows	15-18 gyrations =75 blows	33-40 gyrations =75 blows	24-28 gyrations =75 blows	31-35 gyrations =75 blows	19-27 gyrations =75 blows
3.0 %	18-24 gyrations =75 blows	16-17 gyrations =75 blows	31-36 gyrations =75 blows	20-21 gyrations =75 blows	35-39 gyrations =75 blows	30-32 gyrations =75 blows
Average	18-34 gyrations	15-35 gyrations	31-40 gyrations	20-37 gyrations	31-49 gyrations	19-35 gyrations

8. PERFOMANCE PREDICTION OF MIX DESIGN USING SIMPLE PERFORMANCE TESTS

This task describes the laboratory experiments conducted for evaluating the performance characteristics of CIR-foam mixtures. The simple performance tests, which include dynamic modulus test, dynamic creep test and raveling test, were adopted to evaluate the consistency of a new CIR-foam mix design process to ensure reliable mixture performance over a wide range of traffic and climatic conditions. Table 8-1 summarizes testing conditions for three simple performance tests

Table 8-1. Laboratory conditions for three 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, 05Hz, and 0.1Hz
Dynamic Creep Test	• Testing Temperature: 40˚C • Loading Pressure: 138kPa • Applied Loading Cycle: 10,000 cycles
Raveling Test	• Testing Temperature: 25˚C • Curing Period Conditions: at room temperature for 4hrs at room temperature for 8 hrs

8.1 Dynamic Modulus Test

The dynamic modulus test is to determine the stiffness of asphalt mixtures on the response to traffic loading and various climate 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) reported that the mixtures with softer asphalt exhibited the lower dynamic modulus than those with stiffer asphalt. Ekingen (2004) also found that the dynamic modulus was sensitive to the asphalt viscosity of mixtures. Brown et al. (2004, 2005) measured the dynamic modulus of asphalt mixtures with various aggregate structures but did not find a relationship between the dynamic modulus values and the aggregate structures that would indicate rutting potential of mixtures. On the contrary, Birgisson et al. (2004) reported that there was a significant effect of gradation on dynamic modulus measurements such that both fine-graded and coarse graded mixtures showed high dynamic modulus values. Lundy and Sandoval-Gil et al. (2005) found that the dynamic modulus would be similar if the aggregate structures are similar. However, the mixtures with PG 76-22 binder consistently exhibited the highest modulus, PG 70-28 was next and PG 64-22 was the lowest.

8.1.1 Theory

The fundamental concept behind the dynamic modulus test is a linear viscoelasticity of asphalt mixtures. The stress to strain relationship under a continuous sinusoidal loading for linear viscoelastic materials is defined by a complex number called complex modulus, where its absolute value is defined as the dynamic modulus as shown in Figure 8-1. The dynamic modulus is mathematically defined as the maximum dynamic stress (σ_0) divided by peak recoverable axial strain (ε_0) as follows:

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

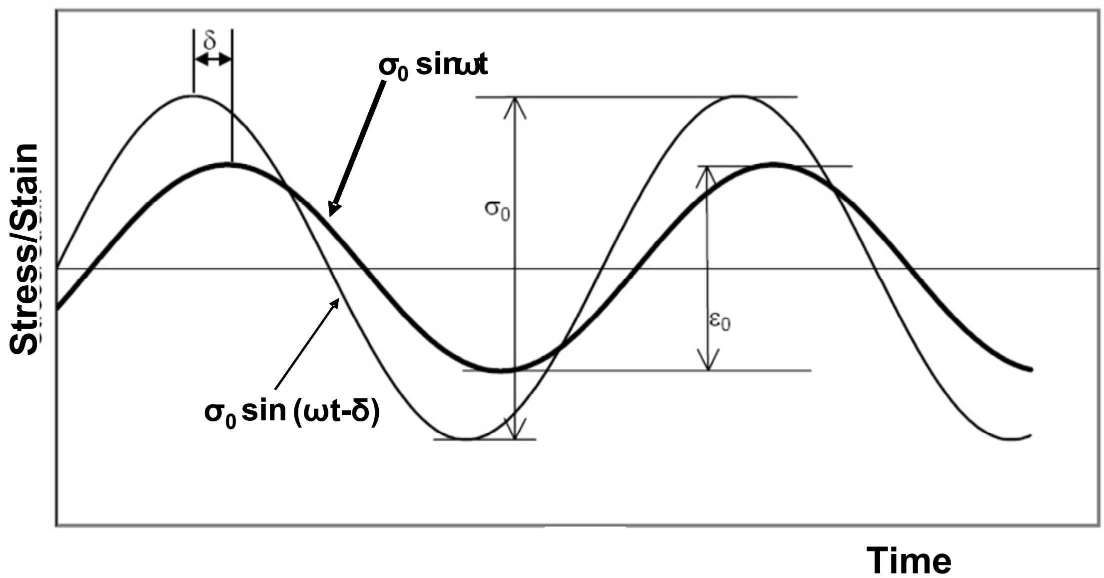


Figure 8-1. Testing components of the dynamic modulus

Based on current practice, dynamic modulus test of asphalt pavement materials is conducted on unconfined or confined cylindrical specimens and uses a uniaxially applied sinusoidal (haversine) stress pattern. Under such conditions, the sinusoidal stress at any given time t, is given as:

$$\sigma_t = \sigma_0 \sin(\omega t)$$

where

σ_0 = peak dynamic stress amplitude (psi);
ω = angular frequency in radian per second;
t = time (sec).

The subsequent dynamic strain at any given time is given by:

$$\varepsilon_t = \varepsilon_0 \sin(\omega t - \varphi)$$

where

ε_0 = peak recoverable strain (in/in);
φ = phase lag or angle (deg.).

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 conduct dynamic modulus test, dynamic creep (flow number) test and static creep (flow time) test at the various temperature and loading conditions. As shown in Figure 8-2, the test specimen is easy to access from all sides when the temperature and pressure vessel is at the open position. Also, this system utilizes a magnetic mounted extensometer, which snaps on the test specimen with minimum disruption to temperature control. A stand-alone environmental unit can provide heated and refrigerated air to the environmental test chamber. Using the environmental chamber, the foamed asphalt specimens are tested at 4˚C and 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 simple performance 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 research, however, the gyratory compacted CIR-foam specimens with 100-mm diameter and 150-mm height were prepared for dynamic modulus test and dynamic creep test because CIR-foam specimens were not sufficiently strong enough to be cored from 150mm-diameter CIR-foam specimens.

In order to perform dynamic modulus test on CIR-foam mixtures, the standard "AASHTO TP 62-03 protocol: Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures" 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. At the low temperature, the dynamic modulus for CIR-foam specimens is large and it is easy to control the applied axial force to obtain the axial strain at 100 microstrain. At the high temperature, however, CIR-foam specimens become soft and it is very difficult to control the applied axial force to obtain the axial strain at 100 microstrain. To minimize a potential damage to the test 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. Two Linear Variable Displacement Transducers (LVDT's) were installed using a glued gauge point system to measure strains on the specimen over a gauge of 70 mm ± 1 mm at the middle of the specimen. As show in Figure 8-3, two transducers were spaced equally around the circumference of the specimen. To begin testing, LVDT's were adjusted to near to the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation. A minimum contact load equal to 5% of the dynamic load was applied to the specimen. As shown in Table 8-2, a sinusoidal axial compressive load was applied to CIR-foam specimen while maintaining the axial strain at 100 microstrain. The test results during the last ten cycles were recorded for each frequency.

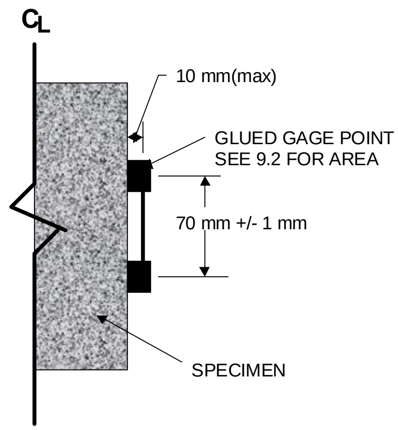


Figure 8-3. Glued magnetic gauge points placed on both sides SPT specimen

Table 8-2. Loading cycles for dynamic modulus test sequence

Frequency (Hz)	Number of Cycles
25	200
10	200
5	100
1	20
0.5	15
0.1	15

8.1.3 Experimental Plan

CIR-foam specimens were prepared to measure the dynamic modulus using seven different RAP sources. As summarized in Table 8-3, the mix design parameters identified in the validation task were used to prepare each test specimen. For each RAP source, two specimens with 100-mm diameter and 150-mm height were prepared for each of three foamed asphalt contents. A total of six CIR-foam specimens were compacted using the gyratory compactor at 30 gyrations and the compacted CIR-foam specimens were cured in the oven at 40°C for three days.

Table 8-3. Design parameters selected for SPT specimens

Parameters	Condition
Foaming temperature	170˚C
Foaming water content	1.3 %
Foaming asphalt type	PG 52-34
Foaming asphalt content	1.0%, 2.0%, and 3.0%
Moisture content	4.0%
Compaction method	gyratory compaction applied 30gyration
Curing condition	at 40˚C oven for 72 hours
Number of Specimen	2 specimens at each foamed asphalt content

8.1.4 Results and Discussion

The bulk specific gravities and air voids were measured for each CIR-foam specimen. The dynamic modulus tests were performed to determine:

1. variations in dynamic modulus values among seven different RAP sources;
2. effect of the foamed asphalt content on dynamic modulus;
3. effect of test temperature and loading frequency on dynamic modulus; and
4. correlation between dynamic modulus and RAP material characteristics.

8.1.4.1 Volumetric Characteristics

The bulk specific gravities and air voids of each CIR-foam specimen were determined following the AASHTO T 166 by measuring the dry mass and height. As summarized in Table 8-4, overall, the bulk specific gravities seemed to increase as the foamed asphalt content increased. RAP materials from Hardin County showed the lowest bulk specific gravity where as those from Wapello County showed highest bulk specific gravity. Air voids decreased gradually as the foamed asphalt content increased.

Table 8-4. Bulk specific gravities (G_{mb}) and air voids of CIR-foam specimens prepared for dynamic modulus test

RAP Source	FAC (%)	G_{mb} Individual		G_{mb} Average	G_{mm}	Air Void (%) Individual	Air Void (%) Average
Hardin County	1.0	# 1 # 2	2.023 2.024	2.024	2.388	15.3 15.2	15.3
	2.0	# 1 # 2	2.056 2.058	2.057	2.362	13.0 12.9	13.0
	3.0	# 1 # 2	2.057 2.065	2.061	2.343	12.2 11.9	12.1
Lee County	1.0	# 1 # 2	2.076 2.068	2.072	2.452	15.3 15.7	15.5
	2.0	# 1 # 2	2.103 2.094	2.099	2.422	13.2 13.6	13.4
	3.0	# 1 # 2	2.117 2.121	2.119	2.410	12.2 12.0	12.1
Webster County	1.0	# 1 # 2	2.067 2.048	2.058	2.411	14.3 15.1	14.7
	2.0	# 1 # 2	2.098 2.092	2.095	2.391	12.3 12.5	12.4
	3.0	# 1 # 2	2.122 2.085	2.104	2.358	10.0 11.6	10.8
Bremer County	1.0	# 1 # 2	2.092 2.107	2.100	2.442	14.3 13.7	14.0
	2.0	# 1 # 2	2.120 2.129	2.125	2.416	12.2 11.9	12.1
	3.0	# 1 # 2	2.155 2.158	2.157	2.396	10.1 9.9	10.0
Wapello County	1.0	# 1 # 2	2.114 2.092	2.103	2.459	14.0 14.9	14.5
	2.0	# 1 # 2	2.149 2.122	2.136	2.444	12.1 13.2	12.7
	3.0	# 1 # 2	2.152 2.112	2.132	2.411	10.7 12.4	11.6
Montgomery County	1.0	# 1 # 2	2.058 2.080	2.069	2.432	15.0 15.3	15.2
	2.0	# 1 # 2	2.097 2.096	2.097	2.375	11.7 11.8	11.8
	3.0	# 1 # 2	2.141 2.108	2.125	2.358	9.2 10.6	9.9
Muscatine County	1.0	# 1 # 2	2.071 2.073	2.072	2.464	15.9 15.9	15.9
	2.0	# 1 # 2	2.077 2.073	2.075	2.445	15.1 15.2	15.2
	3.0	# 1 # 2	2.130 2.133	2.132	2.413	11.7 11.6	11.7

8.1.4.2 Dynamic Modulus Test Results

The dynamic modulus tests were performed on CIR-foam mixtures at six different loading frequencies and three different test temperatures. The dynamic modulus was measured from each specimen twice. Table 8-5 to Table 8-11 summarize the average dynamic moduli of seven RAP sources measured for three different foamed asphalt contents. Table 8-12 summarizes the rankings of dynamic modulus at three different foamed asphalt contents for seven RAP sources. As can be easily observed from table, the rankings of RAP materials changed when the foamed asphalt was increased from 1.0% to 3.0%, which indicates that the dynamic modulus values are affected by both foamed asphalt contents and RAP aggregate structure. Based on the dynamic modulus test results performed at 4.4˚C, the coarser RAP materials were more resistant to fatigue cracking. Based on the dynamic modulus test results performed at 37.8˚C, the finer RAP materials with the harder binder with a higher amount were more resistant to rutting.

Table 8-5. Summary of dynamic moduli of CIR-foam mixtures from Hardin County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,081,420	6,882,529	6,981,974	4,440,067	4,469,904	4,454,985	2,019,063	1,991,481	2,005,272
10	6,479,614	6,202,243	6,340,929	3,709,922	3,801,794	3,755,858	1,766,071	1,687,017	1,726,544
5	5,944,728	5,679,646	5,812,187	3,120,247	3,289,965	3,205,106	1,482,976	1,394,910	1,438,943
1	4,607,879	4,447,881	4,527,880	2,133,153	2,271,020	2,202,086	1,010,656	968,929	989,792
0.5	4,142,827	4,034,176	4,088,502	1,722,972	1,938,874	1,830,923	825,888	805,872	815,880
0.1	3,271,972	3,191,779	3,231,875	1,212,218	1,427,320	1,319,769	575,419	591,681	583,550
Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,328,866	8,289,288	8,309,077	4,093,888	4,616,356	4,355,122	1,927,713	2,078,862	2,003,287
10	7,370,456	7,559,750	7,465,103	3,467,142	3,981,662	3,724,402	1,572,530	1,743,027	1,657,778
5	6,716,530	6,949,067	6,832,798	3,007,286	3,446,466	3,226,876	1,274,460	1,444,418	1,359,439
1	5,244,260	5,418,258	5,331,259	2,225,858	2,364,752	2,295,305	858,206	1,025,249	941,727
0.5	4,692,030	4,886,296	4,789,163	1,771,231	1,988,443	1,879,837	715,161	850,929	783,045
0.1	3,607,188	3,810,151	3,708,669	1,259,889	1,396,511	1,328,200	517,118	633,704	575,411
Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,307,780	8,160,588	8,234,184	3,875,405	3,919,275	3,897,340	1,596,872	1,570,777	1,583,825
10	7,354,225	7,231,677	7,292,951	3,135,414	3,298,013	3,216,713	1,339,527	1,261,872	1,300,700
5	6,594,005	6,554,761	6,574,383	2,631,001	2,778,878	2,704,940	1,088,474	1,036,452	1,062,463
1	4,910,642	4,915,396	4,913,019	1,718,679	1,825,241	1,771,960	717,379	695,270	706,324
0.5	4,319,949	4,329,230	4,324,589	1,386,742	1,488,658	1,437,700	584,125	569,888	577,006
0.1	3,185,064	3,241,616	3,213,340	915,600	979,951	947,775	443,903	410,256	427,080

Table 8-6. Summary of dynamic moduli of CIR-foam mixtures from Lee County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,842,629	8,095,422	7,969,025	4,204,950	4,287,050	4,246,000	2,088,770	1,838,019	1,963,395
10	6,801,359	7,174,036	6,987,698	3,472,310	3,397,758	3,435,034	1,761,683	1,569,674	1,665,678
5	6,258,756	6,616,345	6,437,550	2,966,847	2,881,232	2,924,039	1,479,187	1,319,012	1,399,099
1	4,872,456	5,182,481	5,027,468	1,976,252	1,885,010	1,930,631	975,633	866,822	921,227
0.5	4,364,029	4,644,829	4,504,429	1,673,346	1,538,702	1,606,024	803,379	700,852	752,116
0.1	3,487,061	3,733,048	3,610,054	1,171,406	1,066,794	1,119,100	582,749	513,527	548,138
Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,808,436	7,423,043	7,615,739	4,370,489	3,843,038	4,106,763	2,140,287	1,961,838	2,051,062
10	7,067,300	6,676,568	6,871,934	3,718,580	3,083,954	3,401,267	1,883,105	1,666,301	1,774,703
5	6,429,540	6,020,827	6,225,184	3,141,815	2,565,236	2,853,526	1,559,552	1,306,611	1,433,081
1	4,857,811	4,553,435	4,705,623	2,013,994	1,607,752	1,810,873	1,065,031	879,213	972,122
0.5	4,334,531	4,070,927	4,202,729	1,655,937	1,276,548	1,466,242	866,395	706,915	786,655
0.1	3,350,929	3,176,529	3,263,729	1,141,204	923,300	1,032,252	645,901	498,631	572,266
Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	7,627,337	7,973,660	7,800,498	4,056,574	4,363,503	4,210,038	1,871,714	1,912,584	1,892,149
10	6,587,986	7,022,607	6,805,296	3,422,826	3,439,640	3,431,233	1,546,263	1,579,887	1,563,075
5	5,875,698	6,295,337	6,085,517	2,867,346	2,810,012	2,838,679	1,244,497	1,289,997	1,267,247
1	4,273,706	4,641,009	4,457,358	1,815,580	1,681,338	1,748,459	832,365	879,990	856,177
0.5	3,741,335	4,042,236	3,891,785	1,489,403	1,368,982	1,429,193	669,169	702,661	685,915
0.1	2,794,600	3,034,013	2,914,306	1,016,420	918,484	967,452	495,864	525,871	510,867

Table 8-7. Summary of dynamic moduli of CIR-foam mixtures from Webster County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,233,945	9,012,592	9,123,268	5,696,051	5,687,946	5,691,998	2,427,663	2,527,409	2,477,536
10	8,507,457	8,641,064	8,574,260	4,894,512	5,063,267	4,978,889	2,000,215	2,087,652	2,043,933
5	7,958,213	8,241,050	8,099,631	4,202,011	4,396,795	4,299,403	1,619,352	1,715,053	1,667,202
1	6,715,226	6,572,393	6,643,809	2,716,718	2,885,058	2,800,888	972,348	1,077,532	1,024,940
0.5	6,179,604	6,020,018	6,099,811	2,254,103	2,397,290	2,325,696	791,803	900,277	846,040
0.1	5,010,165	4,838,191	4,924,178	1,523,308	1,691,955	1,607,632	550,738	637,490	594,114

Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	11,096,615	9,949,414	10,523,014	5,316,677	5,349,560	5,333,118	2,641,678	2,613,541	2,627,609
10	10,284,110	9,582,834	9,933,472	4,535,933	4,566,558	4,551,246	2,174,725	2,133,610	2,154,167
5	9,437,728	8,691,609	9,064,668	3,790,675	3,838,895	3,814,785	1,740,136	1,757,311	1,748,724
1	7,455,972	6,991,015	7,223,494	2,537,384	2,506,443	2,521,913	1,066,638	1,050,441	1,058,539
0.5	6,594,284	6,294,626	6,444,455	2,118,743	2,094,933	2,106,838	882,125	856,087	869,106
0.1	5,261,986	5,022,697	5,142,342	1,521,882	1,510,667	1,516,274	634,816	588,836	611,826

Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,743,510	10,203,841	9,973,676	5,200,941	4,959,039	5,079,990	2,168,865	1,832,419	2,000,642
10	8,678,760	9,502,767	9,090,763	4,359,787	4,061,434	4,210,610	1,725,779	1,422,496	1,574,137
5	8,012,725	8,827,272	8,419,998	3,728,916	3,374,908	3,551,912	1,410,653	1,129,722	1,270,187
1	6,069,932	6,912,626	6,491,279	2,372,269	2,084,225	2,228,247	867,961	682,990	775,476
0.5	5,383,310	6,131,524	5,757,417	1,970,677	1,706,951	1,838,814	715,709	579,826	647,768
0.1	4,253,301	4,778,300	4,515,800	1,284,917	1,089,064	1,186,991	514,567	384,558	449,563

Table 8-8. Summary of dynamic moduli of CIR-foam mixtures from Bremer County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,610,538	9,309,709	9,460,124	5,553,410	5,461,658	5,507,534	1,960,906	2,206,189	2,083,548
10	9,002,200	8,591,237	8,796,718	4,691,672	4,670,190	4,680,931	1,620,755	1,857,975	1,739,365
5	8,124,660	7,921,772	8,023,216	4,015,523	4,061,068	4,038,295	1,317,159	1,486,608	1,401,883
1	6,324,759	6,280,479	6,302,619	2,603,546	2,706,821	2,655,183	858,954	943,464	901,209
0.5	5,543,389	5,698,038	5,620,713	2,157,634	2,285,618	2,221,626	764,222	803,669	783,946
0.1	4,437,192	4,612,099	4,524,645	1,448,665	1,622,409	1,535,537	573,970	581,056	577,513
Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,333,059	9,578,862	9,455,961	4,890,695	4,664,566	4,777,631	1,720,225	1,651,787	1,686,006
10	8,460,552	8,654,151	8,557,351	3,965,400	3,703,931	3,834,665	1,408,424	1,299,144	1,353,784
5	7,614,481	7,836,380	7,725,430	3,304,054	3,061,944	3,182,999	1,159,288	1,047,329	1,103,308
1	5,628,056	5,920,801	5,774,428	2,079,879	1,858,087	1,968,983	855,248	755,558	805,403
0.5	5,004,796	5,219,595	5,112,196	1,730,692	1,522,819	1,626,756	743,455	621,307	682,381
0.1	3,841,617	4,018,285	3,929,951	1,162,209	994,039	1,078,124	576,584	492,337	534,461
Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,277,440	9,108,480	8,692,960	4,263,810	4,521,788	4,392,799	1,562,324	1,700,815	1,631,569
10	7,284,399	8,596,083	7,940,241	3,354,443	3,783,587	3,569,015	1,217,351	1,334,032	1,275,692
5	6,413,235	7,247,808	6,830,521	2,749,809	3,132,222	2,941,016	958,390	1,083,537	1,020,963
1	4,557,515	5,397,617	4,977,566	1,623,301	1,925,289	1,774,295	659,248	777,291	718,269
0.5	3,925,297	4,634,924	4,280,110	1,319,593	1,597,714	1,458,653	528,702	620,797	574,749
0.1	2,838,689	3,383,980	3,111,334	810,796	1,023,886	917,341	338,743	443,337	391,040

Table 8-9. Summary of dynamic moduli of CIR-foam mixtures from Wapello County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	10,114,430	9,727,568	9,920,999	5,897,147	5,380,531	5,638,839	2,422,555	2,416,942	2,419,748
10	9,252,723	8,783,376	9,018,049	4,961,430	4,488,652	4,725,041	1,801,687	1,672,314	1,737,001
5	8,444,110	7,966,321	8,205,216	4,188,526	3,795,226	3,991,876	1,436,403	1,341,114	1,388,758
1	6,576,209	6,086,633	6,331,421	2,720,237	2,497,608	2,608,923	903,744	907,553	905,648
0.5	5,829,753	5,435,652	5,632,703	2,225,195	2,106,747	2,165,971	717,712	712,533	715,123
0.1	4,606,384	4,271,682	4,439,033	1,569,527	1,485,016	1,527,271	560,305	558,938	559,622
Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,133,011	9,522,650	9,327,830	5,249,376	5,004,667	5,127,021	2,234,175	2,328,675	2,281,425
10	8,191,954	8,617,649	8,404,801	4,007,652	3,910,745	3,959,198	1,650,379	1,594,379	1,622,379
5	7,348,839	7,706,666	7,527,753	3,301,751	3,231,996	3,266,873	1,353,787	1,303,487	1,328,637
1	5,385,663	5,674,574	5,530,118	2,098,109	2,041,460	2,069,784	919,558	909,898	914,728
0.5	4,717,381	4,829,116	4,773,249	1,665,296	1,588,851	1,627,074	740,995	718,795	729,895
0.1	3,566,702	3,480,166	3,523,434	1,130,068	1,046,453	1,088,260	605,759	560,549	583,154
Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,095,491	9,516,549	9,306,020	4,755,556	4,516,698	4,636,127	2,186,675	2,028,510	2,107,593
10	8,217,179	8,340,146	8,278,663	3,709,024	3,644,131	3,676,577	1,574,379	1,381,907	1,478,143
5	7,405,321	7,520,504	7,462,912	3,063,517	3,011,532	3,037,524	1,257,287	1,136,388	1,196,837
1	5,414,551	5,459,612	5,437,081	1,893,607	1,892,635	1,893,121	919,858	811,800	865,829
0.5	4,717,730	4,691,755	4,704,742	1,487,014	1,402,600	1,444,807	707,495	608,745	658,120
0.1	3,487,415	3,449,236	3,468,325	991,037	956,660	973,848	580,554	501,021	540,788

Table 8-10. Summary of dynamic moduli of CIR-foam mixtures from Montgomery County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,404,362	9,137,074	9,270,718	5,056,753	4,895,169	4,975,961	2,275,395	2,371,335	2,323,365
10	8,674,518	8,245,159	8,459,838	3,989,147	3,983,155	3,986,151	1,677,771	1,735,317	1,706,544
5	7,888,187	7,396,091	7,642,139	3,266,387	3,342,952	3,304,670	1,344,092	1,374,608	1,359,350
1	6,117,000	6,062,416	6,089,708	2,084,513	2,179,652	2,132,082	865,245	848,661	856,953
0.5	5,435,371	5,570,524	5,502,947	1,794,140	1,754,096	1,774,118	691,771	677,582	684,676
0.1	4,321,135	4,314,162	4,317,648	1,132,343	1,156,657	1,144,500	499,894	477,408	488,651

Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	9,107,259	9,847,241	9,477,250	5,075,660	5,005,142	5,040,401	2,089,248	1,969,680	2,029,464
10	8,208,835	8,921,809	8,565,322	4,247,248	4,132,828	4,190,038	1,523,540	1,411,571	1,467,555
5	7,150,044	8,107,139	7,628,591	3,566,746	3,439,459	3,503,103	1,199,555	1,101,231	1,150,393
1	5,411,672	6,137,742	5,774,707	2,258,761	2,150,348	2,204,555	720,882	643,676	682,279
0.5	4,786,098	5,434,700	5,110,399	1,807,112	1,708,512	1,757,812	580,858	539,913	560,385
0.1	3,692,322	4,214,280	3,953,301	1,180,156	1,134,846	1,157,501	396,008	419,998	408,003

Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	8,999,738	9,942,187	9,470,962	4,687,388	4,961,610	4,824,499	1,965,259	1,949,371	1,957,315
10	8,191,768	8,846,596	8,519,182	3,652,661	4,004,698	3,828,679	1,368,075	1,404,269	1,386,172
5	7,396,223	7,894,227	7,645,225	2,942,936	3,333,116	3,138,026	1,064,494	1,083,306	1,073,900
1	5,528,696	5,753,806	5,641,251	1,832,976	2,161,129	1,997,053	618,691	650,837	634,764
0.5	4,870,251	5,066,944	4,968,597	1,392,014	1,651,160	1,521,587	524,431	539,628	532,029
0.1	3,682,269	3,804,409	3,743,339	880,964	1,065,820	973,392	396,760	400,056	398,408

Table 8-11. Summary of dynamic moduli of CIR-foam mixtures from Muscatine County

Dynamic Modulus (kPa) at FAC=1.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	10,726,210	10,997,880	10,862,045	5,388,346	5,731,690	5,560,018	2,275,188	2,138,345	2,206,767
10	9,860,600	10,144,425	10,002,513	4,355,456	4,672,132	4,513,794	1,517,472	1,478,447	1,497,959
5	9,061,389	9,299,353	9,180,371	3,703,140	3,917,060	3,810,100	1,166,748	1,159,397	1,163,072
1	7,068,715	7,312,956	7,190,836	2,406,044	2,490,844	2,448,444	732,795	797,062	764,928
0.5	6,312,074	6,498,837	6,405,455	1,986,375	2,011,662	1,999,019	592,502	615,689	604,095
0.1	4,919,621	5,048,109	4,983,865	1,332,486	1,315,100	1,323,793	463,019	453,679	458,349
Dynamic Modulus (kPa) at FAC=2.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	10,371,830	11,611,980	10,991,905	5,165,643	5,352,970	5,259,306	2,041,886	2,090,446	2,066,166
10	9,583,822	10,382,800	9,983,311	4,035,771	4,408,160	4,221,965	1,341,415	1,370,498	1,355,957
5	8,692,047	9,551,855	9,121,951	3,336,309	3,684,733	3,510,521	998,533	1,047,691	1,023,112
1	6,559,208	7,295,969	6,927,588	2,068,727	2,346,621	2,207,674	612,397	709,124	660,761
0.5	5,795,735	6,440,961	6,118,348	1,562,772	1,878,068	1,720,420	457,030	520,330	488,680
0.1	4,311,617	4,937,684	4,624,651	958,415	1,199,597	1,079,006	290,860	336,944	313,902
Dynamic Modulus (kPa) at FAC=3.0%									
Freq. (Hz)	4.4˚C			21.1˚C			37.8˚C		
	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	11,889,475	11,102,930	11,496,203	5,081,586	5,284,682	5,183,134	1,940,419	1,926,404	1,933,412
10	10,436,845	9,911,910	10,174,377	3,935,597	4,177,963	4,056,780	1,384,184	1,303,607	1,343,895
5	9,353,655	8,882,993	9,118,324	3,229,008	3,458,709	3,343,858	937,820	872,906	905,363
1	6,821,164	6,605,752	6,713,458	1,938,559	2,128,017	2,033,288	590,270	542,851	566,561
0.5	5,927,454	5,745,216	5,836,335	1,435,490	1,656,191	1,545,840	420,406	392,345	406,375
0.1	4,323,000	4,227,677	4,275,338	861,315	988,041	924,678	295,237	295,014	295,125

Table 8-12. Rankings of dynamic modulus at three foamed asphalt contents and three different testing temperatures for seven different RAP sources

FAC (%)		Individual Rankings of Dynamic Modulus																					Total Ave.	Overall Rank.
	Temp.	4.4˚C							21.1˚C							37.8˚C								
	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.		
1.0	Hardin	7	7	7	7	7	7	**7**	6	6	6	5	5	5	**5**	6	4	2	2	2	2	**2**	5.17	**5**
	Lee	6	6	6	6	6	6	**6**	7	7	7	7	7	7	**6**	7	6	4	3	4	5	**5**	5.94	**7**
	Webster	5	4	3	2	2	2	**3**	1	1	1	1	1	1	**1**	1	1	1	1	1	1	**1**	1.67	**1**
	Bremer	3	3	4	4	4	3	**4**	4	3	2	2	2	2	**2**	5	2	3	5	3	3	**3**	3.17	**3**
	Wapello	2	2	2	3	3	4	**2**	2	2	3	3	3	3	**3**	2	3	5	4	5	4	**4**	3.06	**2**
	Montgomery	4	5	5	5	5	5	**5**	5	5	5	6	6	6	**5**	3	5	6	6	6	6	**6**	5.22	**6**
	Muscatine	1	1	1	1	1	1	**1**	3	4	4	4	4	4	**4**	4	7	7	7	7	7	**7**	3.78	**4**
2.0	Hardin	6	6	6	6	5	5	**6**	6	6	5	2	2	2	**4**	6	3	3	3	3	3	**4**	4.33	**5**
	Lee	7	7	7	7	7	7	**7**	7	7	7	7	7	7	**7**	4	2	2	2	2	4	**2**	5.56	**7**
	Webster	2	2	2	1	1	1	**1**	1	1	1	1	1	1	**1**	1	1	1	1	1	1	**1**	1.17	**1**
	Bremer	4	4	3	4	3	4	**4**	5	5	5	6	6	6	**6**	7	7	6	5	5	5	**6**	5.00	**6**
	Wapello	5	5	5	5	6	6	**5**	3	4	4	5	5	4	**5**	2	4	4	4	4	2	**3**	4.28	**4**
	Montgomery	3	3	4	3	4	3	**3**	4	3	3	4	3	3	**3**	5	5	5	6	6	6	**5**	4.06	**3**
	Muscatine	1	1	1	2	2	2	**1**	2	2	2	3	4	5	**2**	3	6	7	7	7	7	**7**	3.56	**2**
3.0	Hardin	6	6	6	6	6	5	**6**	7	7	7	6	6	6	**7**	7	6	5	5	4	4	**5**	5.83	**7**
	Lee	7	7	7	7	7	7	**7**	6	6	6	2	7	4	**5**	5	2	2	2	1	2	**3**	4.83	**5**
	Webster	2	2	2	2	2	1	**2**	2	1	1	1	1	1	**1**	2	1	1	3	3	3	**2**	1.72	**1**
	Bremer	5	5	5	5	5	6	**5**	5	5	5	5	4	7	**5**	6	7	6	4	5	5	**6**	5.28	**6**
	Wapello	4	4	4	4	4	4	**4**	4	4	4	4	5	2	**4**	1	3	3	1	2	1	**1**	3.22	**2**
	Montgomery	3	3	3	3	3	3	**3**	3	3	3	3	3	3	**3**	3	4	4	6	6	6	**4**	3.61	**4**
	Muscatine	1	1	1	1	1	2	**1**	1	2	2	2	2	5	**2**	4	5	7	7	7	7	**7**	3.22	**2**

The dynamic moduli for seven different RAP sources are plotted against six loading frequencies at 4.4°C, 21.1°C, and 37.8°C in Figures 8-4, Figure 8-5 and Figure 8-6, respectively. Under a constant loading frequency, the magnitude of the dynamic modulus decreases as temperature increases. Under a constant testing temperature, the magnitude of the dynamic modulus increases with an increase in the frequency. As expected, the dynamic moduli measured at three foamed asphalt contents were different among seven RAP sources. At 4.4°C, RAP materials from Muscatine County exhibited the highest dynamic modulus values, RAP materials from Webster County was second and RAP materials from Lee and Hardin Counties were the lowest for nearly all loading frequencies. At 21.1°C, dynamic modulus of RAP materials from Webster County was the highest followed by Muscatine County whereas Lee and Hardin Counties stayed at the lowest level. At 37.8°C, it is interesting to note that dynamic modulus of RAP materials from Muscatine became the lowest whereas Webster County was the highest. It can be postulated that RAP material from Muscatine is sensitive to temperature because they were the coarsest with least amount of residual asphalt content. Therefore, the coarse RAP materials with a small amount of residual asphalt content may be more fatigue resistant at a low temperature but more susceptible to rutting at a high temperature. On the other hand, fine RAP materials with a large amount of hard residual asphalt content like Hardin County may be more resistant to rutting at high temperature but more susceptible to fatigue cracking at low temperature.

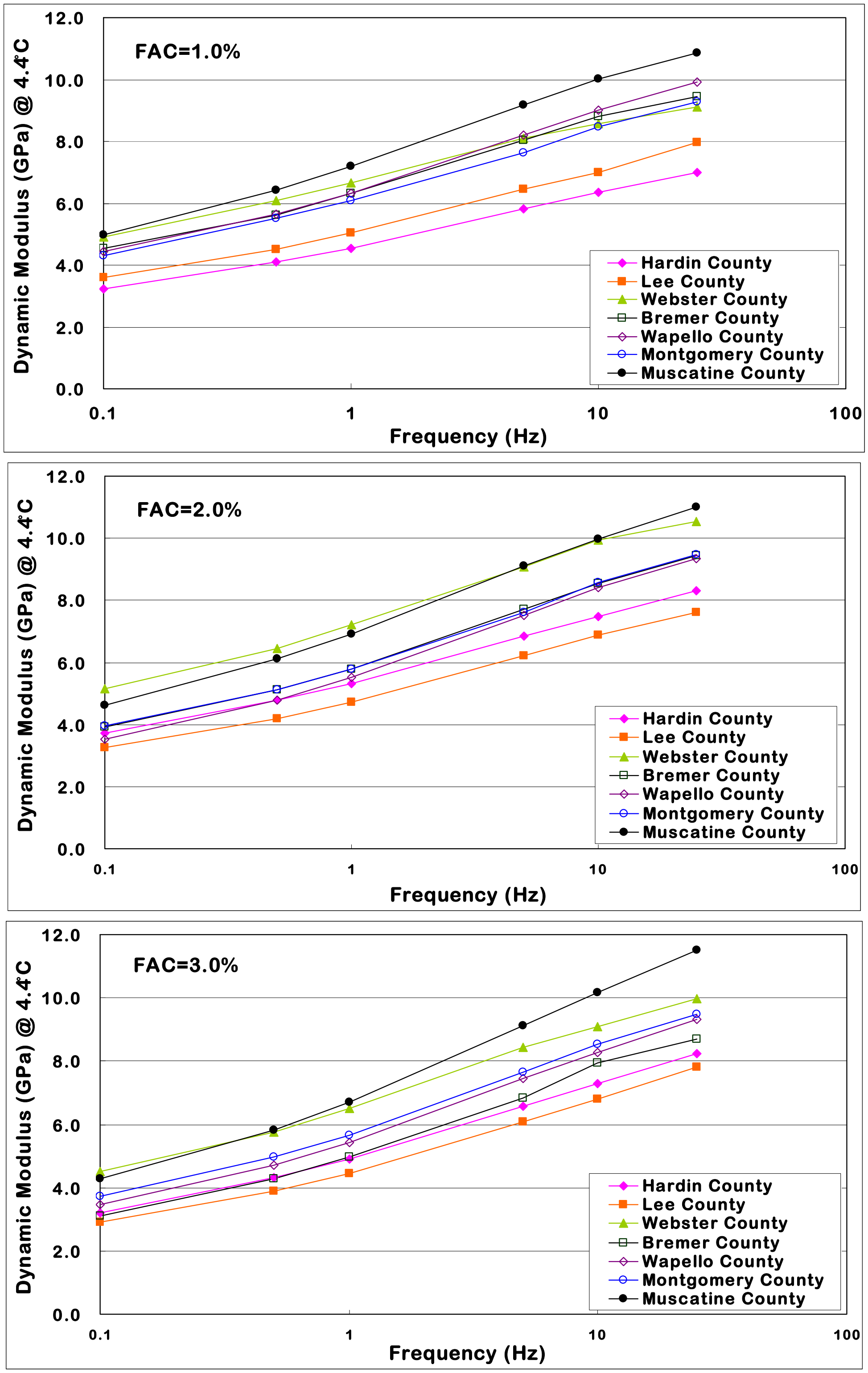


Figure 8-4. Plots of dynamic moduli against six loading frequencies for three foamed asphalt contents at 4.4˚C

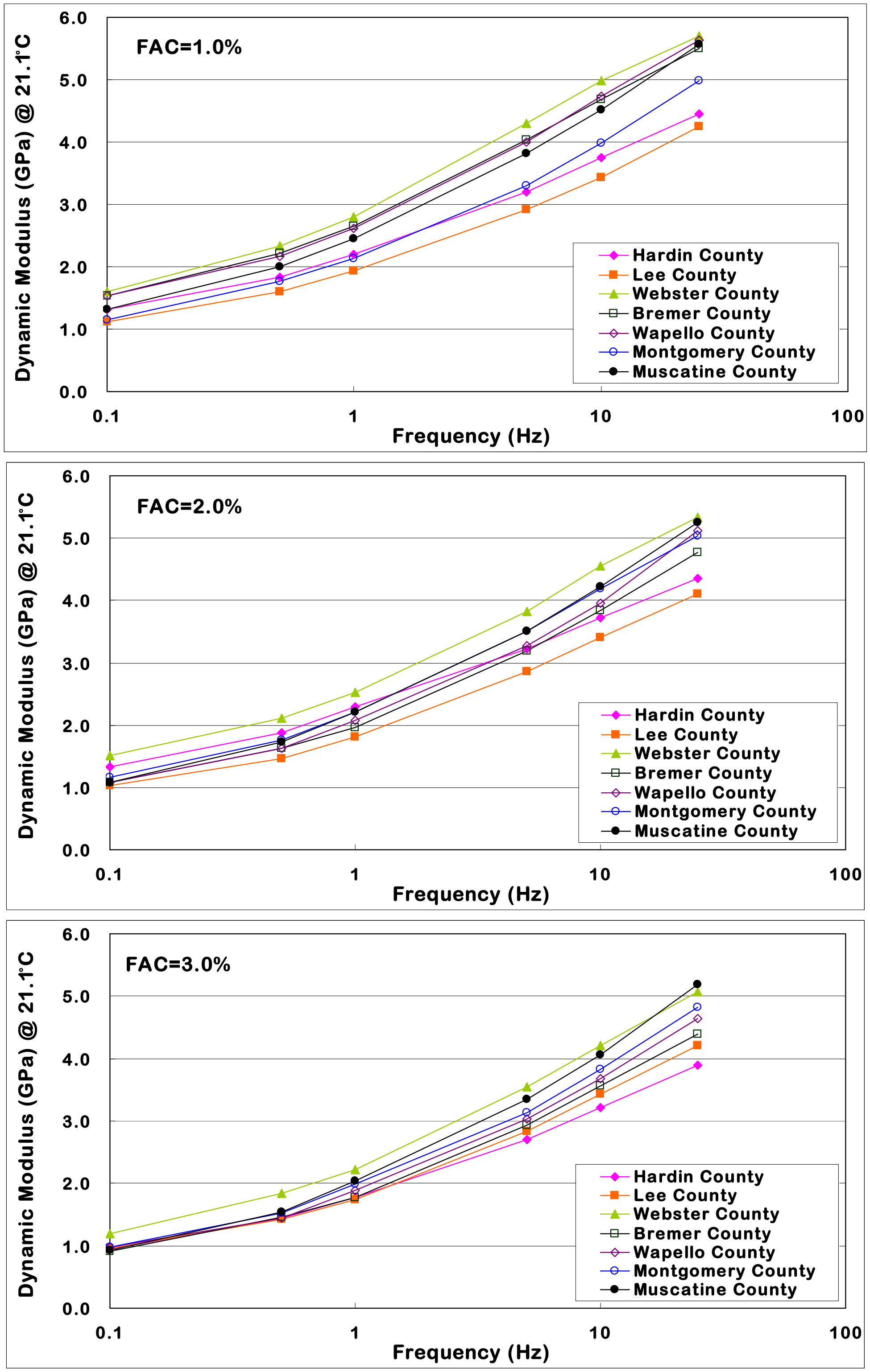


Figure 8-5. Plots of dynamic moduli against six loading frequencies for three foamed asphalt contents at 21.1˚C

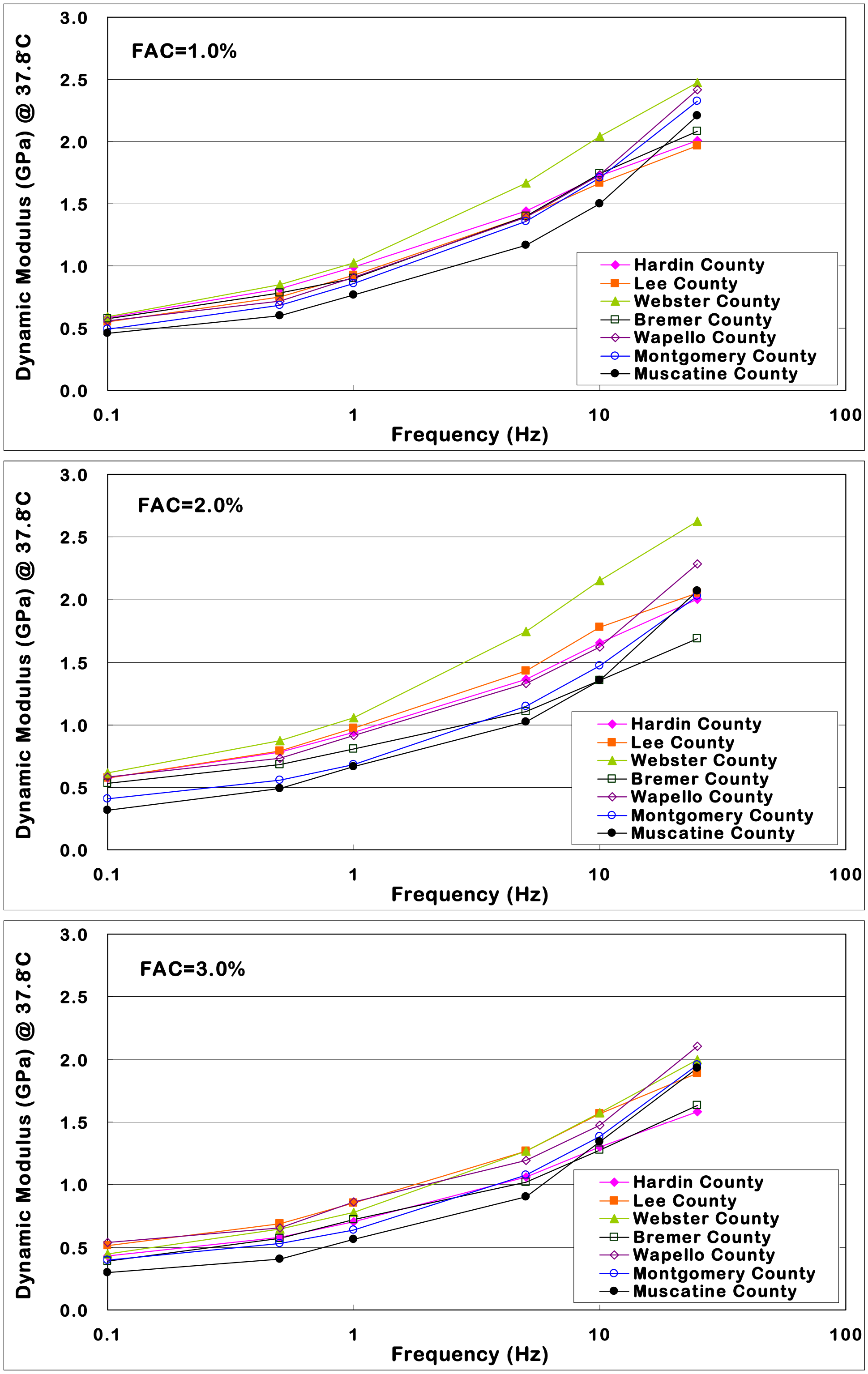


Figure 8-6. Plots of dynamic modulus value against six loading frequencies for three foamed asphalt contents at 37.8˚C

Since dynamic modulus of RAP materials was not significantly affected by loading frequencies, the frequency of 25 Hz, which represents a highway speed, was selected for further analysis. Figure 8-7 shows dynamic moduli of RAP materials from seven RAP sources plotted against three different temperatures. As shown in Figure 8-7, dynamic modulus values were significantly lower at higher temperatures. It seemed that the dynamic modulus values from seven different RAP sources were very similar at 37˚C. Particularly, RAP materials form Muscatine County exhibited the highest dynamic modulus at 4.4˚C but they decreased more than others at higher temperatures of 21.1˚C and 37.8˚C.

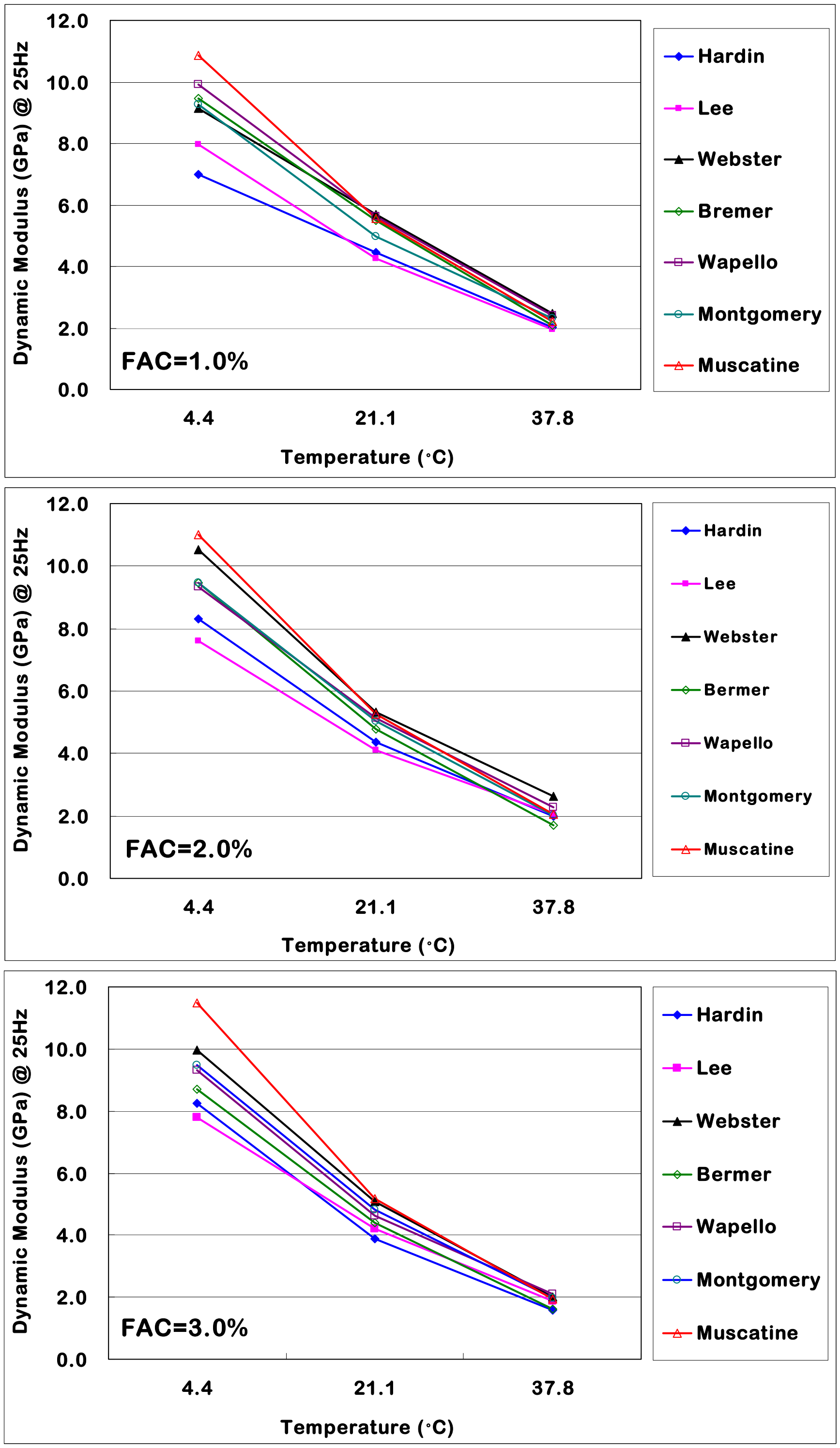


Figure 8-7. Dynamic moduli against three temperatures at 25Hz

As shown in Figure 8-8, dynamic moduli measured at 25Hz and three different temperatures are plotted against three foamed asphalt contents. At 4.4˚C, the RAP materials from Muscatine County exhibited the highest dynamic modulus values, which were not significantly affected by the foamed asphalt contents. It is interesting to note that the RAP materials from Muscatine County were the coarsest and one of the lowest in residual asphalt content. RAP materials from Montgomery, Wapello and Webster Counties were next coarsest and they also exhibited the high dynamic modulus values, which were not significantly affected by the foamed asphalt contents except Webster County. It can be postulated that dynamic modulus values of RAP materials from Webster County were influenced by foamed asphalt contents because they contain the higher amount of residual asphalt than the others. This trend was also observed from RAP materials from Hardin County, which include the highest amount of residual asphalt.

At 21.1˚C, relative dynamic modulus values of RAP materials did not change among seven different RAP sources although they became significantly lower. It is interesting to note that dynamic modulus values decreased as the foamed asphalt content increased. At 37.8˚C, the dynamic modulus values became closer each other. However, the dynamic modulus of RAP materials from Muscatine County has decreased more than others whereas that of Webster County remained high. It is interesting to note that the residual asphalt content is low in the RAP materials from Muscatine County and high in Webster County. This behavior can be explained that at the higher temperature, the contribution of residual asphalt to the dynamic modulus value is rather pronounced.

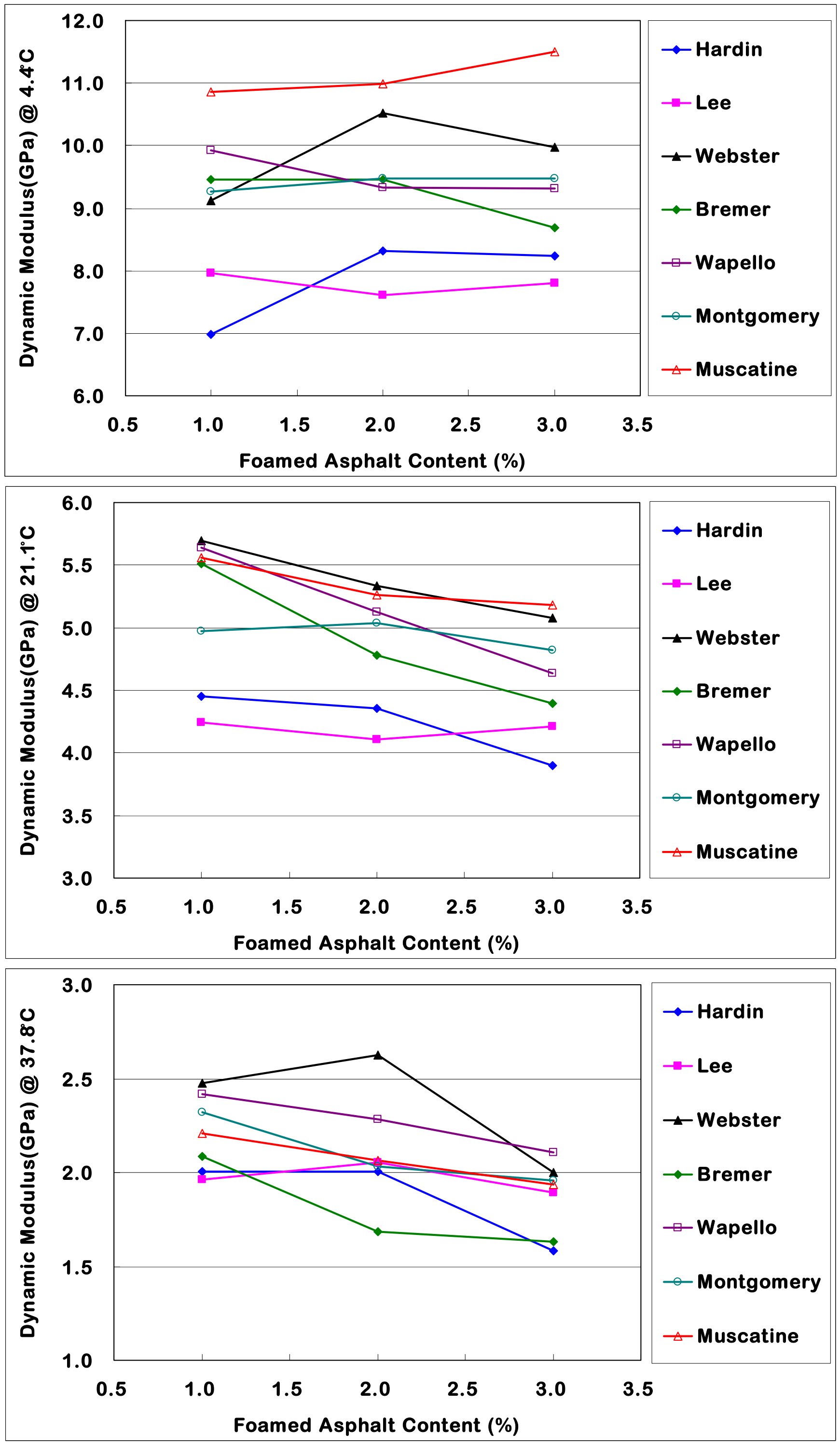


Figure 8-8. Dynamic moduli against three foamed asphalt contents at 25Hz

8.1.4.3 Master Curve Construction Procedure

The measured dynamic modulus at different temperatures can be then shifted relative to the time of frequency so that the various curves can be aligned to form a single master curve. In constructing the master curves, as shown in **Figure 8-9**. the measured dynamic moduli at test temperatures above the reference temperature horizontally shifted to the left (low frequencies) and the measured dynamic moduli at test temperatures below the reference temperature are shifted to the right (higher frequencies). The master curve of an asphalt mixture allows comparisons to be made over extended ranges of frequencies and temperature.

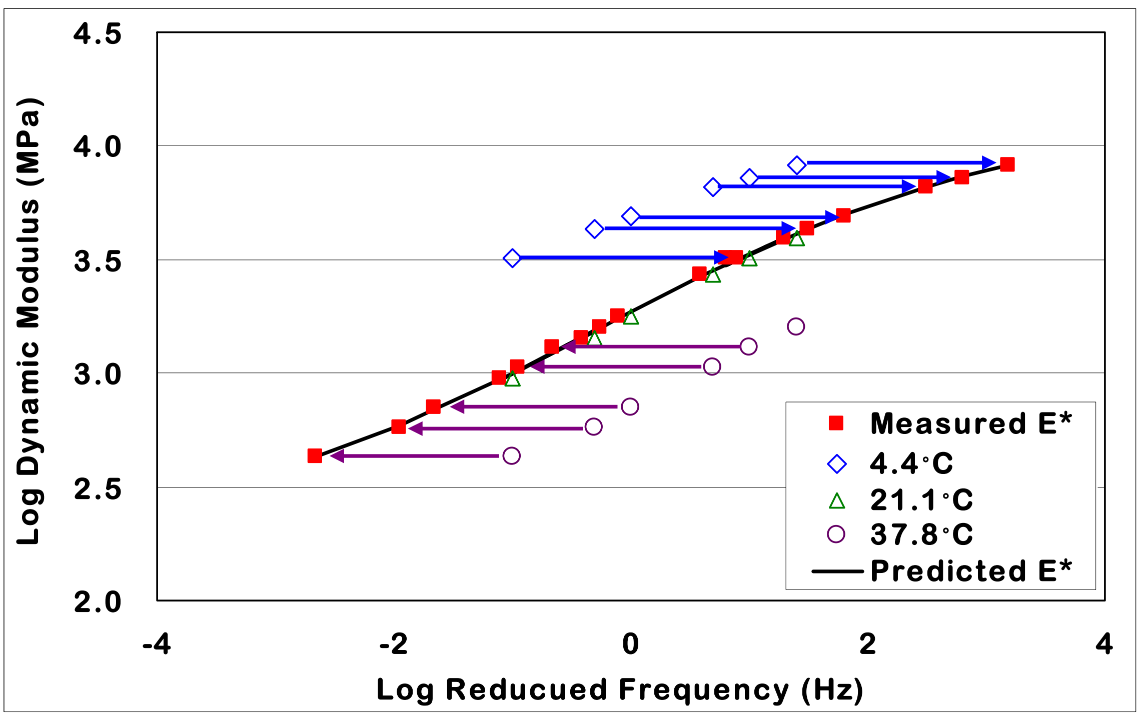


Figure 8-9. Construction of master curve

Master curves can be constructed using the time-temperature correspondence principle, which uses the following equivalency between frequency and temperature for the range of dynamic moduli of asphalt mixtures.

$$\log(fr) - \log(f) = \log[\alpha(T)]$$

fr = reduced frequency (Hz)
f = loading frequency (Hz)
α(T)= shifting factor

First, the master curve should be constructed using an arbitrarily selected reference temperature, T*ref*, to which all data are shifted. A commonly used formula for the shift factor is the Williams-Landel-Ferry (WLF) equation (Williams et al., 1955). In the WLF equation, the shift factor α(T) is defined as:

$$\text{Log}\, f_r - \log f = \log \alpha(\text{T}) = -\frac{C_1(T - T_{ref})}{C_2 + T - T_{ref}}$$

f_r = reduced frequency (Hz)
f = loading frequency (Hz)
C_1, C_2 = empirical constants

The frequency where the master curve should be read *fr* is defined as:

$$f_r = \alpha(\text{T}) \times f$$

A master curve represented by a nonlinear sigmoidal function is defined in AASHTTO 2002 Design Guide as:

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log f_r}}$$

$\log\left|E^*\right|$ = log of dynamic modulus (MPa),
δ=minimum modulus value,
f_r = reduced frequency (Hz),
α=span of modulus value,
β, γ= shape parameters,

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 20˚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 8-13 summarizes all model parameters and the empirical parameters from the WLF equation.

Figure 8-10 To Figure 8-16 show measured dynamic modulus data and a master curve constructed for each of three foamed asphalt contents for each of seven RAP sources. A mater curve constructed for each of three different foamed 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 foamed asphalt mixtures are not as viscoelastic as HMA. More viscoelastic behavior was observed from the foamed asphalt mixtures with higher foamed asphalt content. Figure 8-17 shows a plot of shift factors against temperatures at each foamed asphalt content for each of seven RAP sources.

Table 8-14, Table 8-15, and Table 8-16 summarize the measured dynamic moduli and predicted dynamic moduli of seven different RAP materials for each of three foamed asphalt contents.

Table 8-13. Model parameters of constructed master curves

Parameter	Hardin County			Lee County		
	FAC=1.0%	FAC=2.0%	FAC=3.0%	FAC=1.0%	FAC=2.0%	FAC=3.0%
C_1	94.37	17.76	16.33	11.19	7.30	14.50
C_2	1000.00	168.59	157.72	117.06	84.55	170.23
α	1.4486	2.0130	1.9402	1.6307	1.4944	1.5982
δ	2.5102	2.1671	2.2194	2.4315	2.5244	2.4678
β	-0.3693	-0.3964	-0.1648	-0.1650	-0.0118	-0.0069
γ	0.7201	0.4711	0.5566	0.6560	0.7490	0.7323

Parameter	Webster County			Bremer County		
	FAC=1.0%	FAC=2.0%	FAC=3.0%	FAC=1.0%	FAC=2.0%	FAC=3.0%
C_1	21.23	7.18	18.66	110.56	27.56	44.91
C_2	202.72	70.51	179.11	1000.00	260.88	468.55
α	1.6414	2.0350	2.0220	1.9165	1.5583	1.9240
δ	2.4117	2.1618	2.1651	2.2643	2.5524	2.2359
β	-0.6179	-0.5077	-0.4168	-0.4809	-0.0006	-0.1855
γ	0.6927	0.5402	0.5817	0.5214	0.7481	0.6306

Parameter	Wapello County			Montgomery County		
	FAC=1.0%	FAC=2.0%	FAC=3.0%	FAC=1.0%	FAC=2.0%	FAC=3.0%
C_1	30.41	11.33	7.37	8.27	22.29	12.36
C_2	313.86	134.96	86.13	86.73	230.17	132.37
α	1.9280	1.5353	1.5932	1.8756	2.1050	1.9216
δ	2.2532	2.5677	2.5215	2.2311	2.0714	2.2216
β	-0.4869	0.0041	0.0919	-0.4340	-0.4718	-0.2742
γ	0.5892	0.8194	0.7885	0.6493	0.5914	0.6810

Parameter	Muscatine County		
	FAC=1.0%	FAC=2.0%	FAC=3.0%
C_1	13.90	10.82	11.16
C_2	130.25	104.86	112.16
α	2.0653	2.6124	2.5424
δ	2.1345	1.6333	1.7501
β	-0.5070	-0.6852	-0.4965
γ	0.5911	0.5412	0.5638

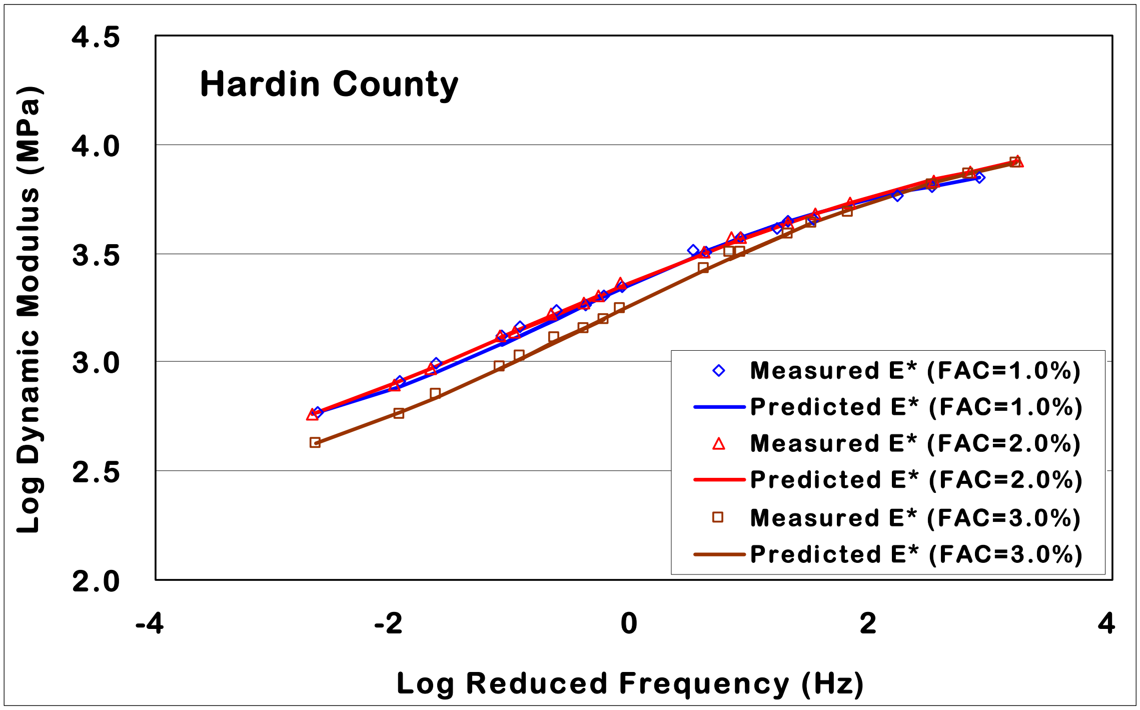


Figure 8-10. Mater curves at three FACs from Hardin County

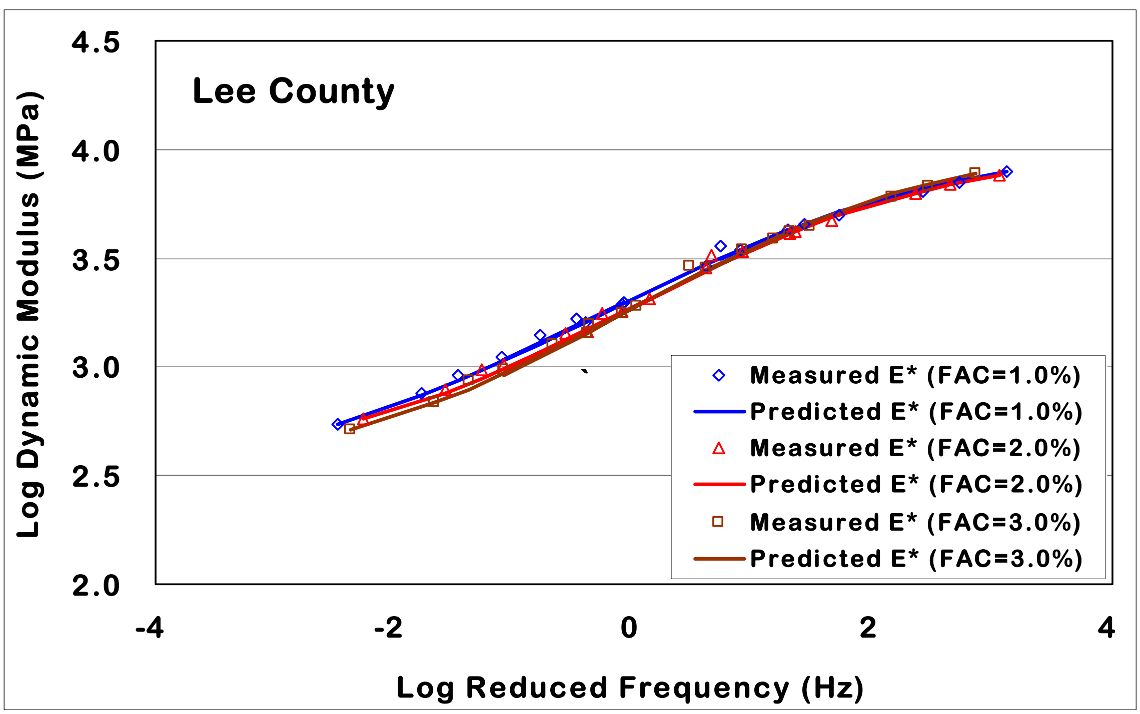


Figure 8-11. Mater curves at three FACs from Lee County

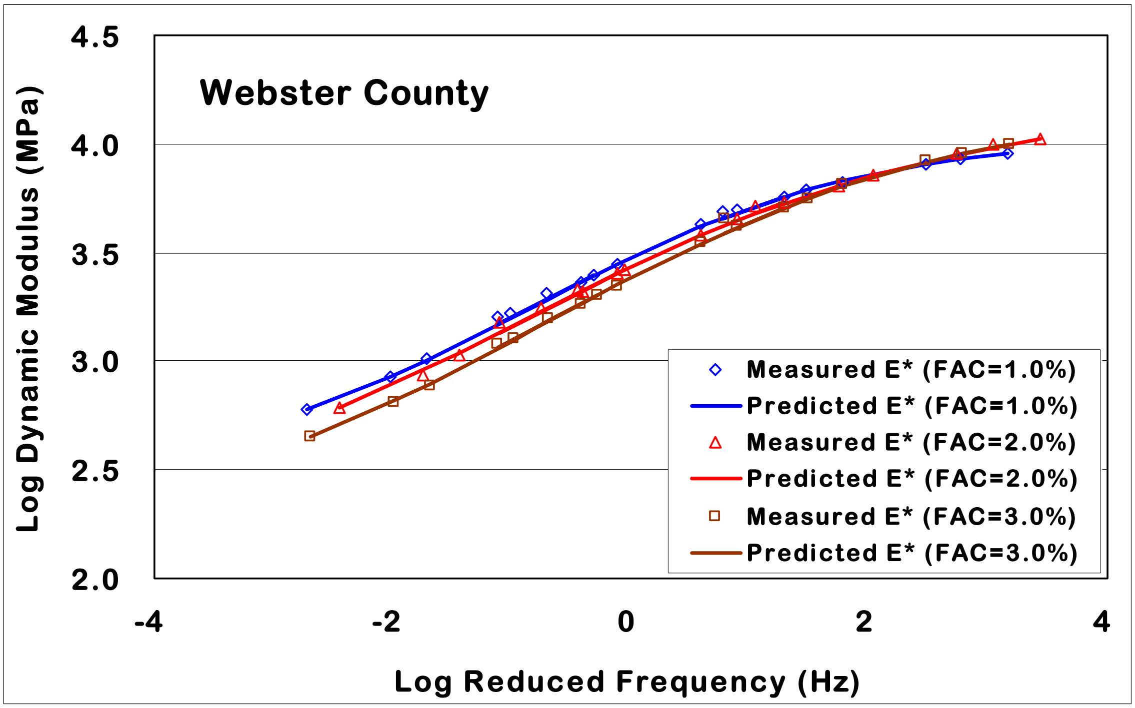


Figure 8-12. Mater curves at three FACs from Webster County

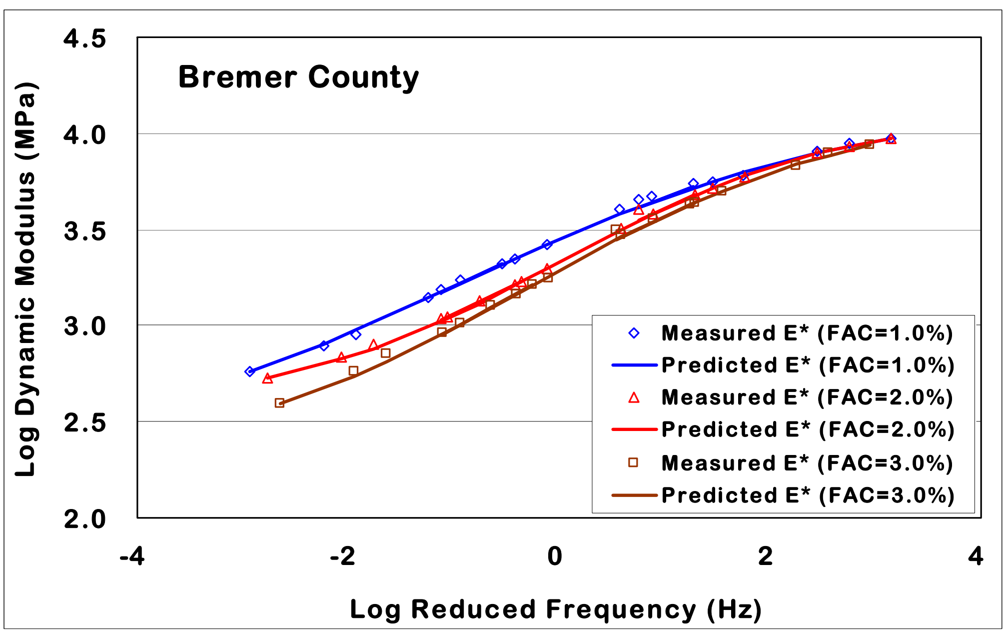


Figure 8-13. Mater curves at three FAC's from Bremer County

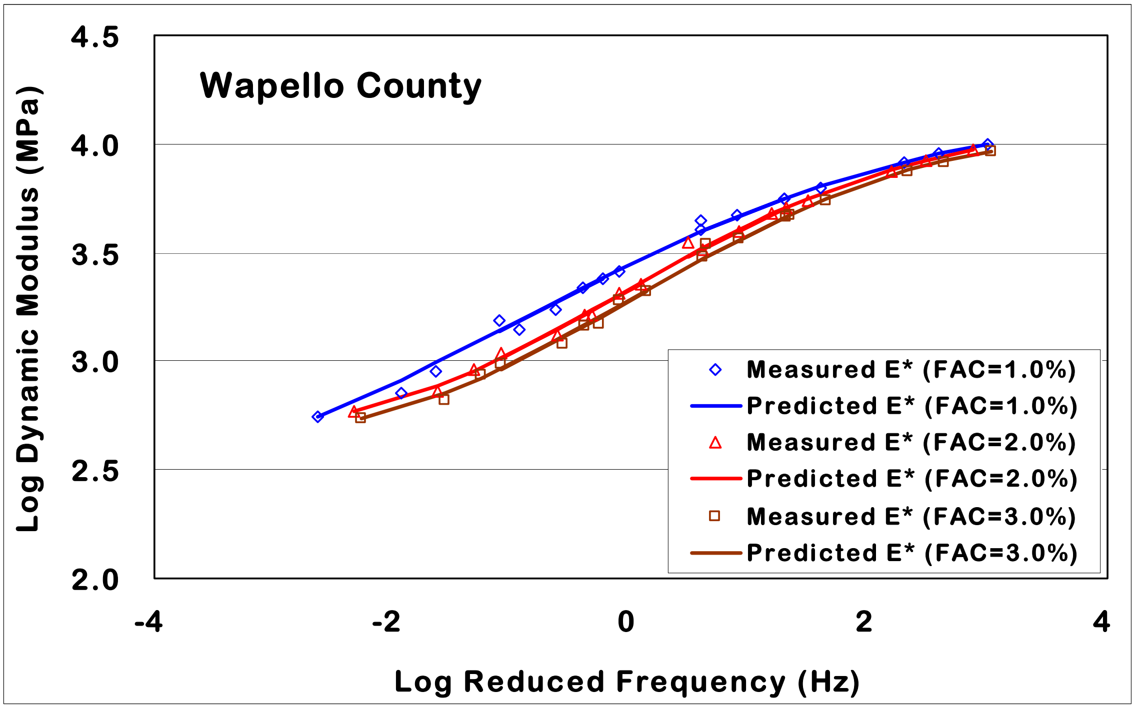


Figure 8-14. Mater curves at three FACs from Wapello County

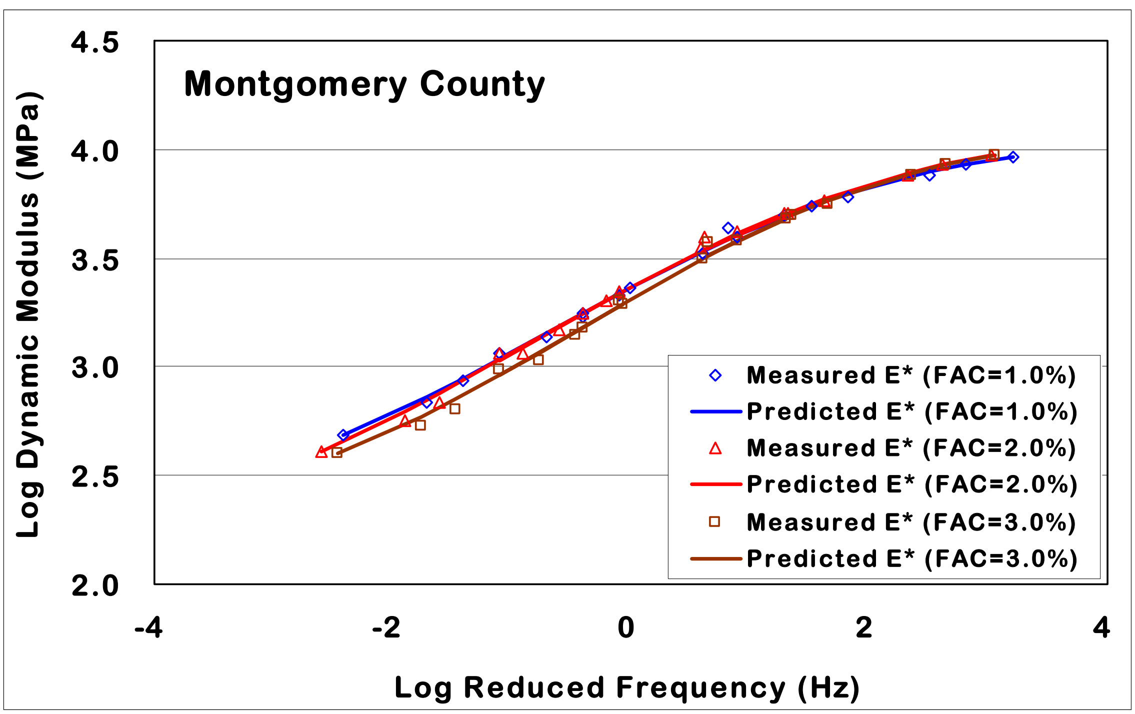


Figure 8-15. Mater curves at three FAC from Montgomery County

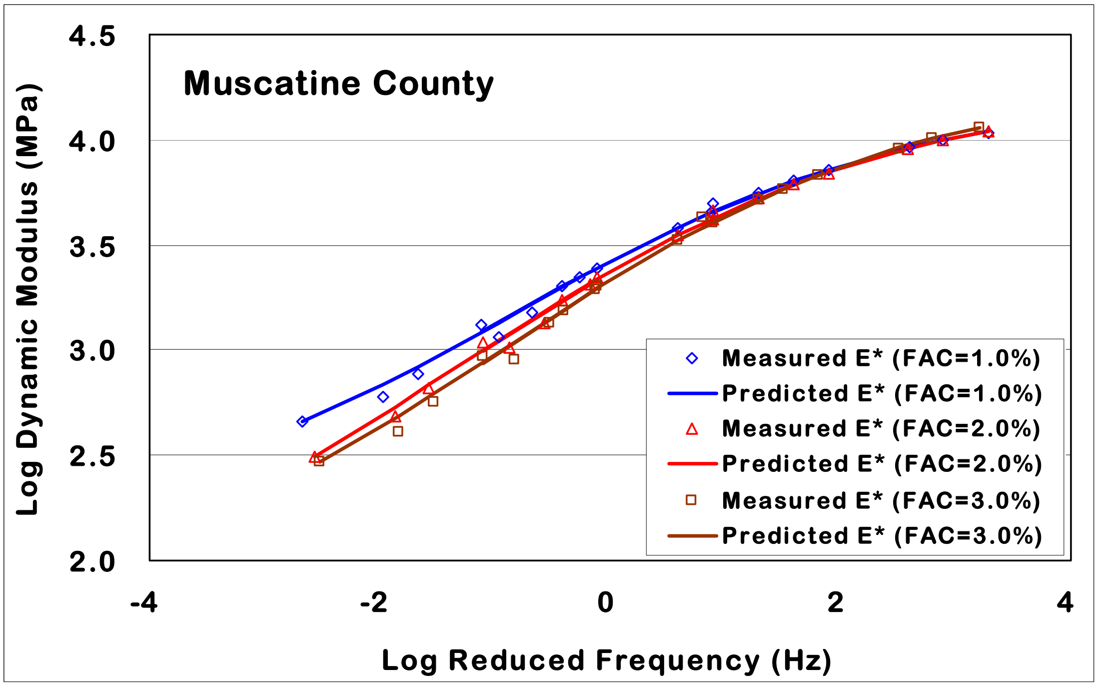


Figure 8-16. Mater curves at three FAC from Muscatine County

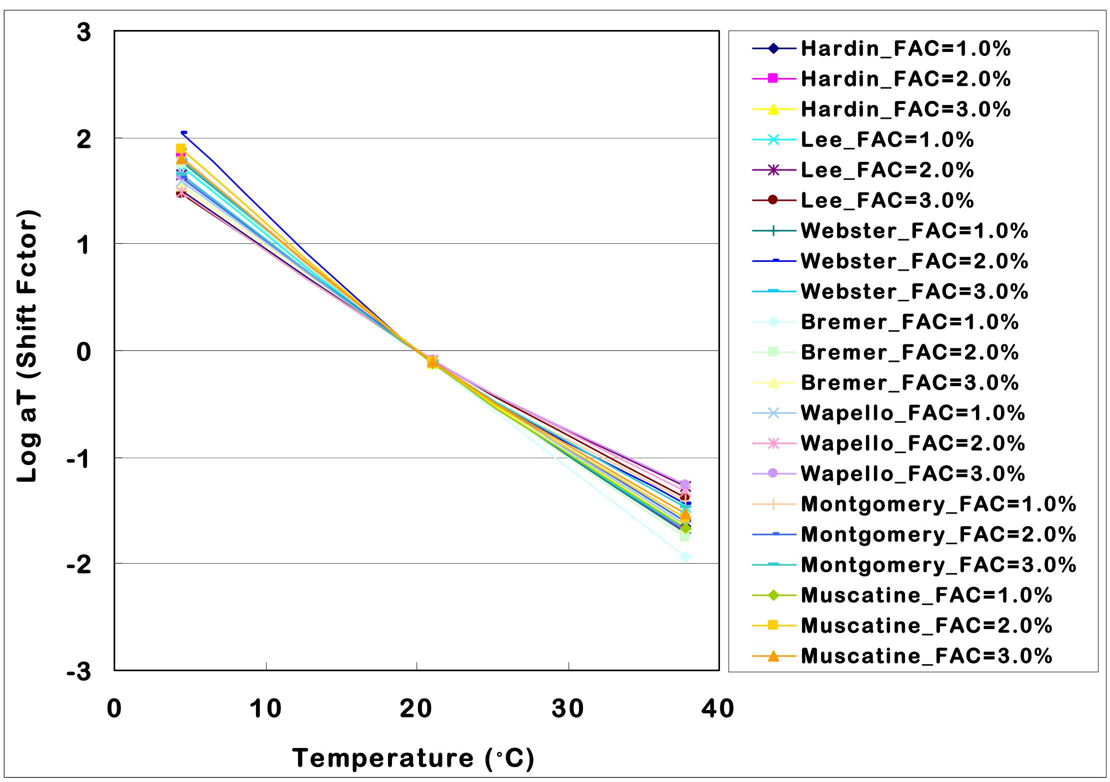


Figure 8-17. Shift factors against three temperatures

Table 8-14. Summary of measured dynamic moduli and predicted dynamic moduli from seven RAP sources at FAC=1.0%

Temp. (˚C)	Freq. (Hz)	Hardin		Lee		Webster		Bremer		Wapello		Montgomery		Muscatine	
		Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)
4.4	25	3.844	3.844	3.901	3.901	3.960	3.960	3.976	3.976	3.997	3.997	3.967	3.967	4.036	4.036
	10	3.802	3.810	3.844	3.859	3.933	3.933	3.944	3.935	3.955	3.954	3.927	3.930	4.000	3.997
	5	3.764	3.778	3.809	3.821	3.908	3.907	3.904	3.899	3.914	3.916	3.883	3.896	3.963	3.962
	1	3.656	3.683	3.701	3.711	3.822	3.829	3.781	3.800	3.802	3.807	3.785	3.795	3.857	3.860
	0.5	3.612	3.631	3.654	3.654	3.785	3.785	3.750	3.750	3.751	3.751	3.741	3.741	3.807	3.807
	0.1	3.509	3.486	3.558	3.498	3.692	3.659	3.656	3.616	3.647	3.598	3.635	3.588	3.698	3.658
21.1	25	3.649	3.649	3.628	3.628	3.755	3.755	3.741	3.719	3.751	3.751	3.697	3.697	3.745	3.745
	10	3.575	3.573	3.536	3.540	3.697	3.682	3.670	3.642	3.674	3.668	3.601	3.608	3.655	3.656
	5	3.506	3.509	3.466	3.468	3.633	3.619	3.606	3.579	3.601	3.598	3.519	3.533	3.581	3.582
	1	3.343	3.340	3.286	3.286	3.447	3.448	3.424	3.420	3.416	3.419	3.329	3.339	3.389	3.390
	0.5	3.263	3.263	3.206	3.206	3.367	3.367	3.347	3.347	3.336	3.336	3.249	3.249	3.301	3.301
	0.1	3.120	3.083	3.049	3.025	3.206	3.169	3.186	3.173	3.184	3.138	3.059	3.037	3.122	3.088
37.8	25	3.302	3.302	3.293	3.293	3.394	3.394	3.319	3.319	3.384	3.384	3.366	3.366	3.344	3.344
	10	3.237	3.199	3.222	3.187	3.310	3.283	3.240	3.220	3.240	3.272	3.232	3.248	3.175	3.224
	5	3.158	3.121	3.146	3.108	3.222	3.198	3.147	3.145	3.143	3.187	3.133	3.156	3.066	3.132
	1	2.996	2.953	2.964	2.936	3.011	3.005	2.955	2.976	2.957	2.993	2.933	2.948	2.884	2.924
	0.5	2.912	2.890	2.876	2.870	2.927	2.928	2.894	2.907	2.854	2.914	2.835	2.863	2.781	2.839
	0.1	2.766	2.766	2.739	2.739	2.774	2.774	2.762	2.762	2.748	2.748	2.689	2.689	2.661	2.661

Table 8-15. Summary of measured dynamic moduli and predicted dynamic moduli from seven RAP sources at FAC=2.0%

Temp. (˚C)	Freq. (Hz)	Hardin		Lee		Webster		Bremer		Wapello		Montgomery		Muscatine	
		Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)
4.4	25	3.920	3.920	3.882	3.882	4.022	4.022	3.976	3.976	3.970	3.970	3.977	3.977	4.041	4.041
	10	3.873	3.875	3.837	3.840	3.997	3.984	3.932	3.935	3.925	3.925	3.933	3.930	3.999	3.997
	5	3.835	3.836	3.794	3.802	3.957	3.951	3.894	3.896	3.877	3.882	3.882	3.889	3.960	3.957
	1	3.727	3.732	3.673	3.686	3.859	3.858	3.772	3.780	3.743	3.750	3.762	3.770	3.841	3.845
	0.5	3.680	3.680	3.624	3.624	3.809	3.809	3.718	3.718	3.679	3.679	3.708	3.708	3.787	3.787
	0.1	3.569	3.547	3.514	3.454	3.711	3.677	3.604	3.546	3.547	3.483	3.597	3.541	3.665	3.626
21.1	25	3.639	3.639	3.613	3.613	3.727	3.727	3.679	3.679	3.710	3.710	3.702	3.702	3.721	3.721
	10	3.571	3.562	3.532	3.520	3.658	3.645	3.584	3.580	3.598	3.607	3.622	3.611	3.626	3.625
	5	3.509	3.499	3.455	3.442	3.581	3.577	3.503	3.499	3.514	3.521	3.544	3.534	3.545	3.544
	1	3.361	3.344	3.258	3.250	3.402	3.404	3.294	3.298	3.316	3.305	3.343	3.336	3.344	3.335
	0.5	3.274	3.274	3.166	3.166	3.324	3.324	3.211	3.211	3.211	3.211	3.245	3.245	3.236	3.236
	0.1	3.123	3.109	3.014	2.985	3.181	3.133	3.033	3.024	3.037	3.012	3.064	3.028	3.033	2.994
37.8	25	3.302	3.302	3.312	3.312	3.420	3.420	3.227	3.227	3.358	3.358	3.307	3.307	3.315	3.315
	10	3.220	3.208	3.249	3.201	3.333	3.314	3.132	3.116	3.210	3.234	3.167	3.185	3.132	3.183
	5	3.133	3.137	3.156	3.119	3.243	3.232	3.043	3.038	3.123	3.143	3.061	3.092	3.010	3.079
	1	2.974	2.974	2.988	2.945	3.025	3.041	2.906	2.882	2.961	2.955	2.834	2.879	2.820	2.832
	0.5	2.894	2.906	2.896	2.880	2.939	2.961	2.834	2.827	2.863	2.888	2.748	2.792	2.689	2.728
	0.1	2.760	2.760	2.758	2.758	2.787	2.787	2.728	2.728	2.767	2.767	2.611	2.611	2.497	2.497

Table 8-16. Summary of measured dynamic moduli and predicted dynamic moduli from seven RAP sources at FAC=3.0%

Temp. (˚C)	Freq. (Hz)	Hardin		Lee		Webster		Bremer		Wapello		Montgomery		Muscatine	
		Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)	Log measured E* (MPa)	Log predicted E* (MPa)
4.4	25	3.916	3.916	3.892	3.892	3.997	3.997	3.939	3.939	3.969	3.969	3.976	3.976	4.061	4.061
	10	3.863	3.865	3.833	3.841	3.959	3.953	3.900	3.885	3.918	3.922	3.930	3.930	4.008	4.009
	5	3.818	3.820	3.784	3.795	3.925	3.914	3.834	3.837	3.873	3.878	3.883	3.888	3.960	3.964
	1	3.691	3.697	3.649	3.660	3.812	3.804	3.697	3.701	3.735	3.744	3.751	3.763	3.827	3.833
	0.5	3.636	3.636	3.590	3.590	3.746	3.746	3.631	3.631	3.673	3.673	3.696	3.696	3.766	3.766
	0.1	3.507	3.475	3.465	3.404	3.655	3.590	3.493	3.447	3.540	3.477	3.573	3.513	3.631	3.583
21.1	25	3.591	3.591	3.624	3.624	3.706	3.706	3.643	3.643	3.666	3.666	3.683	3.683	3.715	3.715
	10	3.507	3.498	3.535	3.525	3.624	3.616	3.553	3.543	3.565	3.559	3.583	3.582	3.608	3.608
	5	3.432	3.423	3.453	3.444	3.550	3.542	3.468	3.460	3.483	3.470	3.497	3.497	3.524	3.520
	1	3.248	3.239	3.243	3.242	3.348	3.351	3.249	3.255	3.277	3.252	3.300	3.280	3.308	3.294
	0.5	3.158	3.158	3.155	3.155	3.265	3.265	3.164	3.164	3.160	3.160	3.182	3.182	3.189	3.189
	0.1	2.977	2.973	2.986	2.965	3.074	3.060	2.963	2.957	2.988	2.965	2.988	2.958	2.966	2.940
37.8	25	3.200	3.200	3.277	3.277	3.301	3.301	3.213	3.213	3.324	3.324	3.292	3.292	3.286	3.286
	10	3.114	3.093	3.194	3.161	3.197	3.185	3.106	3.092	3.170	3.200	3.142	3.162	3.128	3.147
	5	3.026	3.013	3.103	3.076	3.104	3.096	3.009	3.003	3.078	3.109	3.031	3.064	2.957	3.040
	1	2.849	2.839	2.933	2.898	2.890	2.898	2.856	2.812	2.937	2.923	2.803	2.849	2.753	2.792
	0.5	2.761	2.770	2.836	2.832	2.811	2.818	2.759	2.738	2.818	2.856	2.726	2.766	2.609	2.689
	0.1	2.631	2.631	2.708	2.708	2.653	2.653	2.592	2.592	2.733	2.733	2.600	2.600	2.470	2.470

8.1.4.4 Impact of RAP Characteristics on Dynamic Modulus

To identify the impact of RAP characteristics on dynamic modulus values, the following RAP characteristics were measured: 1) residual asphalt content, 2) residual asphalt stiffness, 3) gradation and 4) flat and elongation ratio. As discussed earlier, the dynamic moduli measured at 25 Hz were used to identify their correlations with these RAP characteristics. Dynamic modulus values measured at three different temperatures are plotted against of each of four RAP characteristics in Figure 8-18, Figure 8-19, Figure 8-20 and Figure 8-21. As can be seen these figures, correlations were observed from the dynamic modulus values measured at 4.4˚C and 21.1˚C only. At 37.8˚C, the RAP characteristics did not influence the dynamic modulus values, where values were quite small. Particularly, as shown in Figure 8-20**,** a correlation was observed between dynamic moduli and the amount of fines passing No. 8 sieve in the RAP materials. As the amount of fine RAP materials passing No. 8 sieve increased, the dynamic modulus value decreased. Therefore, to obtain the high dynamic modulus at 4.4˚C and 21.1˚C, it is important to have a sufficient fine content passing No. 8 sieve.

There is rather weak correlation between dynamic moduli vs. stiffness and content of residual asphalt binder where the dynamic modulus values increased as softer the residual asphalt and lesser the residual asphalt amount. It is somewhat contrary to the concept that the dynamic modulus of the RAP materials would increase with stiff and more residual asphalt content.

Given the assumption that RAP materials with the high modulus value at 4.4˚C would be more resistant to fatigue cracking, CIR-foam pavements constructed using RAP materials from both Muscatine and Webster Counties will last longer than others. However, based on the assumption that RAP materials with the high modulus at 37.8˚C would be more resistant to rutting, CIR-foam pavements constructed using RAP materials from Webster and Wapello Counties will have a longer service life than others.

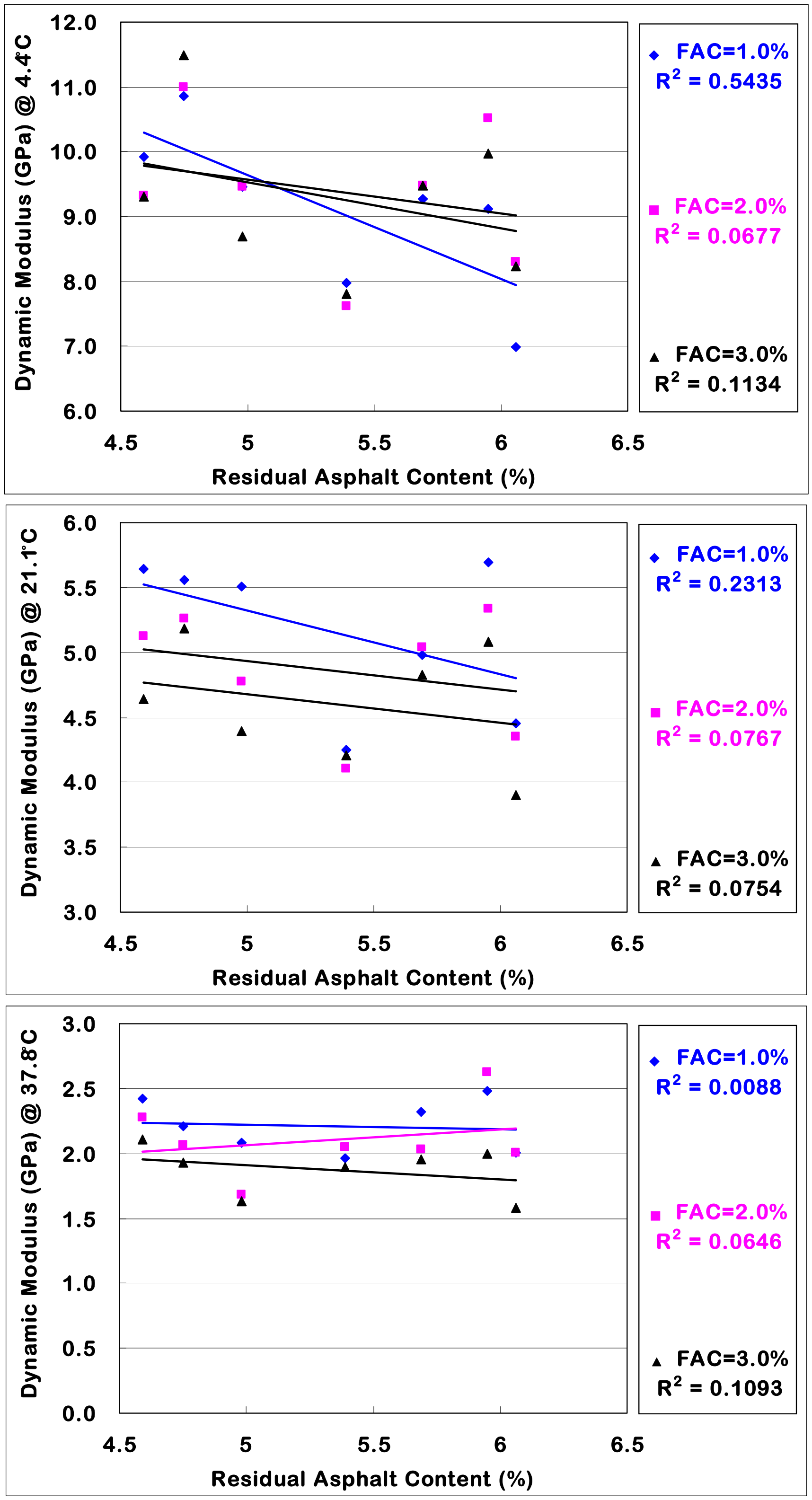


Figure 8-18. Correlation between dynamic moduli and residual asphalt content at three different temperatures

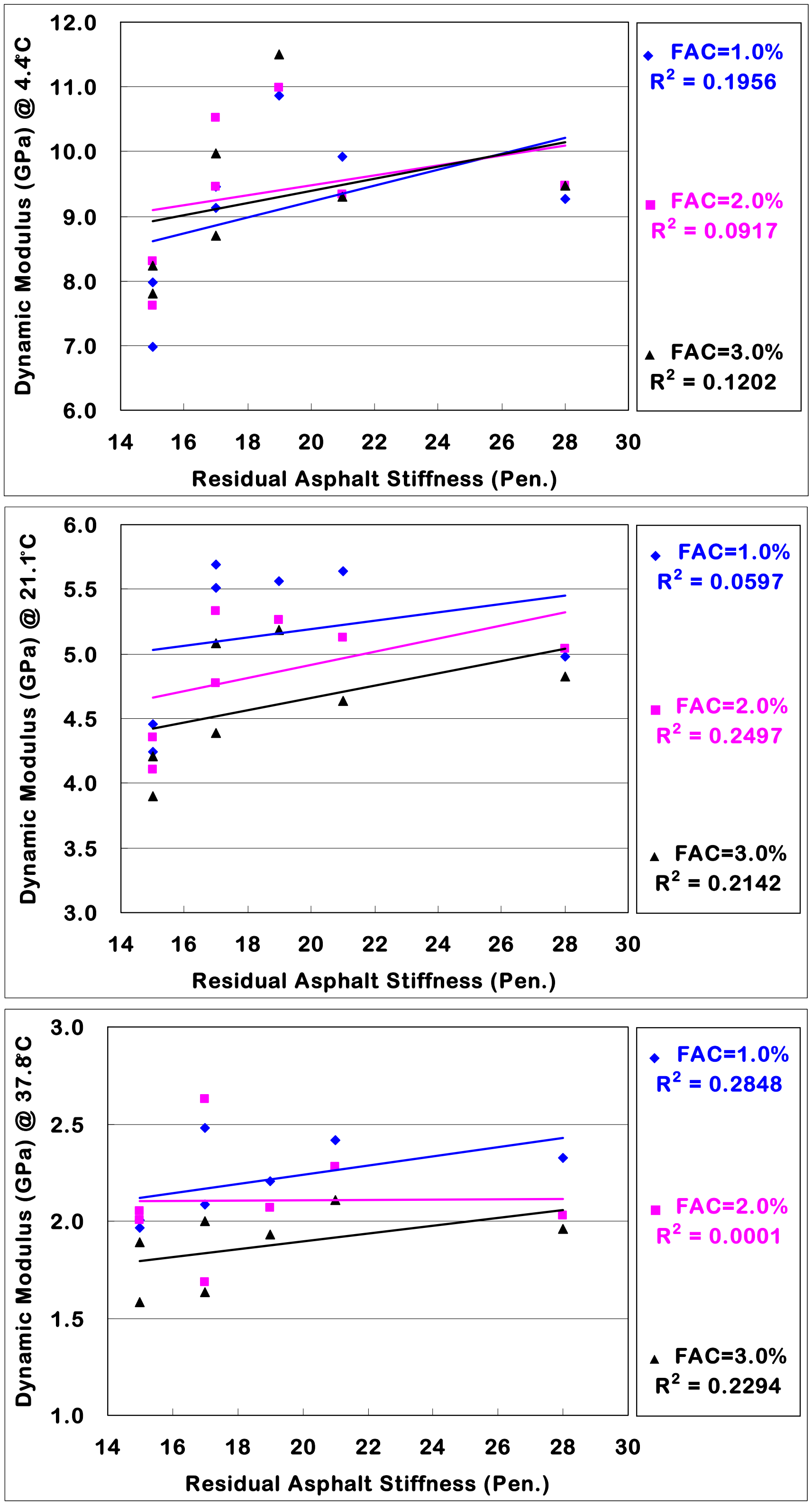


Figure 8-19. Correlation between dynamic moduli and residual asphalt stiffness at three different temperatures

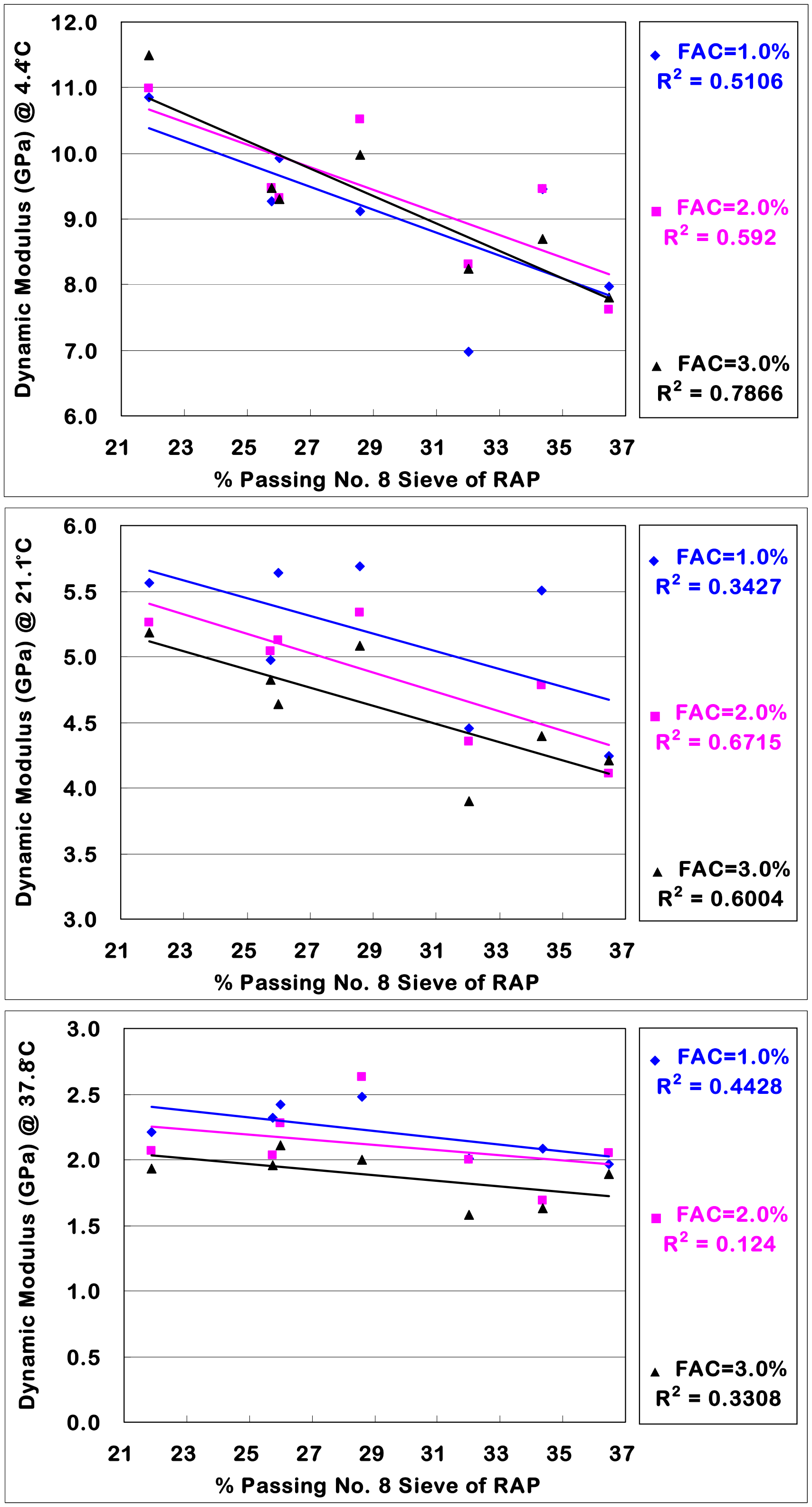


Figure 8-20. Correlation between dynamic moduli and amount of fine RAP materials passing No. 8 sieve at three different temperatures

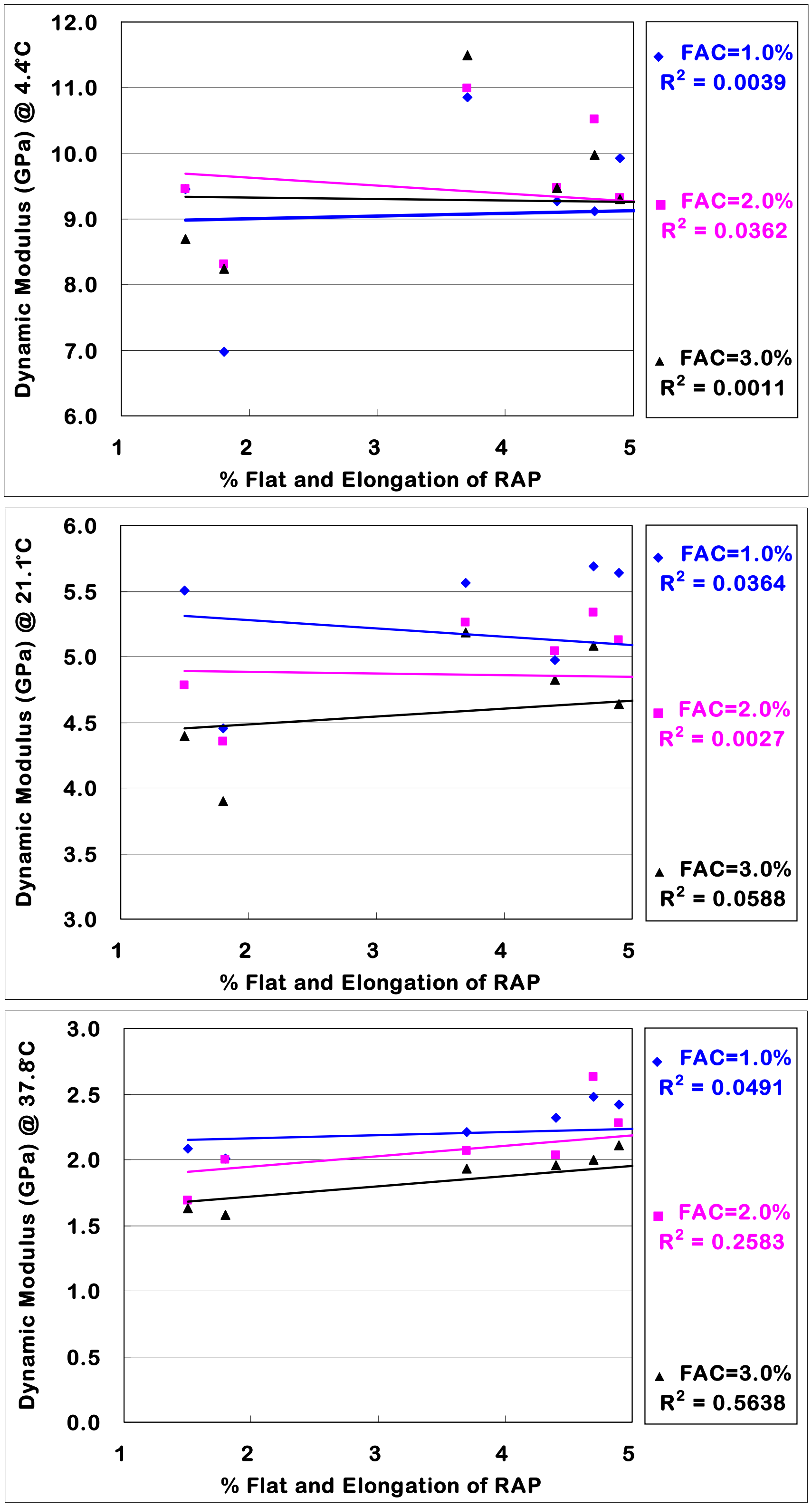


Figure 8-21. Correlation between dynamic moduli and flat & elongation ratio at three different temperatures

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) recommended the dynamic creep test as one of the simple performance tests for permanent deformation indicator for HMA mixtures. Kaloush et al. (2002) compared the flow time and flow number of HMA mixtures against rutting measurements from three experimental sites: Mn Road, FHWA-ALF, and WesTrack and reported that the flow time and flow number showed an excellent correlation with rut depths in these test tracks. Pan et al. (2006) reported the correlation between the flow number of HMA mixtures and the aggregate angularity and surface texture. Mohammand et al. (2006) reported that the flow number value of HMA mixtures had a fairly good relationship with the rut depth measured using Hamburg rut testing device. However, no research has been done to evaluate the permanent deformation potential of CIR mixtures using a dynamic creep test.

8.2.1 Theory

The dynamic creep test was developed to identify the permanent deformation characteristics of HMA mixtures, by applying several thousand repetitions of a repeated 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 8-22, 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):

1. Primary stage: high initial level of rutting, with a decreasing rate of plastic deformations, predominantly; associated with volumetric change.
2. Secondary stage: small rate of rutting exhibiting a constant rate of change of rutting that is also associated with volumetric changes; however, shear deformations start to increase at increasing rate.
3. Tertiary stage: high rate (level) of rutting predominantly associated with plastic (shear) deformations under no volume change conditions.

The permanent deformation increase rapidly in the primary stage and the incremental deformation decreases in the secondary stage. In the tertiary stage, the permanent deformations increase rapidly. The flow number (FN) is defined as number of loading cycles until the beginning of tertiary stage.

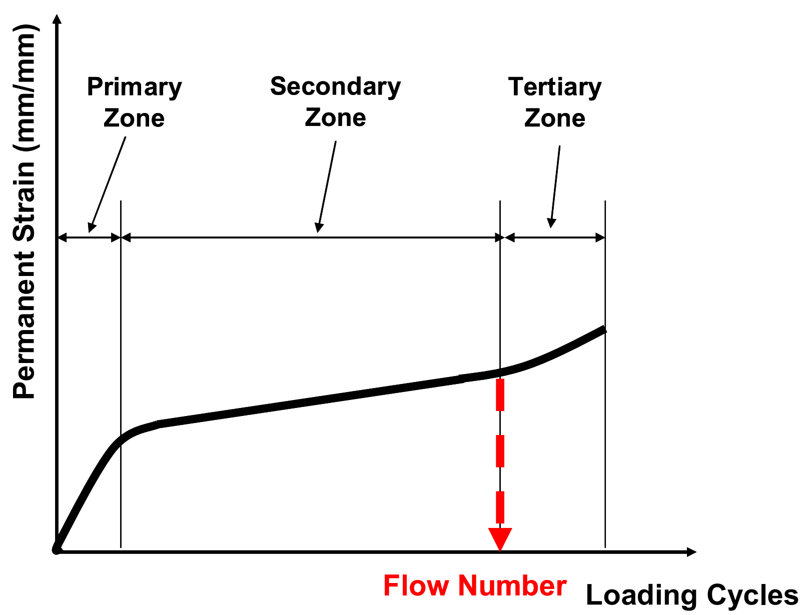
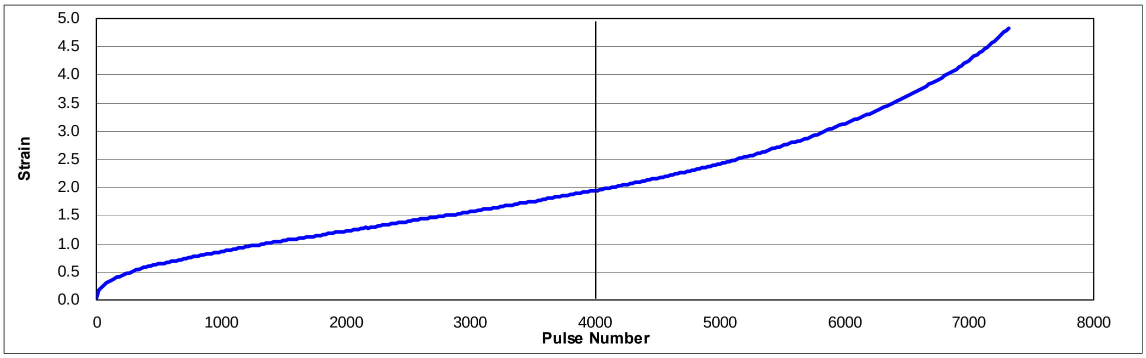
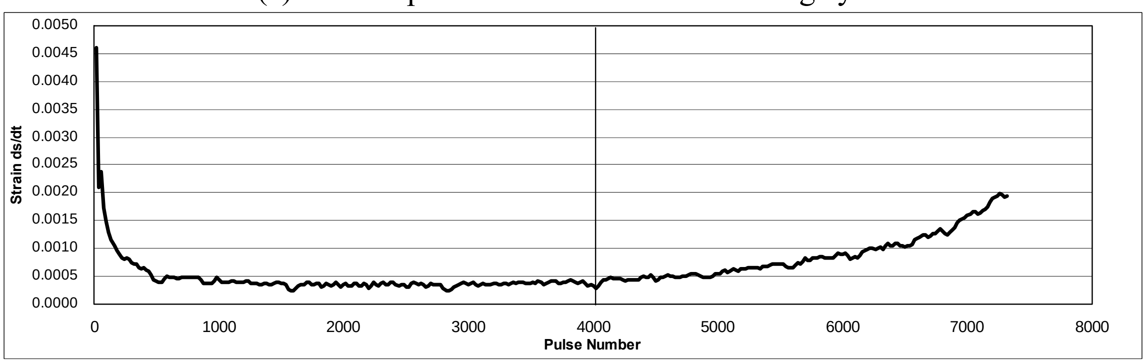


Figure 8-22. Permanent deformation behavior against loading cycles

Figure 8-23 (a) and (b) show plots of the accumulated permanent strain and the rate of change in permanent strain versus loading cycles, respectively, from the dynamic creep test conducted on the RAP materials from Hardin County. As shown in Figure 8-23 (b), the flow number is determined at the number of loading cycles when the rate of change in axial strain starts to increase near the 4,000 loading cycles.



(a) Plots of permanent strain versus loading cycle



(b) Rate of change in permanent strain versus loading cycle

Figure 8-23. Dynamic creep test results

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-foam 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 138kPa (20 psi) at 40˚C. A loading stress level of 138kPa 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 the 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% of cumulative permanent stain.

8.2.3. Experimental Plan

CIR-foam specimens were prepared to measure a flow number using seven different RAP sources. As summarized in Table 8-3**,** the mix design parameters identified in validation task were used to prepare each test specimen. For each RAP source, two specimens with 100-mm diameter and 150-mm height were prepared for each of three foamed asphalt contents. Using RAP materials from each source, a total of six CIR-foam specimens were compacted using the gyratory compactor at 30 gyrations and the compacted CIR-foam specimens were cured in the oven at 40°C for three days.

8.2.4 Results and Discussion

The bulk specific gravities and air voids were measured for each CIR-foam specimen. The dynamic creep tests were performed to evaluate:

1. rutting resistance of seven different RAP sources;
2. effect of the foamed asphalt content on rutting; and
3. correlation between flow number and RAP characteristics.

8.2.4.1 Volumetric Characteristics

The bulk specific gravities and air voids of each CIR-foam specimen were determined following the AASHTO T 166 by measuring the dry mass and height. As summarized in Table 8-17, overall, the bulk specific gravities seemed to increase as the foamed asphalt content increased. RAP materials from Hardin County showed the lowest bulk specific gravity whereas those from Wapello County showed highest bulk specific gravity. Air voids decreased gradually as the foamed asphalt content increased.

Table 8-17. Bulk specific gravities (G_{mb}) and air voids of CIR-foam specimens for dynamic creep test

RAP Source	FAC (%)	G_{mb} Individual		G_{mb} Average	G_{mm}	Air Void (%) Individual	Air Void (%) Average
Hardin County	1.0	# 1	2.042	2.037	2.388	14.5	14.7
		# 2	2.032			14.9	
	2.0	# 1	2.041	2.042	2.362	13.6	13.6
		# 2	2.043			13.5	
	3.0	# 1	2.044	2.050	2.343	12.7	12.5
		# 2	2.055			12.3	
Lee County	1.0	# 1	2.077	2.068	2.452	15.3	15.7
		# 2	2.059			16.0	
	2.0	# 1	2.085	2.077	2.422	13.9	14.3
		# 2	2.069			14.6	
	3.0	# 1	2.096	2.094	2.410	13.0	13.1
		# 2	2.091			13.2	
Webster County	1.0	# 1	2.069	2.060	2.411	14.2	14.6
		# 2	2.051			14.9	
	2.0	# 1	2.068	2.061	2.391	13.5	13.8
		# 2	2.053			14.1	
	3.0	# 1	2.130	2.112	2.358	9.7	10.5
		# 2	2.093			11.2	
Bremer County	1.0	# 1	2.068	2.077	2.442	15.3	15.0
		# 2	2.085			14.6	
	2.0	# 1	2.093	2.099	2.416	13.4	13.2
		# 2	2.104			12.9	
	3.0	# 1	2.121	2.111	2.396	11.5	11.9
		# 2	2.101			12.3	
Wapello County	1.0	# 1	2.118	2.104	2.459	13.9	14.5
		# 2	2.089			15.0	
	2.0	# 1	2.141	2.124	2.444	12.4	13.1
		# 2	2.107			13.8	
	3.0	# 1	2.168	2.151	2.411	10.1	10.8
		# 2	2.134			11.5	
Montgomery County	1.0	# 1	2.024	2.309	2.432	16.5	15.9
		# 2	2.053			15.3	
	2.0	# 1	2.032	2.046	2.375	14.4	13.9
		# 2	2.059			13.3	
	3.0	# 1	2.099	2.092	2.358	11.0	11.3
		# 2	2.085			11.6	
Muscatine County	1.0	# 1	2.040	2.032	2.464	17.2	17.6
		# 2	2.023			17.9	
	2.0	# 1	2.120	2.103	2.445	12.9	13.8
		# 2	2.086			14.7	
	3.0	# 1	2.177	2.163	2.413	9.8	10.4
		# 2	2.149			10.9	

8.2.4.2 Dynamic Creep Test Results

The dynamic creep tests were performed on CIR-foam mixtures under a loading stress level of 138kPa at 40˚C. For each RAP source, a total of six specimens were prepared using three different foamed asphalt contents of 1.0%, 2.0% and 3.0%. Table 8-18 summarizes flow number and cumulative strain for three different foamed asphalt contents of seven RAP sources.

Figure 8-24, Figure 8-25 and Figure 8-26 show plots of cumulative strain against the number of loading cycles measured from fourteen specimens prepared using RAP materials from seven RAP sources at the foamed asphalt contents of 1.0%, 2.0% and 3%, respectively. As shown in these figures, RAP materials from Muscatine County exhibited the lowest flow number at all foamed asphalt contents whereas those from Lee and Webster Counties obtained the highest flow number. It is interesting to note that the lower the foamed asphalt contents, the flow number was higher, which indicates the foamed asphalt content with 1.0% is more resistant to rutting than 2.0% and 3.0%. Characteristics of seven RAP materials are summarized in Table 8-19 along with the rankings in terms of flow number. The failed test specimens with a tertiary flow within 10,000 cycles are shaded in the table. It is interesting to note that more specimens failed as the foamed asphalt was increased from 1.0% to 3.0%. As can be easily observed from the table, rankings of RAP materials did not change when the foamed asphalt was increased from 1.0% to 3.0%, which confirms the consistency of the dynamic creep test in evaluating the rutting susceptibility of RAP aggregate structure. It can be observed that foamed asphalt content negatively affect the rutting resistance of CIR-foam mixtures.

Table 8-18. Flow number and cumulative strain at flow number

RAP Source	FAC (%)	No. of Specimen	Flow Number		Cumulative Stain at FN
			Individual	Average	
Hardin County	1.0	# 1	10000	10000	5.00%
		# 2	10000		5.00%
	2.0	# 1	3641	3841	2.04%
		# 2	4041		1.96%
	3.0	# 1	1161	1471	1.67%
		# 2	1781		1.93%
Lee County	1.0	# 1	10000	10000	5.00%
		# 2	10000		5.00%
	2.0	# 1	10000	8301	5.00%
		# 2	6601		2.31%
	3.0	# 1	2901	2831	1.69%
		# 2	2761		1.69%
Webster County	1.0	# 1	10000	10000	5.00%
		# 2	10000		5.00%
	2.0	# 1	7561	7431	2.22%
		# 2	7301		1.88%
	3.0	# 1	3221	2401	2.41%
		# 2	1581		1.93%
Bremer County	1.0	# 1	4001	4911	1.64%
		# 2	5821		1.49%
	2.0	# 1	1521	1671	1.64%
		# 2	1821		1.45%
	3.0	# 1	501	591	1.43%
		# 2	681		1.42%
Wapello County	1.0	# 1	10000	8271	5.00%
		# 2	6541		1.56%
	2.0	# 1	2701	2651	1.96%
		# 2	2601		1.98%
	3.0	# 1	641	561	1.68%
		# 2	481		1.77%
Montgomery County	1.0	# 1	2841	3441	1.83%
		# 2	4041		1.67%
	2.0	# 1	1041	1131	1.57%
		# 2	1221		1.44%
	3.0	# 1	621	731	1.74%
		# 2	841		1.60%
Muscatine County	1.0	# 1	501	481	1.39%
		# 2	461		1.50%
	2.0	# 1	381	381	1.43%
		# 2	381		1.18%
	3.0	# 1	501	511	1.71%
		# 2	521		1.74%

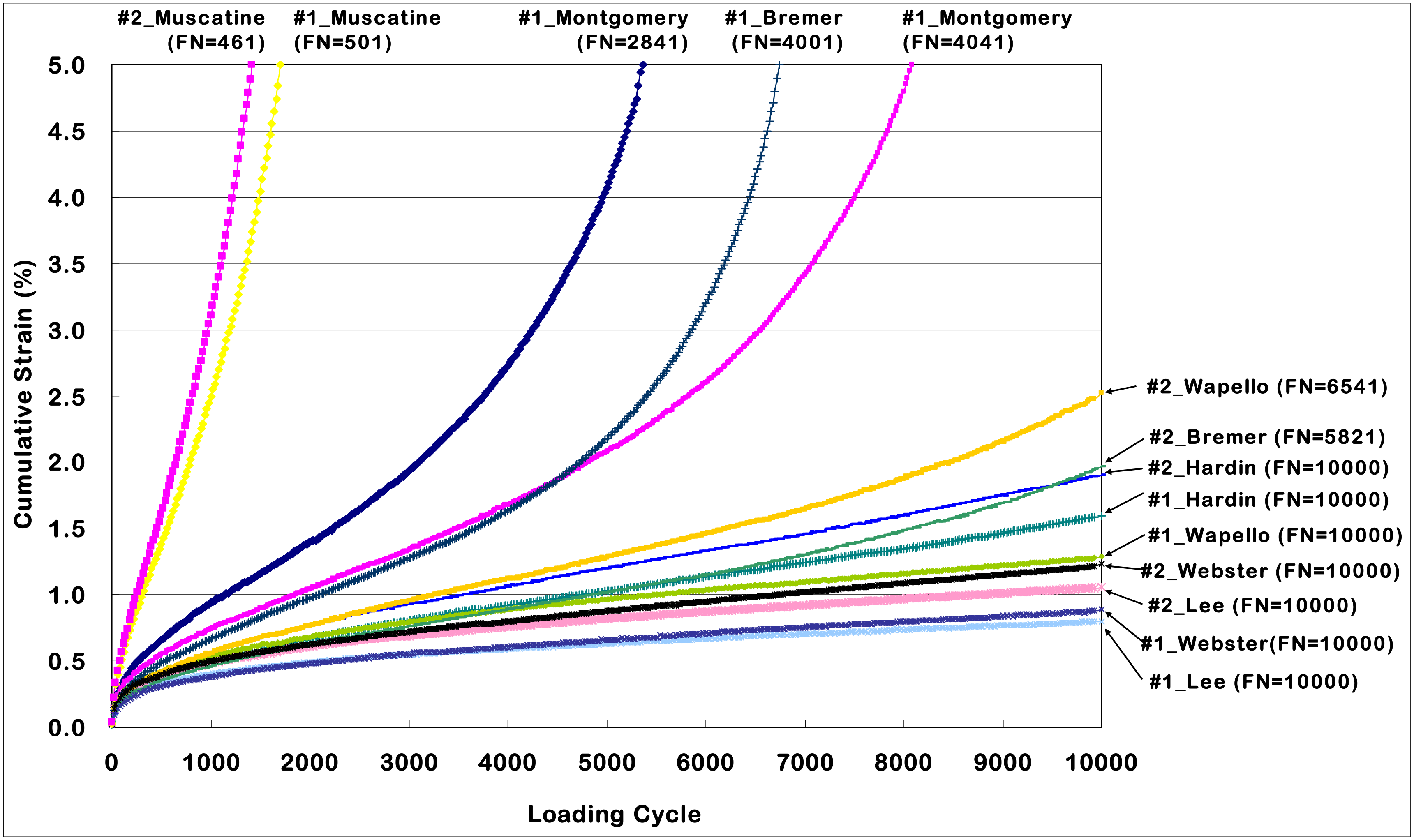


Figure 8-24. Plots of cumulative strain versus loading cycle at FAC=1.0%

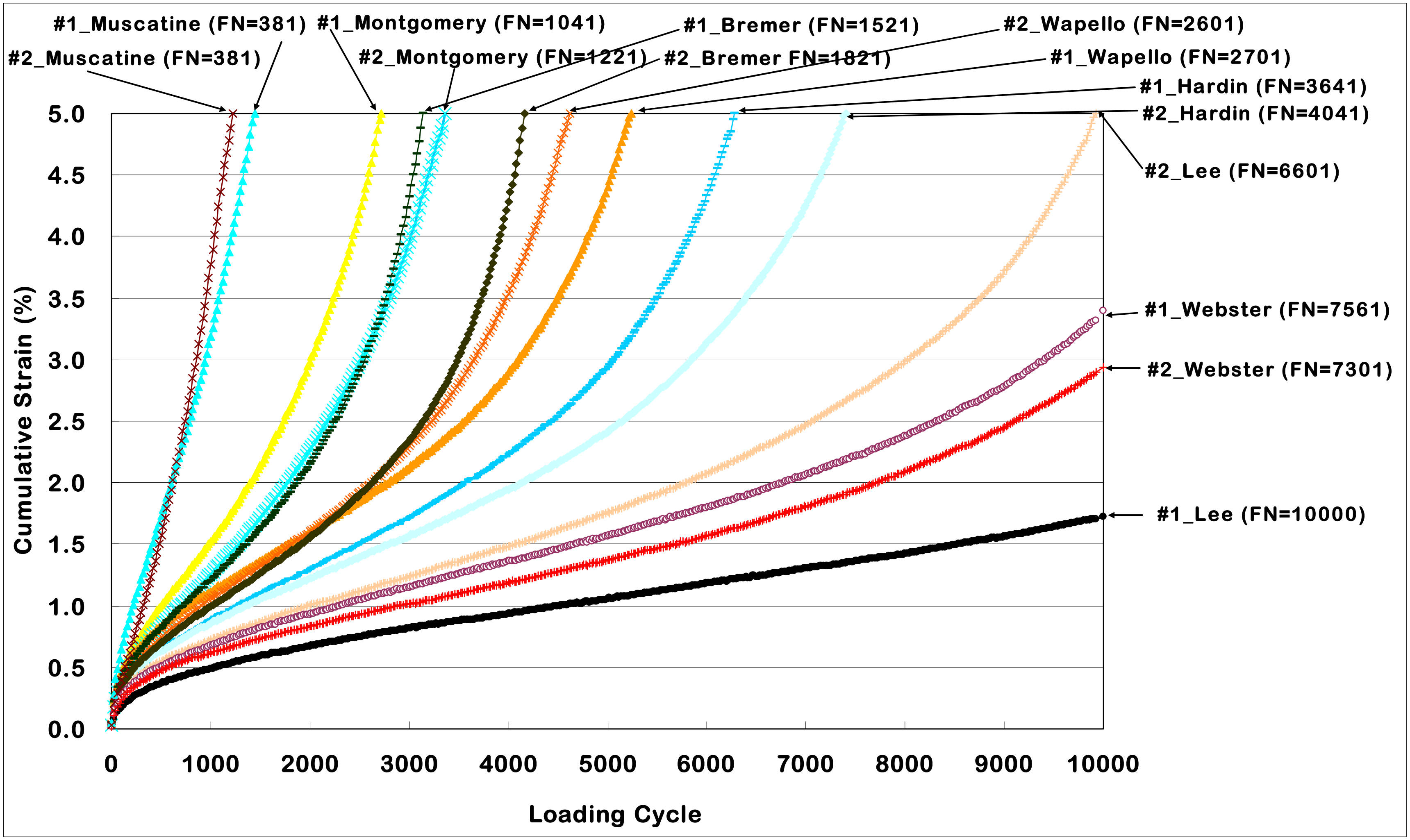


Figure 8-25. Plots of cumulative strain versus loading cycle at FAC=2.0%

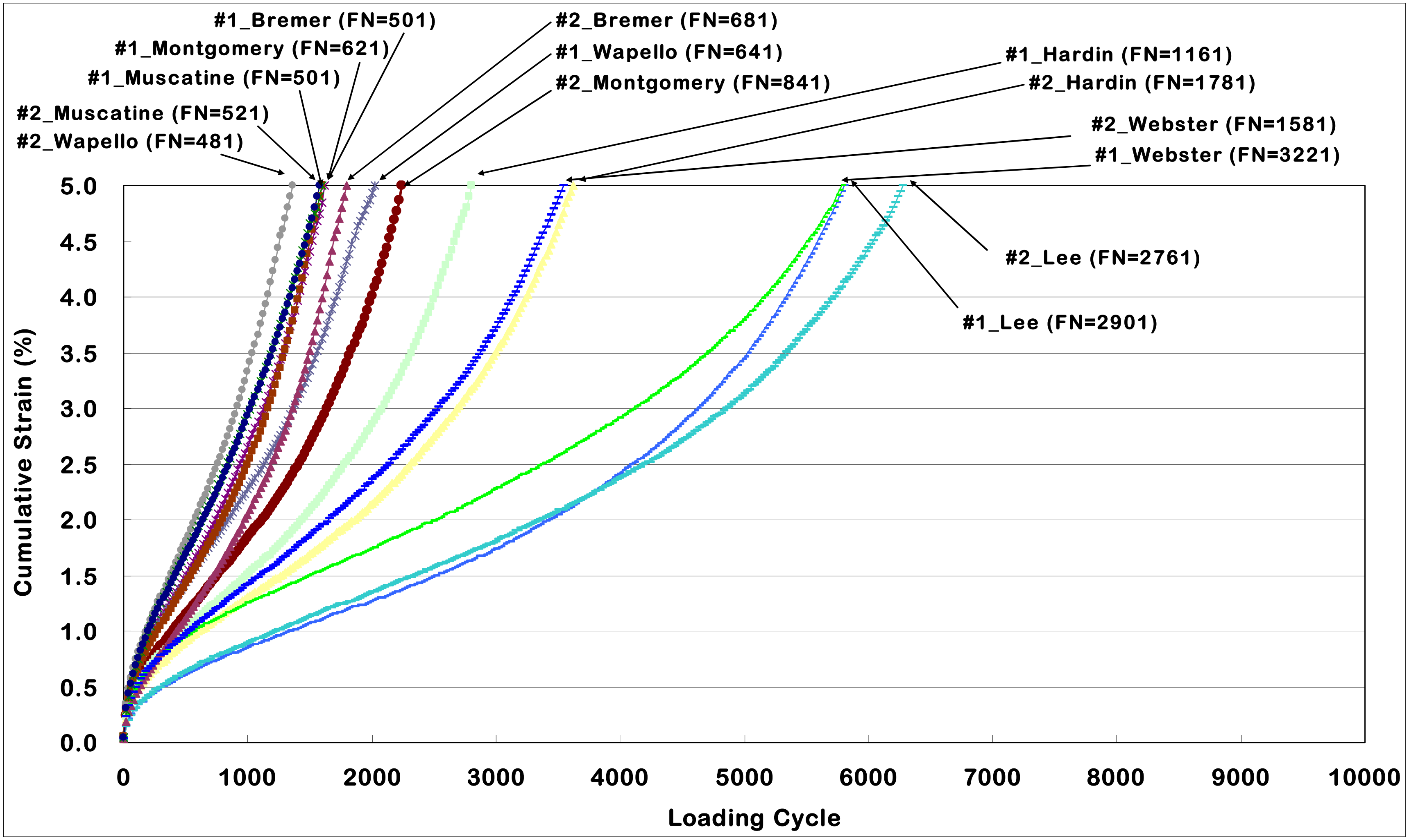


Figure 8-26. Plots of cumulative strain versus loading cycle at FAC=3.0%

Table 8-19. Rankings of flow number from seven different RAP sources

RAP Source	Stiffness (Pen.)	Residual AC (%)	% Passing No.8 Sieve	% Flat & Elongation	Ranking of Flow Number		
					FAC=1.0%	FAC=2.0%	FAC=3.0%
Lee County	Hard (15)	Middle (5.4%)	Fine (36.5%)	High (6.8%)	1	1	1
Webster County	Hard (17)	High (6.0%)	Middle (28.6%)	Middle (4.7%)	2	2	2
Hardin County	Hard (15)	High (6.1%)	Fine (32.0%)	Low (1.8%)	3	3	3
Wapello County	Soft (21)	Low (4.6%)	Coarse (26.0%)	Middle (4.9%)	4	4	6
Bremer County	Hard (17)	Middle (5.0%)	Fine (34.4%)	Low (1.5%)	5	5	5
Montgomery County	Soft (28)	High (5.7%)	Coarse (25.8%)	Middle (4.4%)	6	6	4
Muscatine County	Middle (19)	Low (4.7%)	Coarse (21.9%)	Middle (3.7%)	7	7	7

8.2.4.3 Impact of RAP Characteristics on Flow Number

To identify the impact of RAP characteristics on flow number, the following RAP characteristics were measured: 1) residual asphalt content, 2) residual asphalt stiffness, 3) gradation and 4) flat and elongation ratio. As can be seen from Figure 8-24 (1.0%), seven out of fourteen specimens did not show a tertiary flow within 10,000 loading cycles and it was not possible to obtain the FN. Therefore, the impact of RAP characteristics on flow number at 1.0% foamed asphalt content was not analyzed. Overall, all RAP materials with 1.0% foamed asphalt were extremely resistant to the permanent deformation except those from Muscatine, Montgomery and Bremer counties. Fourteen FN measurements of RAP materials for two foamed asphalt contents of 2.0% and 3.0% and seven RAP sources are plotted against each of four RAP characteristics in Figure 8-27, Figure 8-28, Figure 8-29 and Figure 8-30.

As shown in Figure 8-27, there seems to be a correlation between residual asphalt content and flow number, where the higher the residual asphalt content, the flow number increased. This result indicates that the RAP materials with the more residual binder are more resistant to rutting than ones with a small amount of residual binder. As shown in Figure 8-28, RAP materials with softer residual binder decreased the flow number whereas those with stiffer residual asphalt increased the flow number. This result indicates that the RAP materials with the harder residual binder are more resistant to rutting than ones with soft residual binder. As shown in Figure 8-29, there seems to be a correlation between the amounts of fines in the RAP materials passing No. 8 sieve and flow number. This result indicates that the RAP materials with a larger amount of fine materials are more resistant to rutting than ones with a coarse gradation. As shown in Figure 8-30, flat & elongation ratio of the RAP materials show a correlation where the more flat & elongated RAP materials exist, the flow number increased. It is contrary to the common belief that the more flat & elongated RAP materials would decrease the flow number. However, it can be postulated the other three RAP characteristics might have influenced the flow number more significantly than the flat & elongation ratio resulting in an unreasonable correlation.

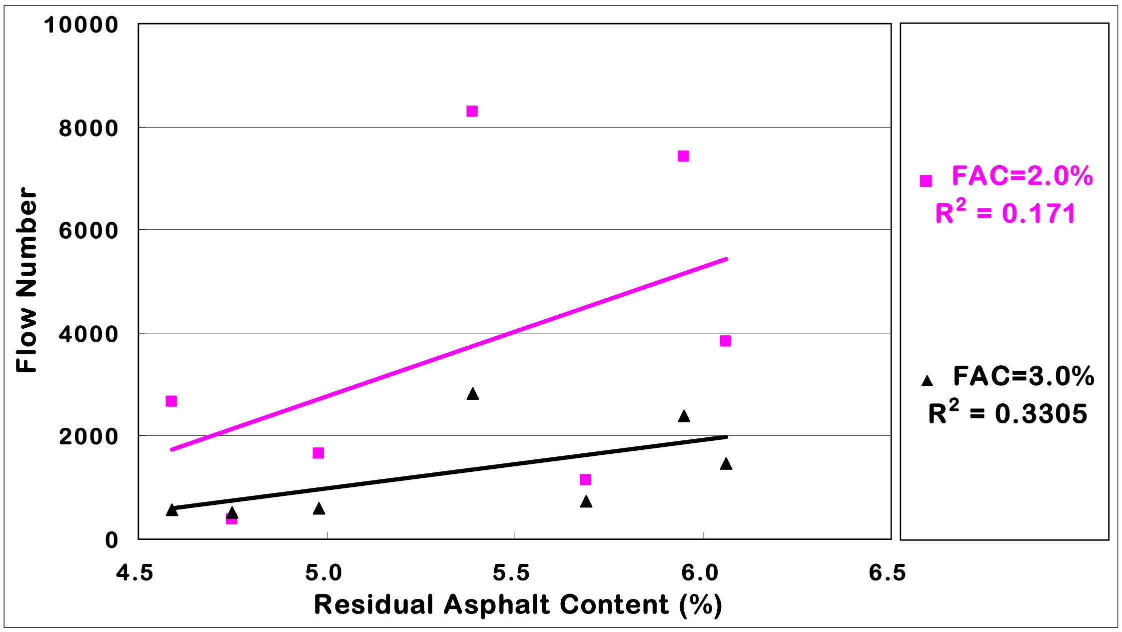


Figure 8-27. Correlation between flow number and residual asphalt content

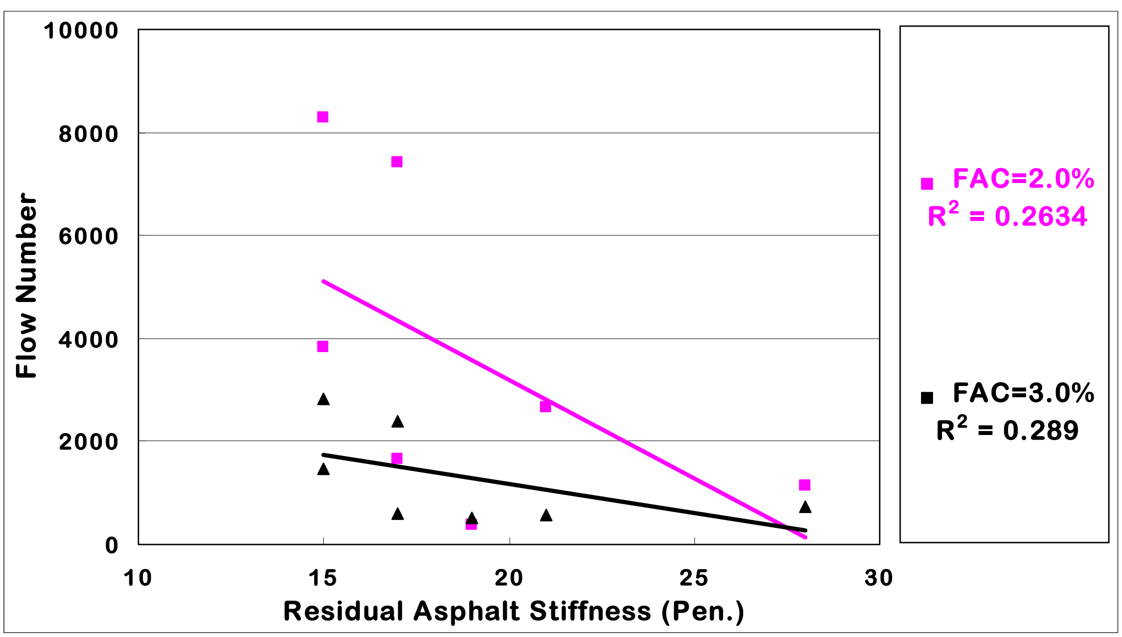


Figure 8-28. Correlation between flow number and residual asphalt stiffness

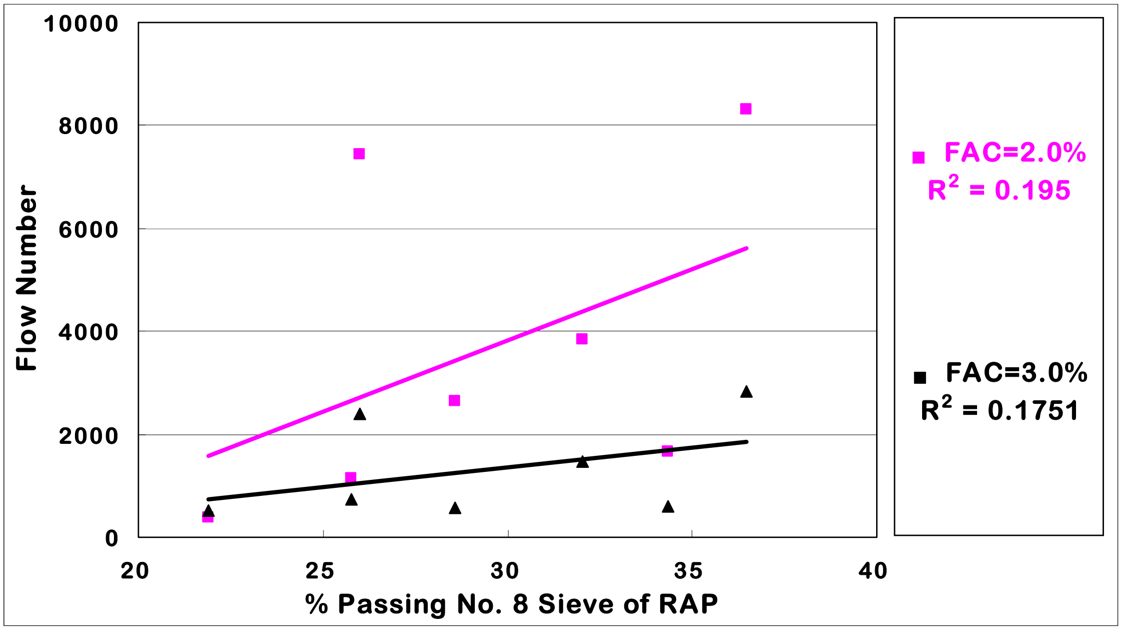


Figure 8-29. Correlation between flow number and % passing No.8 sieve

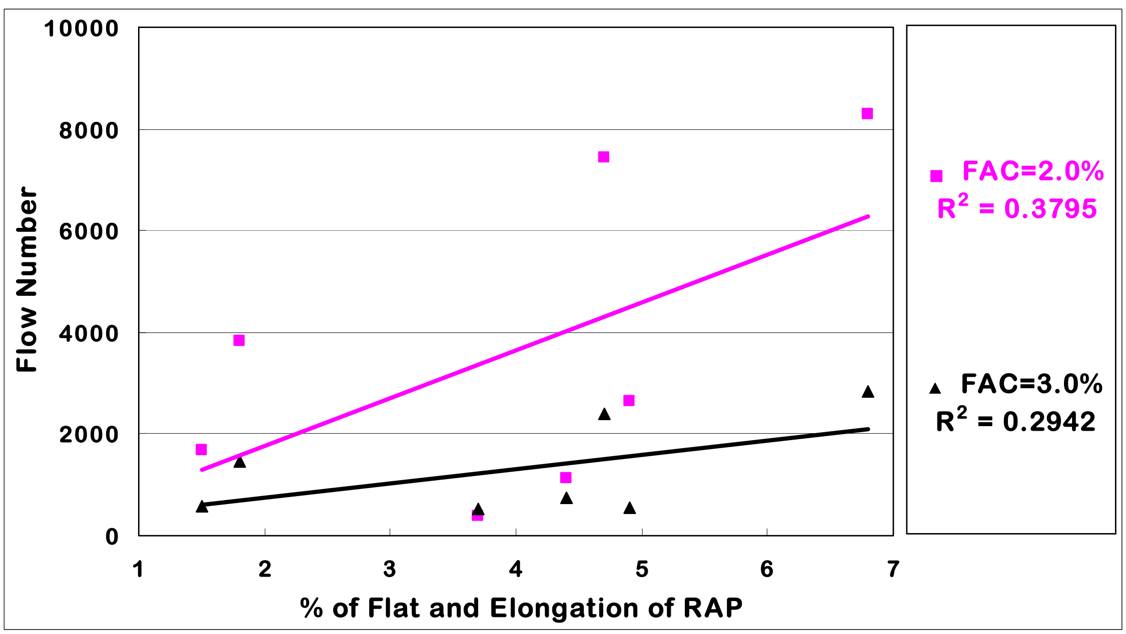


Figure 8-30. Correlation between flow number and % of flat and elongation

8.3. Raveling Test

A CIR-foam 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. Overlaying the CIR surface prior to adequate moisture loss through a proper curing may result in a premature failure of the CIR and/or HMA overlay (ARRA 2001). During the curing in the field, some raveling occurred from the surface of CIR pavement before HMA overlay is placed. Thomas et al. (2003) evaluated the engineering properties on CIR mixtures using the raveling test and they concluded that this test would help pavement engineers determine the optimum curing time of CIR mixtures.

8.3.1 Raveling Testing Procedure

The raveling test was performed to evaluate a resistance to raveling right after construction. As shown in Figure 8-31, Gyratory compacted 150-mm specimen is placed on a 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.

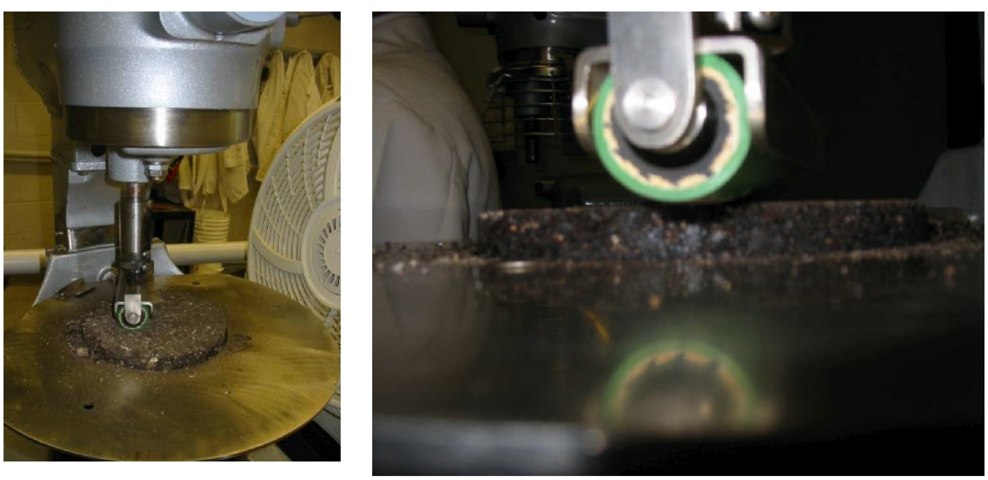
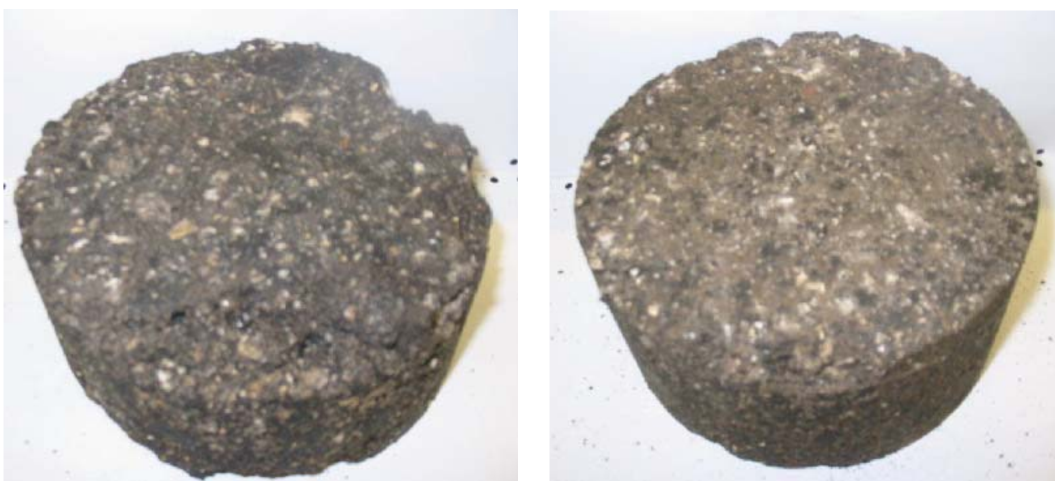


Figure 8-31. Pictures of raveling test equipment

For the raveling test, 150-mm specimens at two foamed asphalt contents, 1.5% and 2.5%, given a fixed moisture content of 4.0%, were prepared using the Superpave gyratory compactor at 25 gyrations. The specimens were cured at two different curing time periods, for 4 hours and 8 hours at the room temperature (24˚C). The specimens were then placed on the Hobart mixer fitted with an abrasion head and hose assembly, and abraded for 15 minutes. Figure 8-32 shows the damaged surface of specimens from after the raveling test from two different curing time periods. The repeatability of raveling test results should be ± 5% 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



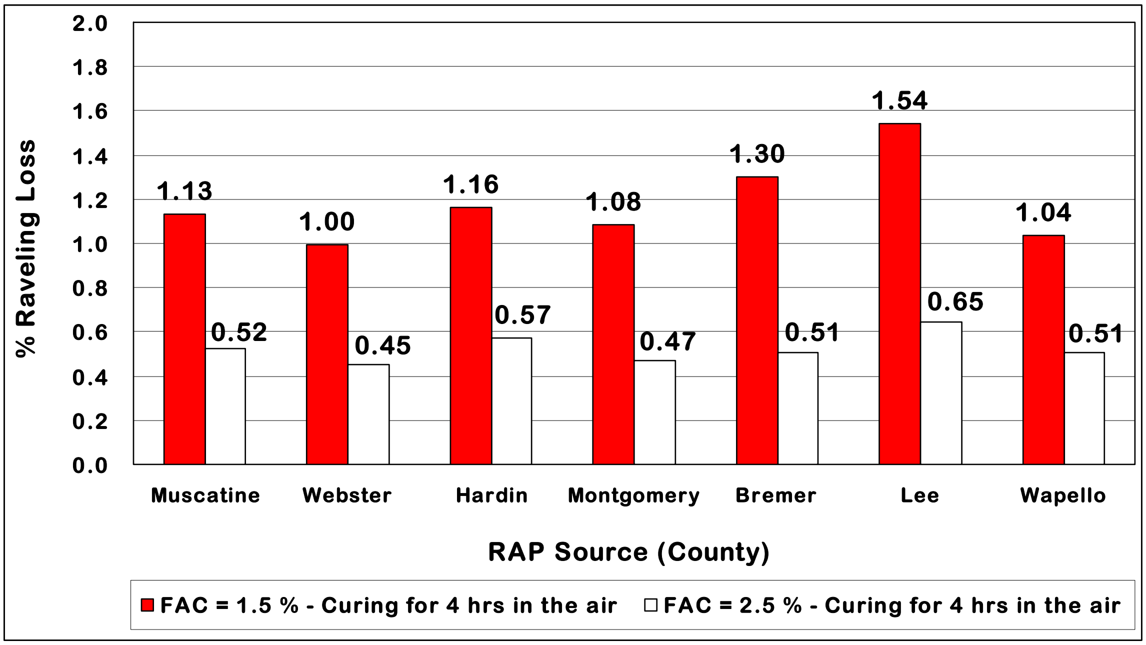
(a) Cured specimen for 4 hrs (b) Cured specimen for 8 hrs

Figure 8-32. Damaged surface of specimens at two curing time periods (FAC=2.5%)

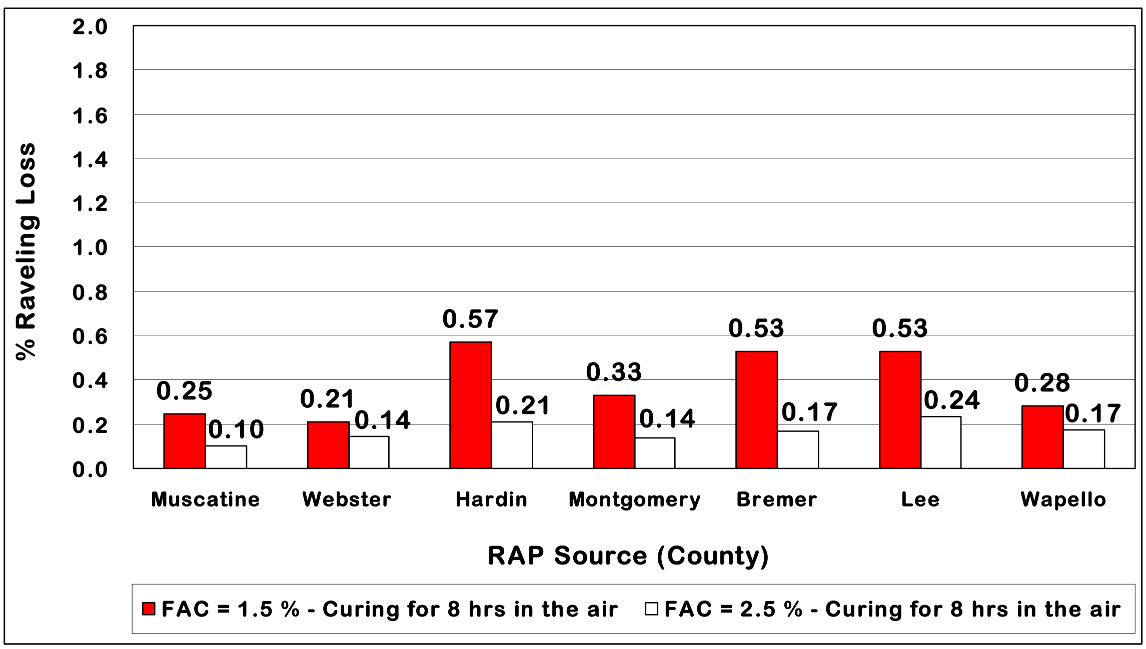
8.3.2 Test Results and Discussion

The percent mass loss of the foamed asphalt specimens at 1.5% FAC and 2.5% FAC for two different cuing time periods is plotted in Figure 8-33. Overall, the foamed asphalt specimens at 2.5% FAC showed less raveling loss than those of 1.5% FAC at either curing time periods. Percent raveling loss of the foamed asphalt specimens cured for 8 hours decreased significantly at either foamed asphalt contents. Given the RAP materials from seven different sources, after 4 hours of curing time in the room temperature, the foamed asphalt specimens of Lee County produced the highest percent raveling loss. However, when the specimens were cured for 8 hours of curing time, percent raveling loss was considerable decreased.

It was found that the raveling test was very sensitive to the curing period and foamed asphalt content of the CIR-foam specimens. The behavior after 4-hour curing would imply that, to increase cohesive strength quickly, it is necessary to use higher foamed asphalt content of 2.5% instead of 1.5%.



(a) Curing time: 4 hours



(b) Curing time: 8 hours

Figure 8-33. Percent raveling losses of foamed asphalt specimens from seven different RAP sources

8.4 Summary and Discussion

The simple performance tests, which include dynamic modulus test, dynamic creep test and raveling test, were adopted to evaluate the consistency of a new CIR-foam mix design process to ensure reliable mixture performance over a wide range of traffic and climatic conditions.

The dynamic modulus tests were performed on CIR-foam mixtures at six different loading frequencies and three different test temperatures. The dynamic moduli measured at three foamed asphalt contents were significantly different among seven RAP sources. At 4.4°C, dynamic modulus of RAP materials from Muscatine County was the highest, Webster County was second and Lee and Hardin Counties were the lowest. At 21.1°C, dynamic modulus of RAP materials from Webster County was the highest followed by Muscatine County whereas Lee and Hardin Counties stayed at the lowest level. At 37.8°C, dynamic modulus of RAP materials from Muscatine became the lowest whereas Webster County was the highest. It can be postulated that RAP material from Muscatine is sensitive to temperature because they were the coarsest with least amount of residual asphalt content. Therefore, the coarse RAP materials with a small amount of residual asphalt content may be more fatigue resistant at a low temperature but more susceptible to rutting at a high temperature. On the other hand, fine RAP materials with a large amount of hard residual asphalt content like Hardin County may be more resistant to rutting at high temperature but more susceptible to fatigue cracking at low temperature.

Since dynamic modulus of RAP materials was not significantly affected by loading frequencies, the frequency of 25 Hz, which represents a highway speed, was selected for further analysis. Based on the assumption that RAP materials with the high modulus at 37.8˚C would be more resistant to rutting, CIR-foam pavements constructed using RAP materials from Webster and Wapello Counties will have a longer service life than others.

A master curve was constructed for a reference temperature of 20˚C for each of seven RAP sources. A mater curve constructed for each of three different foamed asphalt contents matched the measured moduli quite well. Master curves are relatively flat compared to HMA mixtures, which supports that foamed asphalt mixtures are not as viscoelastic as HMA. More viscoelastic behavior was observed from the foamed asphalt mixtures with higher foamed asphalt content.

RAP materials from seven different sources were ranked by the dynamic modulus. Overall, the rankings of RAP materials changed when the foamed asphalt was increased from 1.0% to 3.0%, which indicates that the dynamic modulus values are affected by both foamed asphalt contents and RAP aggregate structure. Based on the dynamic modulus test results performed at 4.4˚C, the coarser RAP materials were more resistant to fatigue cracking. Based on the dynamic modulus test results performed at 37.8˚C, the finer RAP materials with the harder binder with a higher amount were more resistant to rutting.

RAP materials from Muscatine County exhibited the lowest flow number at all foamed asphalt contents whereas those from Lee and Webster Counties obtained the highest flow number. It is interesting to note that the lower the foamed asphalt contents, the flow number was higher, which indicates the foamed asphalt content with 1.0% is more resistant to rutting than 2.0% and 3.0%.

RAP materials from seven different sources were ranked by the flow number. Overall, the rankings of RAP materials did not change when the foamed asphalt was increased from 1.0% to 3.0%, which indicates that flow number is not affected by foamed asphalt content but affected by the RAP aggregate structure. It was also observed that foamed asphalt content negatively affected the rutting resistance of CIR-foam mixtures. The finer RAP materials with the harder binder with a higher amount were more resistant to rutting. This result is consistent with the findings based on dynamic modulus test performed at 37.8˚C.

RAP materials from Wapello and Webster Counties would be more resistant to both fatigue and rutting. RAP materials from Muscatine, Bremer and Montgomery

Counties would be more resistant to fatigue cracking but more susceptible to rutting. RAP materials from Hardin and Lee Counties would be more resistant to rutting but susceptible to fatigue cracking.

Based on the raveling test results, the foamed asphalt specimens at 2.5% FAC showed less raveling loss than those of 1.5% FAC. It was found that the raveling test was very sensitive to the curing period and foamed asphalt content of the CIR-foam specimens. To increase cohesive strength quickly, it is necessary to use higher foamed asphalt content of 2.5% instead of 1.5%.

9. SHORT-TERM PEROFRMANCE OF CIR PAVEMENTS

During the summer of 2004, to validate the developed mix design procedure of CIR-foam mixture, RAP materials were collected from seven CIR project sites, three CIR-foam sites and four CIR-ReFlex sites. To evaluate the short-term performance of CIR pavements, between June 13 and 23, 2005, the digital images were collected from these CIR project sites using Automated Image Collection System (AICS) and the images were analyzed to measure the length, extent, and severity of different types of distress, particularly, longitudinal crack, transverse crack, alligator crack, block crack, and edge crack.

9.1 Data Collection and Analysis Tools for Surveying Pavement Distress

As shown in Figure 9-1, the AICS was used to collect the digital images of the pavement surface at approximately 9-ft (2.7 m) from the ground. As shown in Figure 9-2, the AICS captures an image of 776 by 582 pixels, which covers 140-inch (3.6 m) in width by 98-inch (2.5m) m in length on pavement surface. Each image was analyzed using the Manual Image Analysis System (MIAS) software. Lengths of longitudinal, transverse and edge cracks are measured in inch and the areas of alligator and block cracks are measured in square inch.

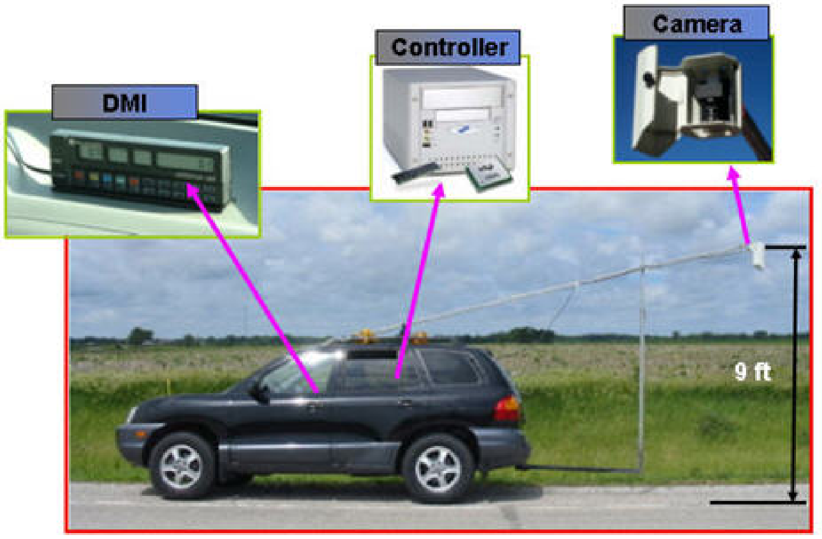


Figure 9-1. Picture of automated image collection system

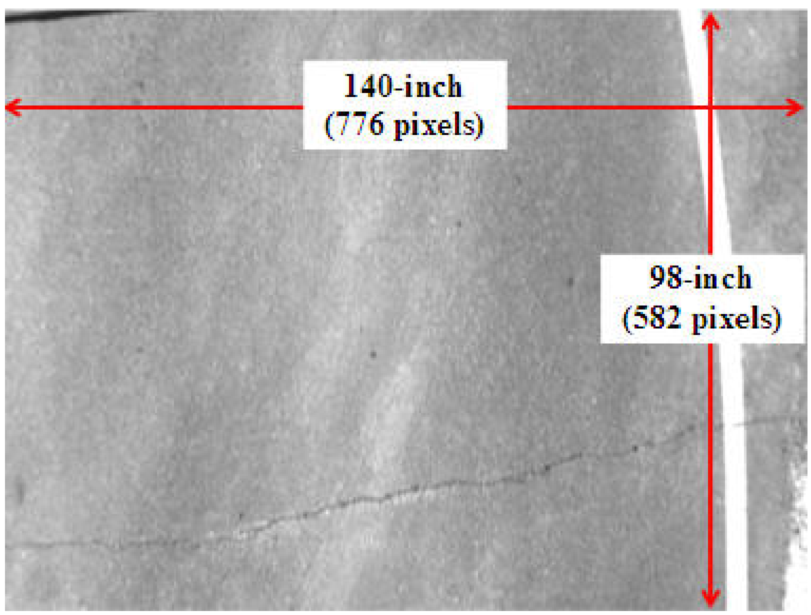


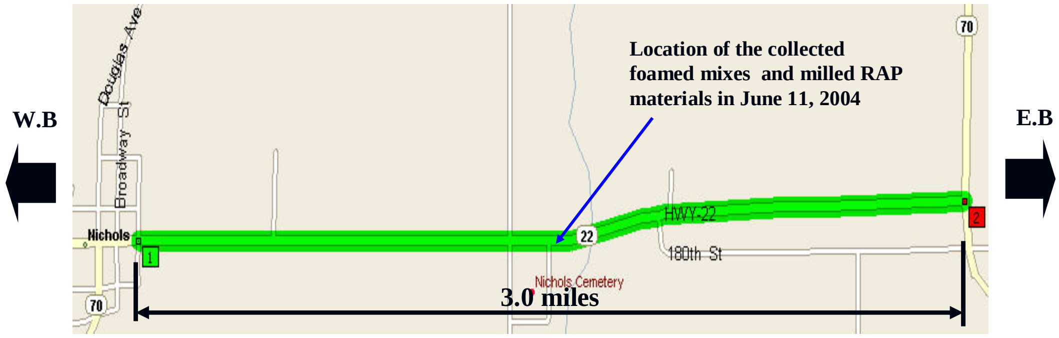
Figure 9-2. Digital image dimension

9.2 Surface Conditions of the Overlaid HMA Pavement on CIR Layer

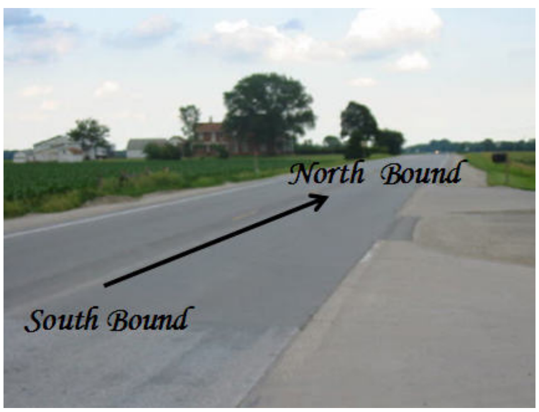
100-ft sections at both beginning and end of the HMA overlay on CIR layer were surveyed, where new and old pavement conditions were observed. Table 9-1 to Table 9-7 summarize the distress on the HMA overlay on the CIR layer from seven CIR project sites.

Table 9-1. Distress data of CIR-foam site surveyed in Muscatine County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-foam Layer



Summary of Distress Data

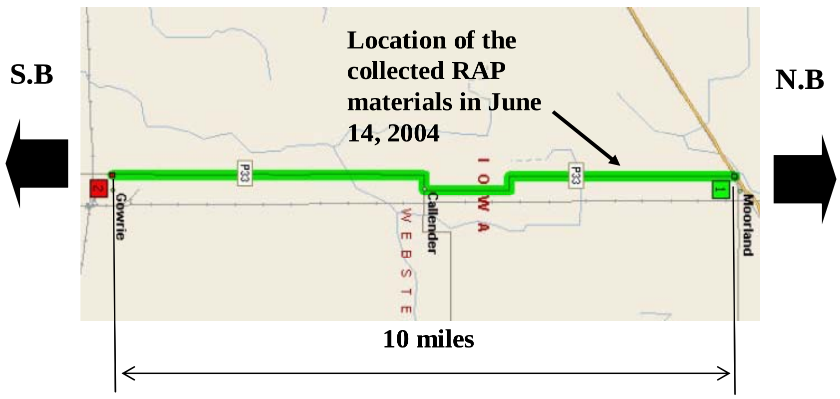
Survey Date	June 13, 2005	
Performance Age	1 year	
Direction	N.B	S.B
Rutting (ft)	0.0	0.0
Longitudinal Crack (ft)	40.8	24.3
Transverse Crack (ft)	217.0	202.6
Alligator Crack (ft^2)	0.0	0.0
Block Crack (ft^2)	0.0	0.0
Edge Crack (ft)	0.0	0.0

Description

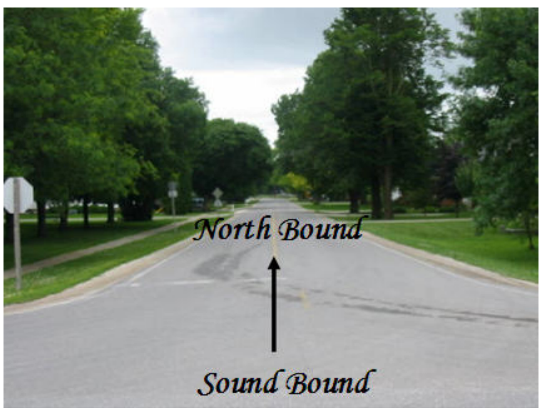
The length of the overlaid HMA pavement on CIR-foam layer is 3 miles. No serious problems were observed during the survey. A few longitudinal cracks were measured and a few transverse cracks were measured by MIAS. These pavement distresses would not create serious performance problems. Longitudinal and transverse cracks were noted at the interface between rehabilitated pavement and un-rehabilitated pavement.

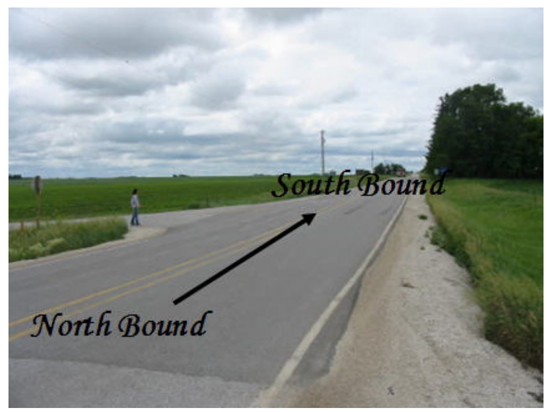
Table 9-2. Distress data of the CIR-ReFlex site surveyed in Webster County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-ReFlex Layer





Summary of Distress Data

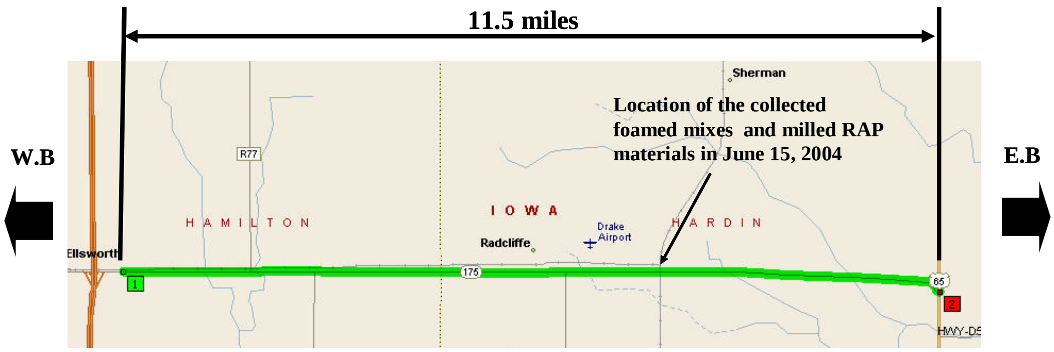
Survey Date	June 15, 2005	
Performance Age	1 year	
Direction	N.B	S.B
Rutting (ft)	0.0	0.0
Longitudinal Crack (ft)	0.0	0.0
Transverse Crack (ft)	290.3	276.3
Alligator Crack (ft^2)	0.0	0.0
Block Crack (ft^2)	0.0	0.0
Edge Crack (ft)	0.0	0.0

Description

The length of the overlaid HMA pavement on CIR-ReFlex layer is 10 miles. No serious problems were observed during the survey. A few transverse cracks were measured by MIAS. A half of transverse cracks were inspected across a lane and a half of them were inspected from center line to the middle of lane. It would not create serious performance problems.

Table 9-3. Distress data of the CIR-foam site surveyed in Hardin County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-foam Layer

Summary of Distress Data

Survey Date	June 15, 2005	
Performance Age	1 year	
Direction	E.B	W.B
Rutting (ft)	0.0	0.0
Longitudinal Crack (ft)	300.8	25.6
Transverse Crack (ft)	2019.1	1977.3
Alligator Crack (ft^2)	13.2	2.8
Block Crack (ft^2)	0.0	0.0
Edge Crack (ft)	0.0	0.0

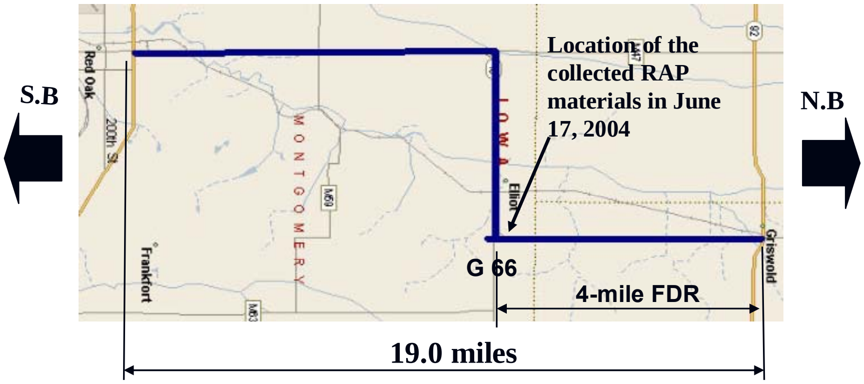
Description

The length of the overlaid HMA pavement on CIR-foam layer is 11.5 miles. No serious problems were observed during the survey. Longitudinal cracks of about 774-ft (236m) were measured and the longest transverse cracks of about 2787-ft (850-m) from the seven CIR project sites were measured by MIAS.

These pavement distresses would not create serious performance problems.

Table 9-4. Distress data of the CIR-ReFlex site surveyed in Montgomery County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-ReFlex Layer

Summary of Distress Data

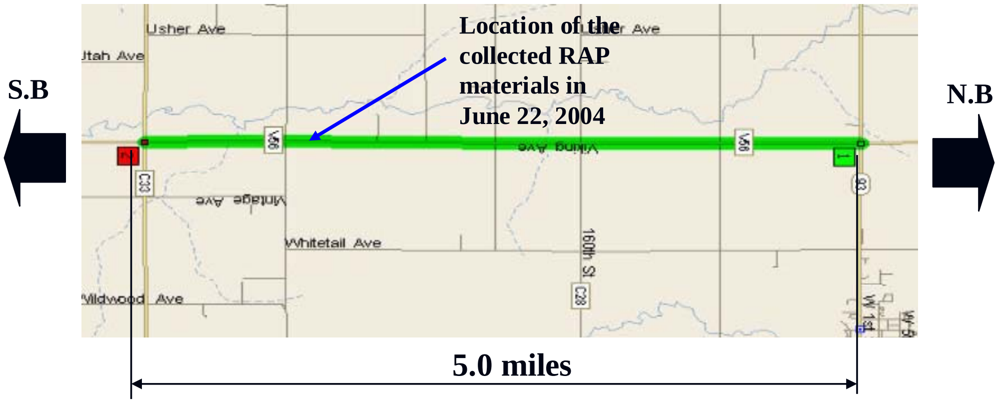
Survey Date	June 23, 2005	
Performance Age	1 year	
Direction	N.B	S.B
Rutting (ft)	0.0	0.0
Longitudinal Crack (ft)	12.0	0.0
Transverse Crack (ft)	68.8	98.4
Alligator Crack (ft^2)	4.8	0.0
Block Crack (ft^2)	0.0	0.0
Edge Crack (ft)	0.0	0.0

Description

The length of the overlaid HMA pavement on CIR-ReFlex layer and FDR-ReFlex is 19 miles. No serious problems were observed during the survey. A few longitudinal cracks were created and transverse cracks of about 181-ft (55-m) were measured by MIAS. These pavement distresses would not create serious performance problems.

Table 9-5. Distress data of the CIR-ReFlex site surveyed in Bremer County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-ReFlex Layer

Summary of Distress Data

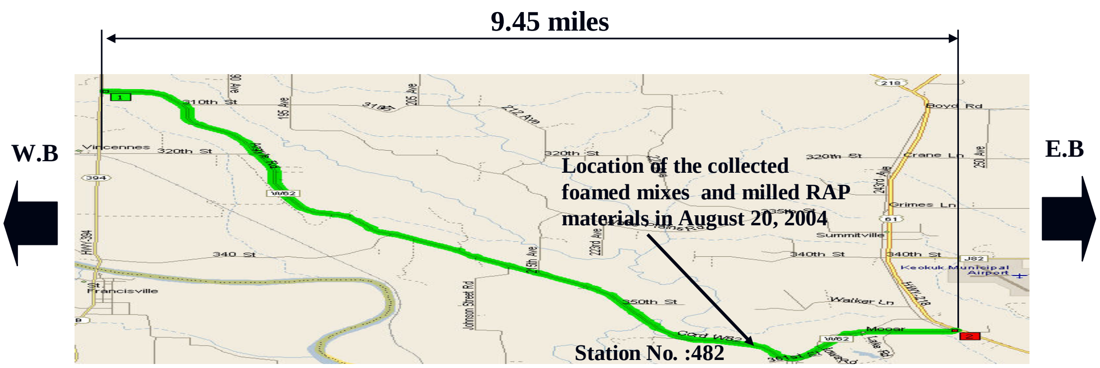
Survey Date	June 17, 2005	
Performance Age	1 year	
Direction	N.B	S.B
Rutting (ft)	0.0	0.0
Longitudinal Crack (ft)	4.8	9.8
Transverse Crack (ft)	30.0	28.5
Alligator Crack (ft^2)	24.9	4.1
Block Crack (ft^2)	0.0	0.0
Edge Crack (ft)	0.0	0.0

Description

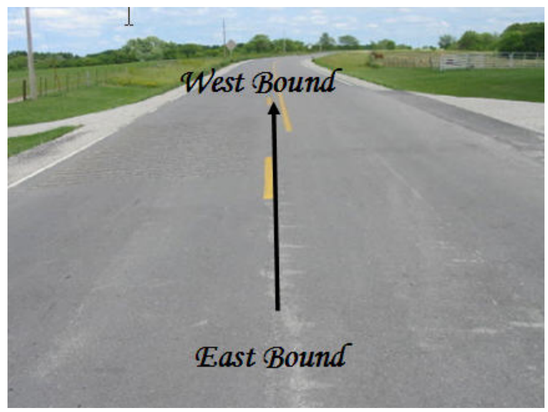
The length of the overlaid HMA pavement on CIR-Flex layer is 5.2 miles. No serious problems were observed during the survey. A few longitudinal and transverses cracks were created. However, These pavement distresses would not create serious performance problems.

Table 9-6. Distress data of the CIR-ReFlex site surveyed in Lee County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-ReFlex Layer



Summary of Distress Data

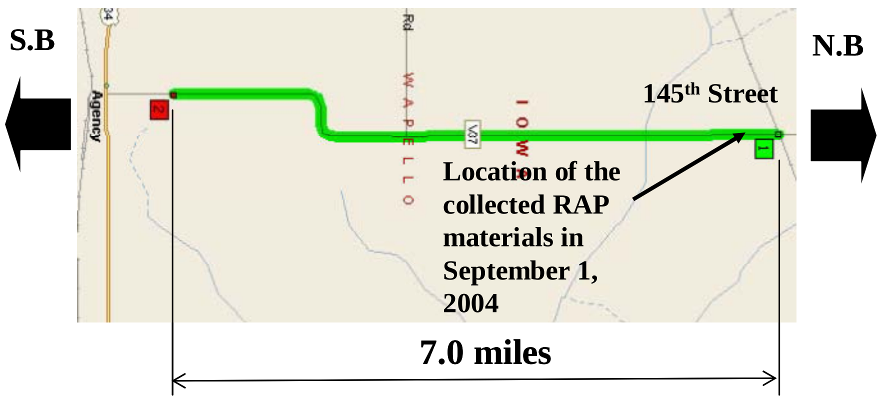
Survey Date	June 13, 2005	
Performance Age	1 year	
Direction	E.B.	W.B.
Rutting (ft)	0.0	0.0
Longitudinal Crack (ft)	2.1	0.0
Transverse Crack (ft)	11.7	0.0
Alligator Crack (ft^2)	0.0	0.0
Block Crack (ft^2)	0.0	0.0
Edge Crack (ft)	0.0	0.0

Description

The length of the overlaid HMA pavement on CIR-Emulsion layer is 9.45 miles. No serious problems were observed during the survey. A few longitudinal and transverses cracks were created. These pavement distresses would not develop serious performance problems.

Table 9-7. Distress data of the CIR-foam site surveyed in Wapello County

Survey Section



Pictures of Overlaid HMA Pavement on the CIR-foam Layer

Summary of Distress Data

Survey Date	June 13, 2005	
Performance Age	1 year	
Direction	N.B.	S.B.
Rutting (in)	0.0	0.0
Longitudinal Crack (in)	0.0	0.0
Transverse Crack (in)	0.0	0.0
Alligator Crack (in^2)	0.0	0.0
Block Crack (in^2)	0.0	0.0
Edge Crack (in)	0.0	0.0

Description

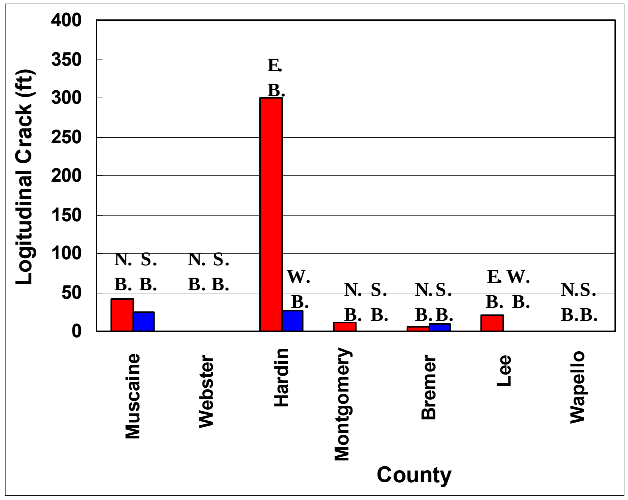
The full length of the overlaid HMA pavement on CIR-foam layer is 7.0 miles. No serious problems were observed during the survey. No distress was observed.

9.3 Analysis Process from the Measured Distress Data

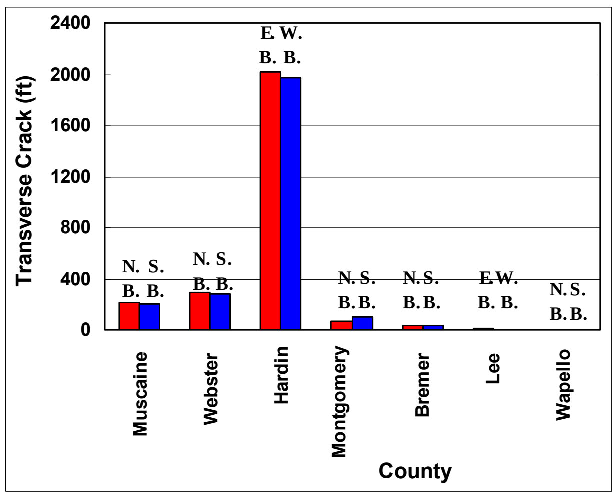
Table 9-8 summarizes distress data collected from seven project sites. All distress types were measured by MIAS for both directions. Minimal longitudinal, transverse, and alligator cracks were observed from six project sites, except Wapello County, which did not show any distress. No block and edge cracks were observed in any of these project sites. Figure 9-3 plots longitudinal, transverse, and alligator cracks for each project site. Although they are relatively small in quantity, pavements in Hardin and Bremer Counties exhibited the highest amounts of distress.

Table 9-8. Summary of distress data fro seven CIR project sites

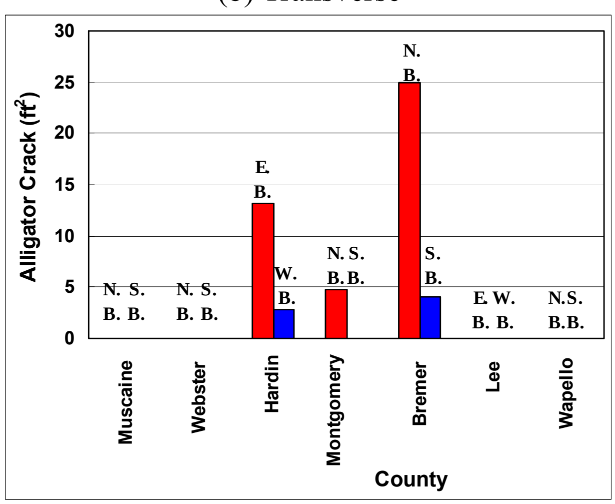
Distress Type / Project Site	Longitudinal crack (ft)		Transverse Crack (ft)		Alligator Crack (ft^2)		Block Crack (ft^2)		Edge Crack (ft^2)	
Direction	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B
Muscatine County	40.8	24.3	217.0	202.6	0.0	0.0	0.0	0.0	0.0	0.0
	65.1		419.6		0.0		0.0		0.0	
Direction	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B
Webster County	0.0	0.0	290.3	276.3	0.0	0.0	0.0	0.0	0.0	0.0
	0.0		566.6		0.0		0.0		0.0	
Direction	E.B	W.B	E.B	W.B	E.B	W.B	E.B	W.B	E.B	W.B
Hardin County	300.8	25.6	2019.1	1977.3	13.2	2.8	0.0	0.0	0.0	0.0
	326.4		3996.4		16.0		0.0		0.0	
Direction	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B
Montgomery County	12.0	0.0	68.8	98.4	4.8	0.0	0.0	0.0	0.0	0.0
	12.0		167.2		4.8		0.0		0.0	
Direction	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B
Bremer County	4.8	9.8	30.0	28.5	24.9	4.1	0.0	0.0	0.0	0.0
	14.6		58.5		29.0		0.0		0.0	
Direction	E.B	W.B	E.B	W.B	E.B	W.B	E.B	W.B	E.B	W.B
Lee County	2.1	0.0	11.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2.1		11.7		0.0		0.0		0.0	
Direction	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B	N.B	S.B
Wapello County	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.0		0.0		0.0		0.0		0.0	



(a) Longitudinal



(b) Transverse



(c) Alligator

Figure 9-3. Longitudinal, transverse, and alligator cracks measured from overlaid HMA pavement on CIR layer

In Muscatine County, as shown in Figure 9-4, a few longitudinal and transverse cracks were observed at the interface between rehabilitated pavement and un-rehabilitated pavement. As shown in Figure 9-5, **a** few longitudinal cracks were developed along the shoulder at both right and left sides in the beginning and end points of project sites.

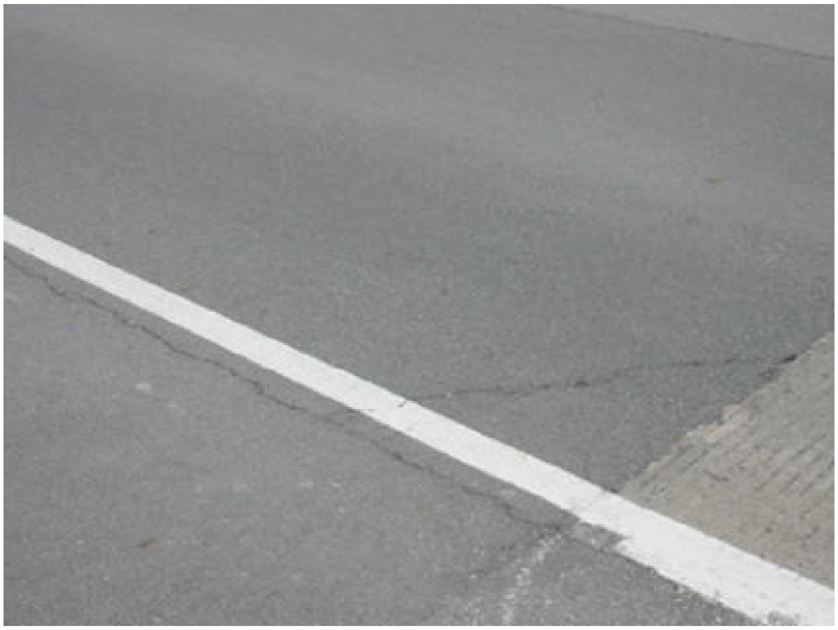


Figure 9-4. Longitudinal and transverse cracks at the interface between rehabilitated pavement and un-rehabilitated pavement

Figure 9-5. Longitudinal cracks created along the shoulder of both lanes

In Webster County, a few transverse cracks were observed. As shown in Figure 9-6, both full and partial-lane transverse cracks were observed.

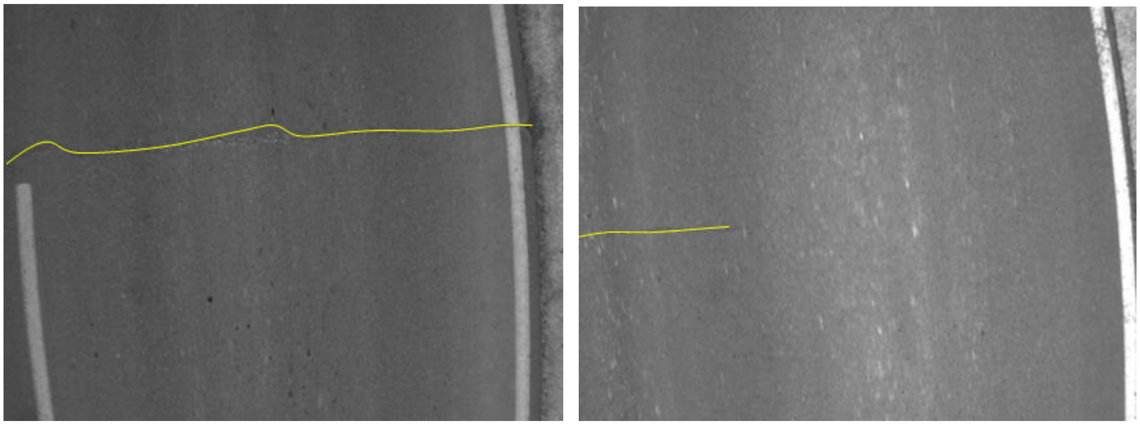


Figure 9-6 Transverse crack patterns measured from Webster County

In Hardin County, the largest amount of distress was observed. As shown in Figure 9-7, the highest amounts of longitudinal cracks were observed along the centerline of the pavement. As shown in Figure 9-8, a few transverse cracks were observed across a lane. As shown in Figure 9-9, alligator cracks were noted at the interface between the rehabilitated pavement and existing concrete bridge.

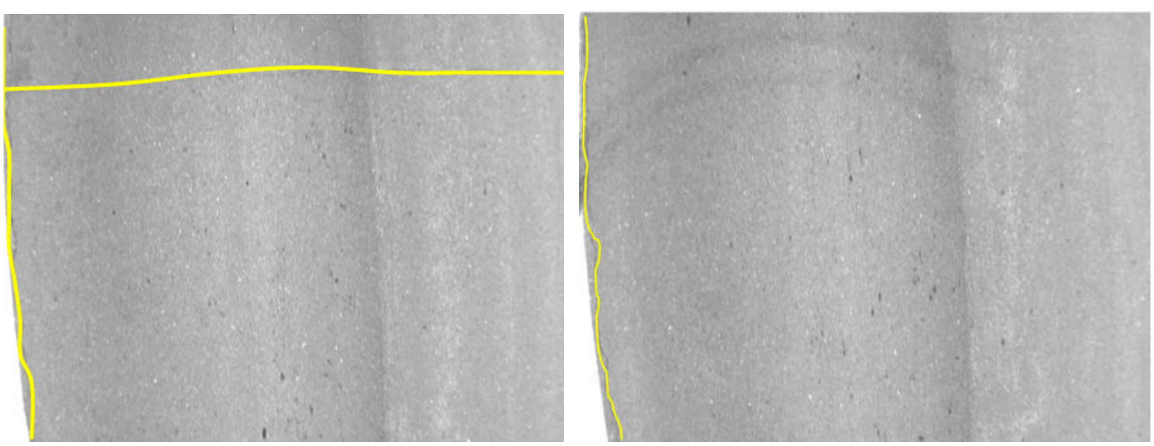


Figure 9-7. Longitudinal crack patterns measured form Hardin County

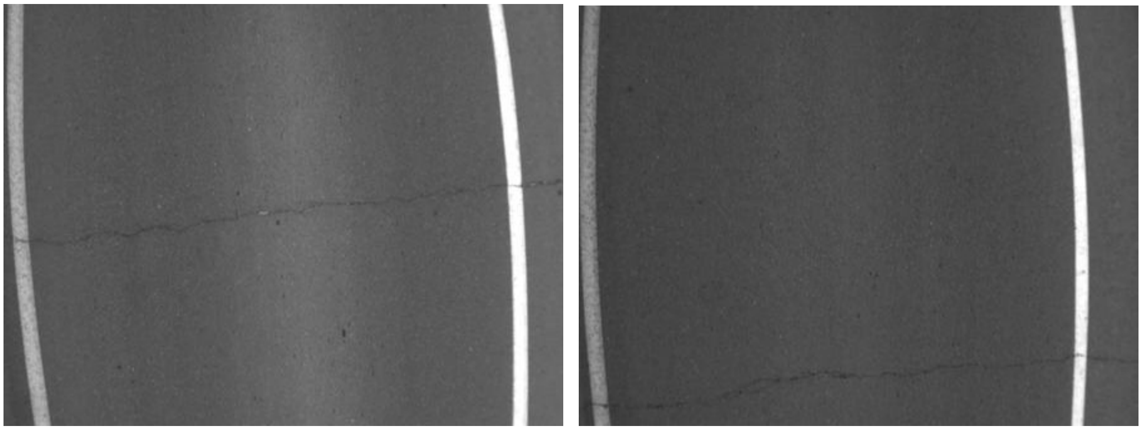


Figure 9-8. Transverse crack patterns measured from Hardin Countyd

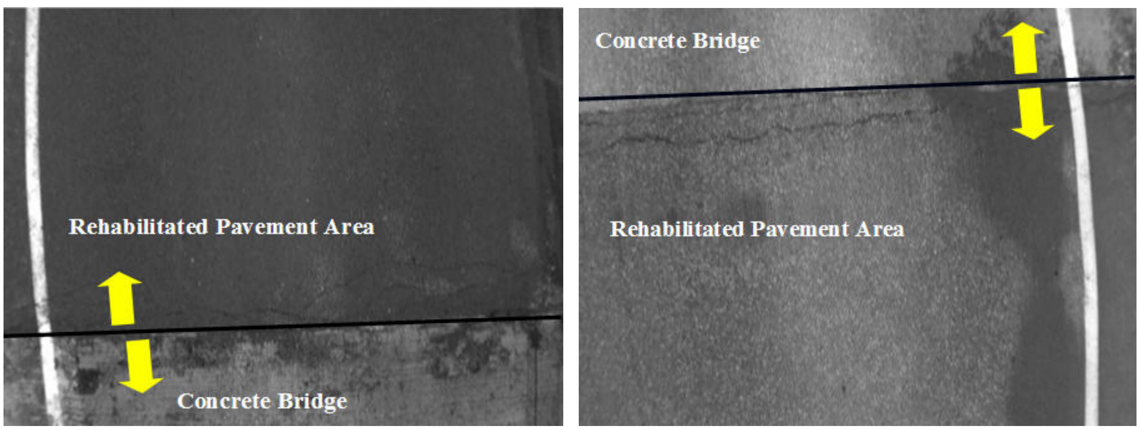


Figure 9-9. Alligator cracks at the interface between rehabilitated pavement and existing concrete bridge.

In Montgomery County, as shown in Figure 9-10, minimal longitudinal and transverse cracks were observed.

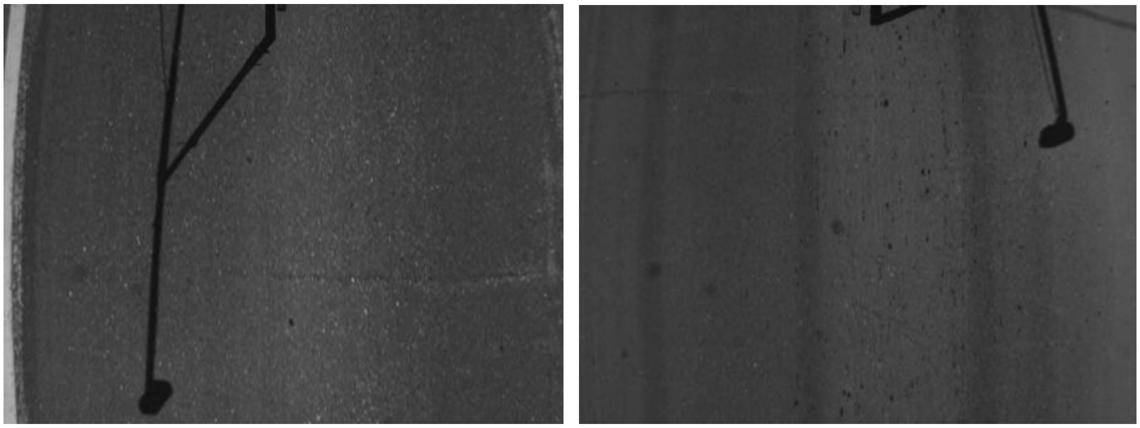


Figure 9-10. Longitudinal and transverse cracks measured from Montgomery County

In Bremer County, as shown in Figure 9-11, a few longitudinal and transverse cracks were observed. As shown in Figure 9-12, some cracks were developed at the interface between rehabilitated and un-rehabilitated pavements at the beginning and the end points of project site.

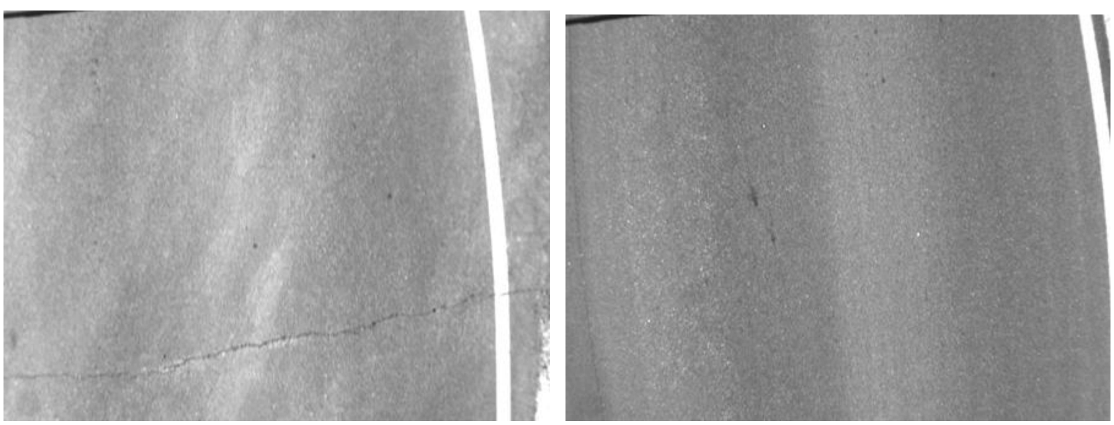


Figure 9-11. Longitudinal and transverse cracks measured from Bremer County

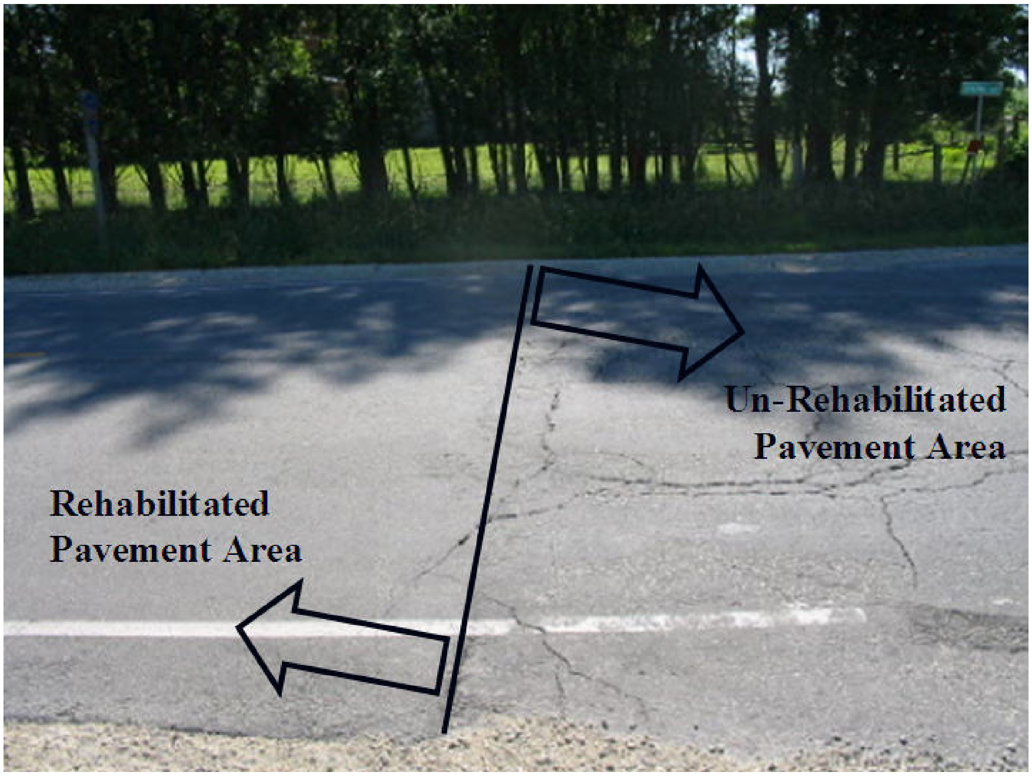


Figure 9-12. Cracks created at the interface between rehabilitated pavement and un-rehabilitated pavement

In Lee County, as shown in Figure 9-13, a small amount of longitudinal and transverse cracks was observed. In Wapello County, as shown in Figure 9-14, no distress was observed.

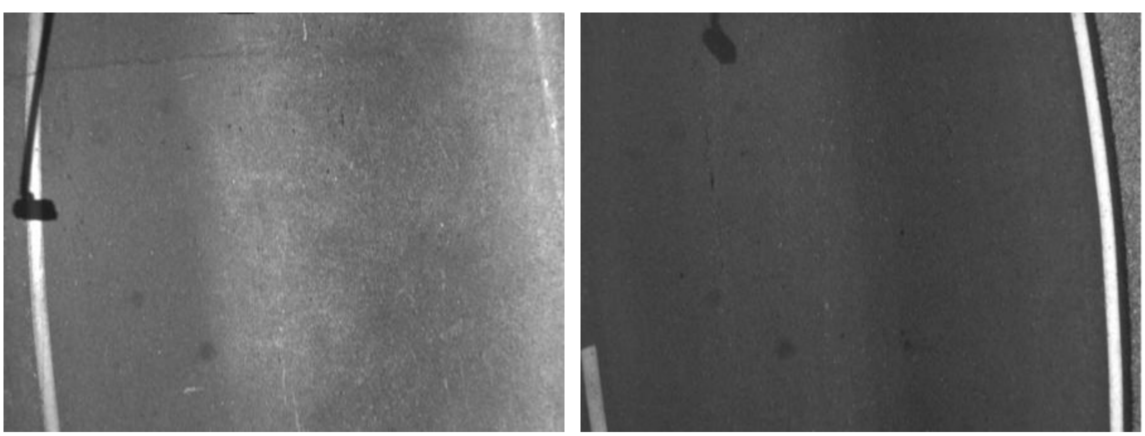


Figure 9-13. Longitudinal and transverse cracks measured from Lee County

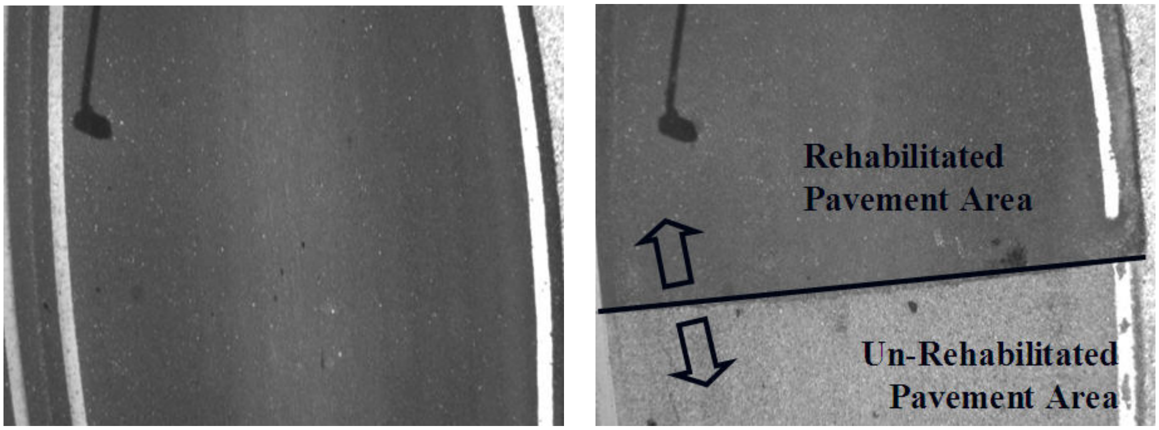


Figure 9-14. Images captured from survey from Wapello County

9.4 Pavement Condition Index (PCI)

Distress data collected from the HMA overlay on CIR layer were used to calculate the Pavement Condition Index (PCI). As shown in Figure 9-15, PCI method was developed by the Construction Engineering Research Laboratory of the U.S. Army Corps of Engineers using PAVER software program. PCI is a numerical rating of the pavement condition that ranges from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition. As shown in Figure 9-16, five CIR project sites in Muscatine, Webster County, Montgomery, Lee and Wapello Counties, obtained the perfect PCI value of 100 whereas two CIR project sites in Hardin and Bremer Counties, obtained PCI value of 97.

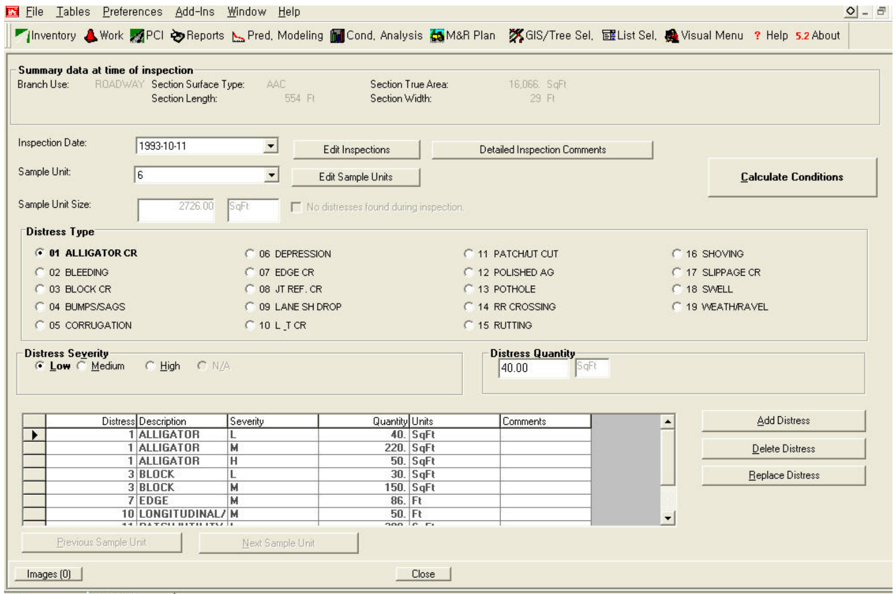


Figure 9-15. Main panel of PAVER software to calculate PCI

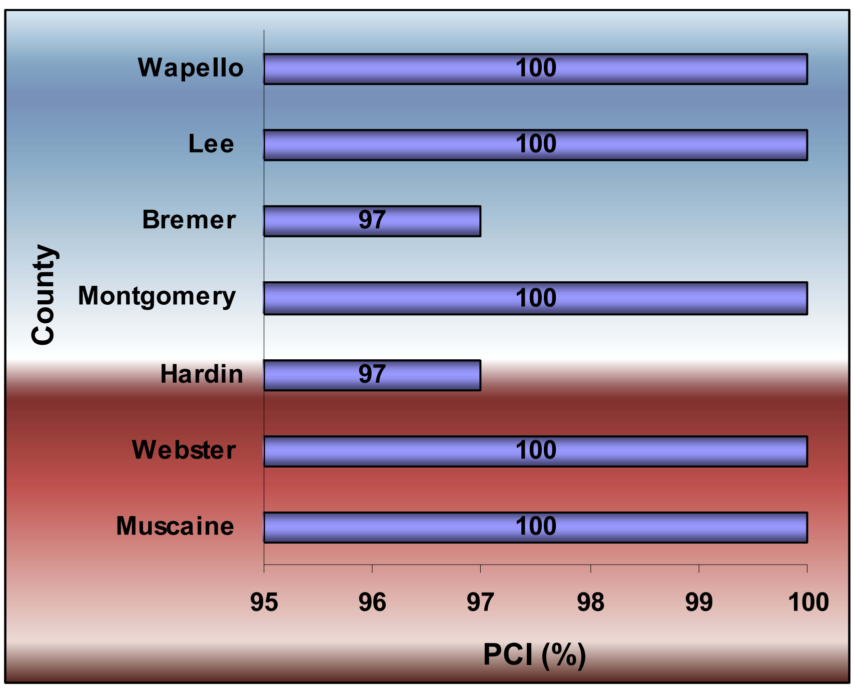


Figure 9-16. Comparison of PCI from distress data at seven CIR project sites

9.5 Summary

Based upon the condition survey result performed in one year after the construction, all have performed very well without any serious distress observed. The following specific observations are offered:

(1) Longitudinal and transverse cracks are observed at the interface between rehabilitated and un-rehabilitated pavements in Montgomery, Hardin, and Bremer Counties.

(2) Transverse crack occurs more frequently than longitudinal crack at most pavement sections, which is considered as the early distress type.

10. OBSERVATION OF CIR-FOAM CONSTRUCTION PROCESS

During the summer of 2005, to observe the construction process from milling operation to compaction process, as show in Figure 10-1, three CIR-foam project sites were selected from Decatur County, Harrison County and Johnson County. Additional RAP materials and foamed asphalt mixtures were collected from these sites verify the mix design as applied in construction.

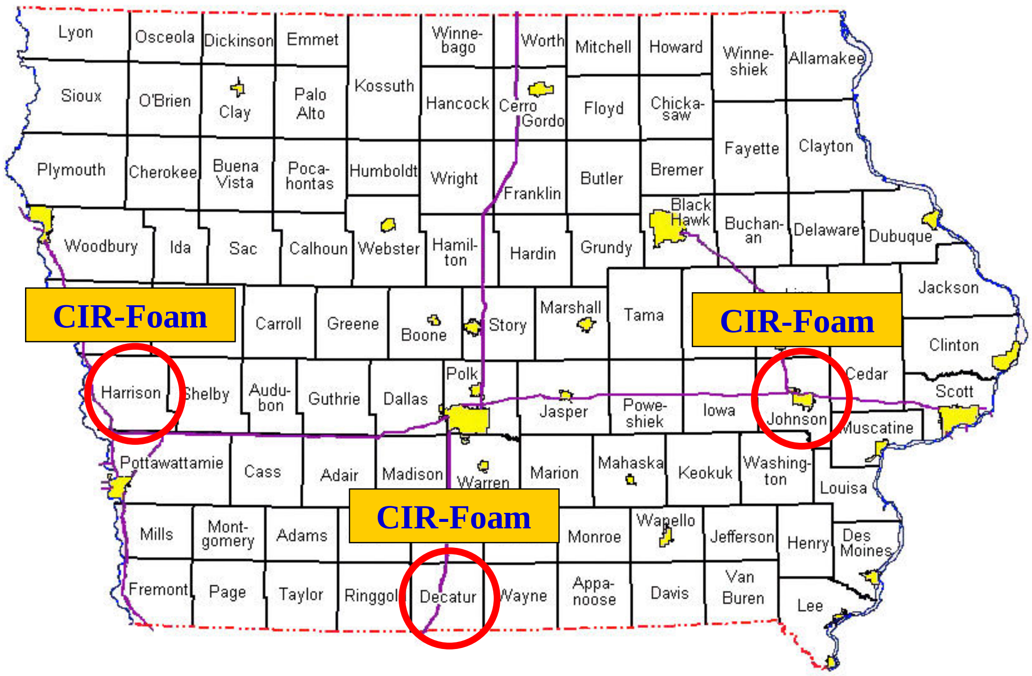


Figure 10-1. Location of specified three CIR project sites

10.1 Description of Project Sites

Three CIR-foam project sites were visited between June 6 and September 26, 2005. The project site background and CIR design information are summarized in Table 10-1 and 10-2, respectively.

Table 10-1. Basic information for demonstration project sites

Item \ Road	County Road R 69 (US Highway 69)	State Highway 37	County Road F 12 (HWY 382)
CIR Project Site	Decatur County	Harrison County	Johnson County
Monitoring Date	June 6, 2005	June 18, 2005	September 26, 2005
RAP Sampling Time	10.30 a.m. – 3:30 p.m.	10:30 a.m. – 3:30 p.m.	8:30 a.m. – 10:30 a.m.
Temperature of Existing Pavement Surface	10:30 a.m. – 3:30 p.m. (36.0°C – 46.0°C)	10:30 a.m. – 3:30 p.m. (39.0°C – 50.0°C)	8:30 a.m. – 10:30 a.m. (18.0°C – 23.0°C)
Temperature of Foamed Asphalt Mixtures	10:30 a.m. – 3:30 p.m. (37.1°C – 45.6°C)	10:30 a.m. – 3:30 p.m. (38.6°C - 50.2°C)	9:30 a.m. (25°C)
Temperature of Compacted Foamed Asphalt Pavement	10:30 a.m. – 3:30 p.m. (36.0°C – 48.0°C)	10:30 a.m. – 3:30 p.m. (33.0°C – 50.0°C)	9:30 a.m. (22°C)
Milling Machine	CMI PR-1000	CMI PR-1000	CMI PR-1000
CIR Method	CIR-foam	CIR-foam	CIR-foam
Construction Company	Koss Construction	Koss Construction	W.K Construction

Table 10-2. CIR design information for demonstration project sites

Item \ Road (County)	County Road R 69 (Decatur County)	State Highway 37 (Harrison County)	County Road F 12 HWY 382 (Johnson County)
CIR Length	4.5 miles	12.1 miles	4 miles
Existing Old HMA Layer Thickness	4 inches	6 inches	3 inches
Base Layer Thickness and Material	2” old HMA 8” rolled stone base 4” granular subbase	N/A	7-inch Asphalt treated Base
CIR Layer Thickness	4 inches	3 inches	6 inches
Overlaid New HMA Thickness	2 inches	1.5 inches intermediate course 1.5 inches surface course	1.5 inches intermediate course 3.0 inches surface course
AADT	260	710	3710 - 3250
Foamed Asphalt Content (%)	2.0 % (RAP sampled) (North to South) 1.8 % (South to North)	2.5 %	1.5% for first 1000 ft (RAP sampled) 2.0 %
Moisture Content (%)	N/A	2.5 %	4.0 %

(1) Decatur County Project

As shown in Figure 10-2, the project site is on County Road R 69, which is located in the intersection of County Road J 20 and State Highway 2 near the city of Leon, Iowa. An average annual daily traffic (AADT) is approximately 260 in both directions. In the job mix formula, 1.8% FAC was used for the right lane from north bound to south bound while 2.0% FAC was used for the left lane from south bound to north bound based on the mixture conditions

Both milled RAP material and foamed asphalt mixtures were collected from 11:30 a.m. and 3:30 p.m. on June 6, 2005. The temperatures were measured from four different locations, which included air, existing pavement, foamed asphalt mixture and compacted foamed asphalt pavement during the CIR-foam construction. Figure 10-3 shows the CIR-foam construction process and the milled RAP material collection process.

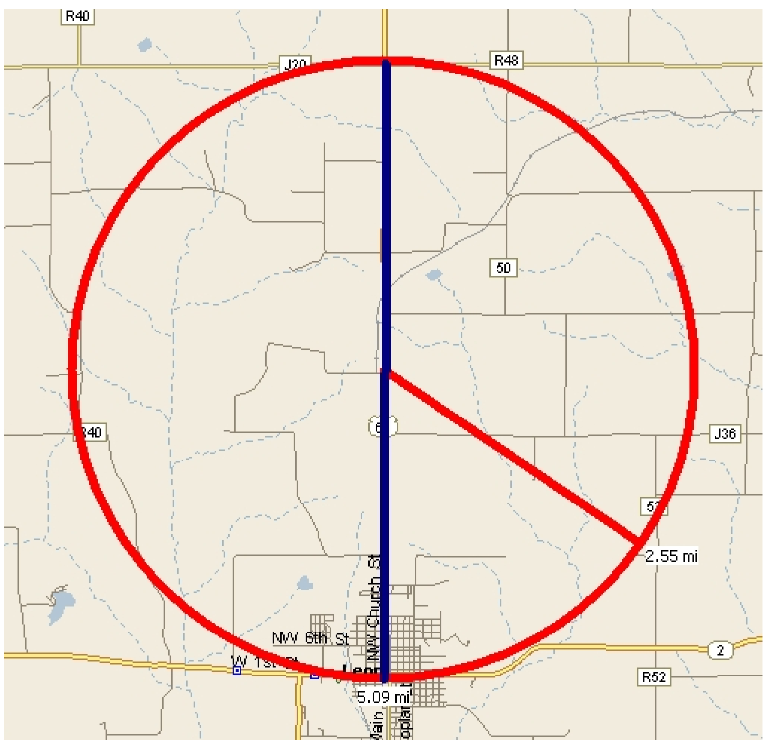


Figure 10-2. Location of the CIR-foam project site in Decatur County

(a) CIR-foam process (b) Collection of RAP materials

Figure 10-3. Pictures of CIR-foam job site in Decatur County

(2) Harrison County Project

As shown in Figure 10-4, the project site is on State Highway 37, which is located near the intersection of Sate Highway 183 and State Highway 30 near the city of Dunlap, Iowa. An average annual daily traffic (AADT) is approximately 710 in both directions. The job mix formula specified PG 58-28 asphalt binder at 2.5%. The water content of 2.5% was also specified to be added to the RAP materials.

Both milled RAP material and foamed asphalt mixtures were collected from 10:30 a.m. and 3:30 p.m. on June 18, 2005. The paved foamed asphalt mixtures were collected from five different spots, which included left side, left center, center, right center, and right side, before they were compacted in order to evaluate a uniformity of foamed asphalt distribution across the lane and along the lane. The temperatures were measured from four different locations, which included air, existing pavement, foamed asphalt mixture and compacted foamed asphalt pavement during the CIR construction. Figure 10-5 shows the CIR-foam construction process and the foamed asphalt mixture collection process.

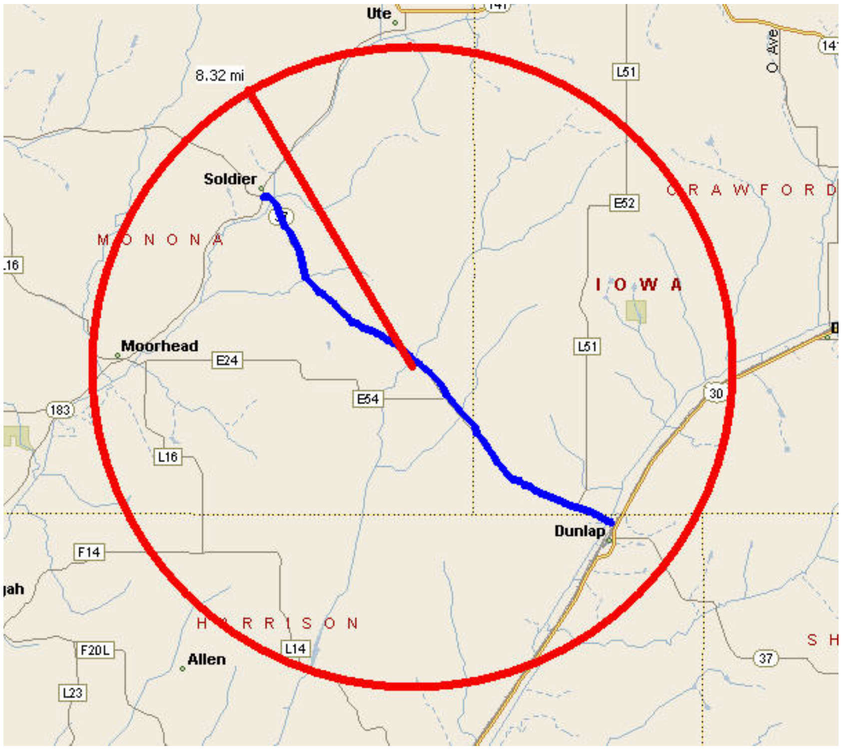


Figure 10-4. Location of the CIR-foam project site in Harrison County

(a) CIR-foam Process

(b) Collection of foamed asphalt mixtures

Figure 10-5. Pictures of CIR-foam job site in Harrison County

(3) Johnson County Project (County Road F 16 – HWY 382)

As shown in Figure 10-6, the project site is on County road F 16, which is located from about 30ft south for the intersection of Douglas Dr. and Highway 382 to Solon City, Iowa. An average annual daily traffic (AADT) is approximately 3,170 to

3,250 in both directions. The job mix formula specified PG 52-34 asphalt binder at 2.0-percent with temperatures between 157°C and 177°C to be foamed with 1.3% to 1.4% of foaming water content. The water content of 4.0% was also specified to be added to the RAP materials. Foaming characteristics were visually observed through the test spray nozzle mounted on the side of the paver but it was difficult to visually measure half-life and expansion ratio in the field. 1.5% FAC was used for the first 1200 m. However, based on the field observation of the CIR surface, the foamed asphalt content was increased to 2.0% for the remainder of the project.

RAP materials were collected from the beginning point of the construction at 8:30 a.m. and foamed asphalt mixtures were collected at 9:30 a.m. on September 26, 2005. Figure 10-7 shows the milling process and mixing process in the CIR-foam field construction.

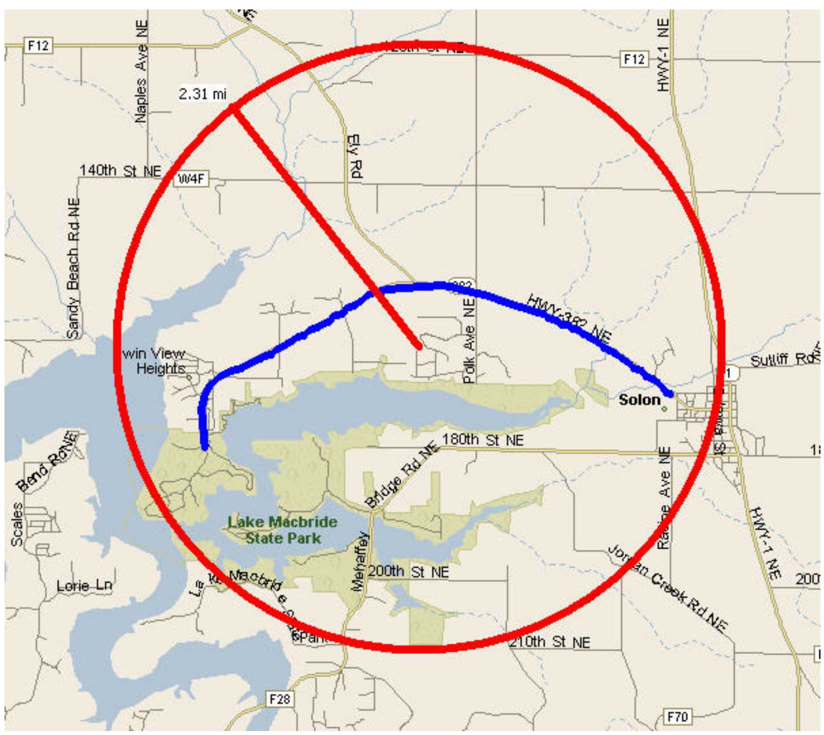


Figure 10-6. Location of the CIR-foam project site in Johnson County

(a) Milling process

(b) Mixing process with foamed asphalt

Figure 10-7. Pictures of CIR-foam job site in Johnson County

10.2 Visual Condition Survey of the Existing Pavement

The surface conditions of the existing pavement were surveyed by visual observation and summarized in Table 10-3. Three 100-ft sections were selected for visual evaluation and pictures of typical condition are shown in Figure 10-8.

Table 10-3. Summary of surface conditions from the existing pavement

Distress Type \ Project Site	Decatur County	Harrison County	Johnson County
Crack			
Alligator Crack	Yes	Yes	Yes
Block Crack	Yes	Yes	Yes
Edge Crack	Yes	Yes	Yes
Longitudinal Crack	Yes	Yes	Yes
Transverse Crack	Yes	Yes	Yes
Reflective Crack	No	No	Yes
Patching /Potholes			
Patch	Yes	Yes	Yes
Potholes	No	Yes	No
Surface Deformation			
Rutting	Yes	Yes	Yes
Shoving	No	No	No
Surface Defects			
Bleeding	No	No	No
Polishing Aggregate	Yes	Yes	Yes
Raveling	Yes	Yes	Yes
Overall Condition	Poor	Poor	Very Poor

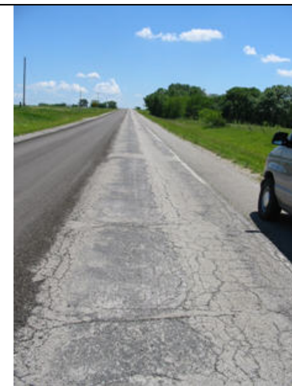
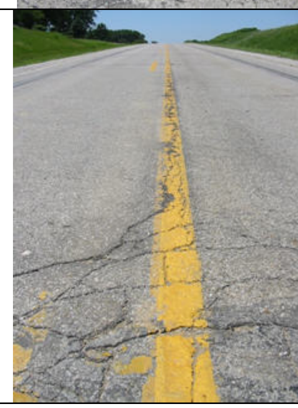
RAP Source	Pictures of Existing Old Pavement Surface Conditions		
Decatur County			
Harrison County			
Johnson County			

Figure 10-8. Pictures of existing old pavement surface conditions

10.3 Description of CIR-foam Construction Process

CIR-foam process in the field consists of four main steps: (1) milling process, (2) mixing process with foamed asphalt, (3) paving process and (4) compaction process. Three CIR-foam construction projects were done by two different construction companies: 1) Koss construction and 2) W.K. construction.   They have very similar CIR-foam process except the mixing process as shown in Figure 10-9. The foamed asphalt mixer used by the KOSS construction company is connected to right behind the milling machine so that the milled RAP materials are directly delivered to the foamed asphalt mixer to produce the foamed asphalt mixtures. A foamed asphalt mixer used by the W.K. construction company is not connected to the milling machine. Milled RAP materials are laid down on the pavement by the conveyor and the foamed asphalt equipment with mixer and paver produce the foamed asphalt mixtures. Figure 10-10 shows pictures of the construction equipment used in the CIR-foam process from two different construction companies.

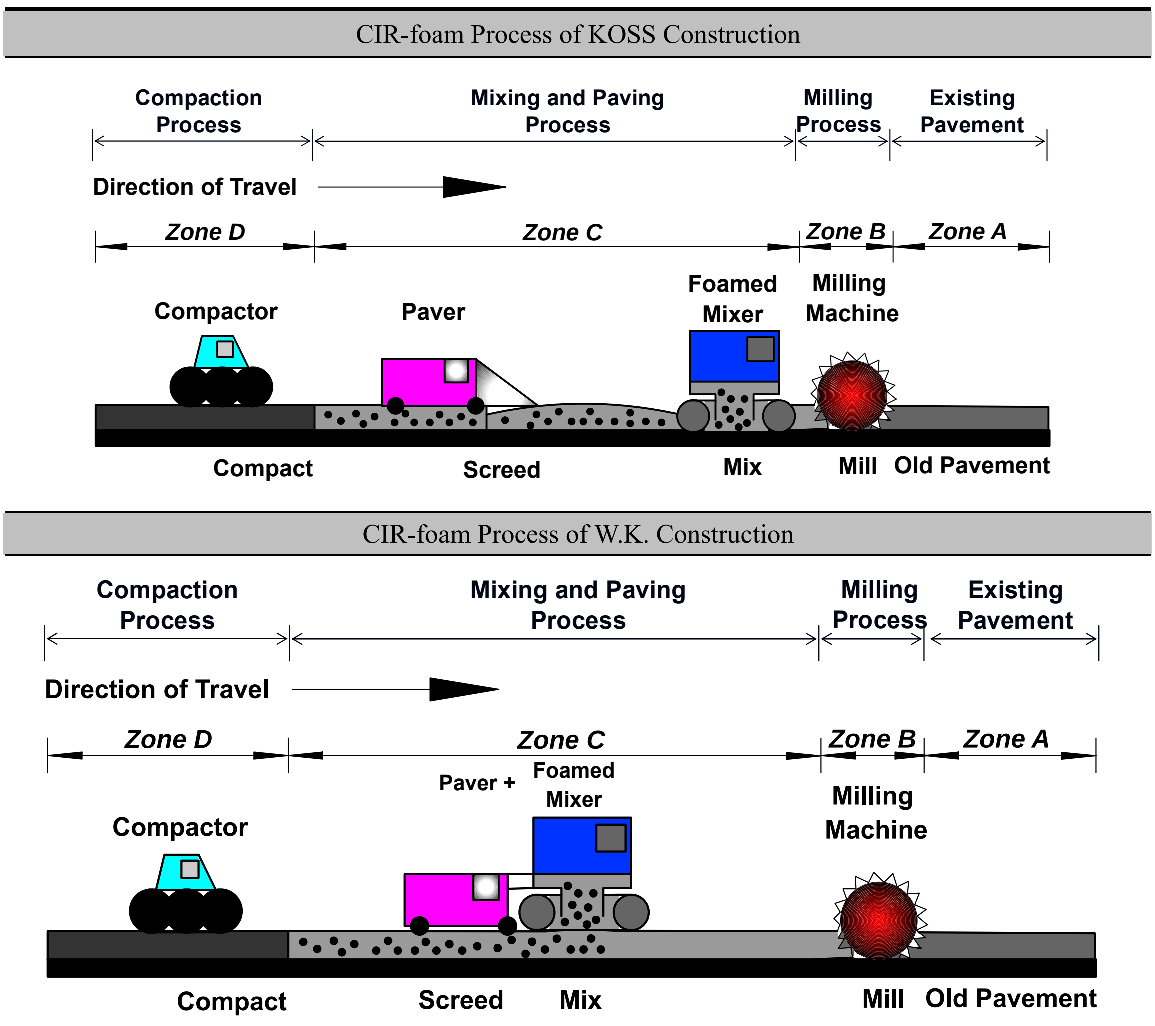


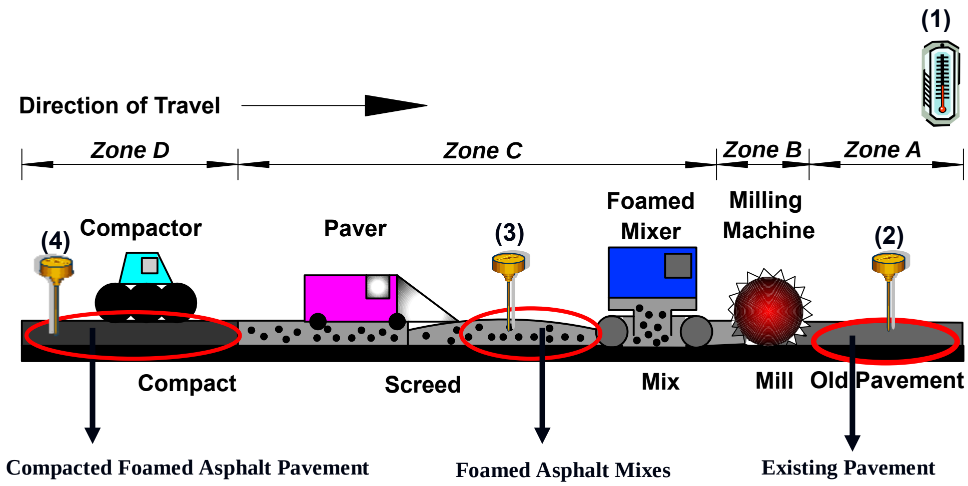
Figure 10-9. Schematic diagram of the CIR-foam process

	KOSS Construction	W.K. Construction
Water and Asphalt Binder Tankers		
Milling Machine		
Foamed Mixer		
Paver		
Compactor		

Figure 10-10. Pictures of CIR-foam construction equipment

10.4 Pavement Temperatures during CIR-foam Process

To monitor the variation of field temperatures during the CIR-foam process, as shown in Figure 10-11, four different temperatures were measured: 1) air temperature, 2) existing pavement temperature, 3) foamed asphalt mixture temperature and 4) compacted foamed asphalt pavement temperature.



Zone A: Existing Pavement, Zone B: Milling Process, Zone C: Mixing and Paving Process
Zone D: Compaction Process

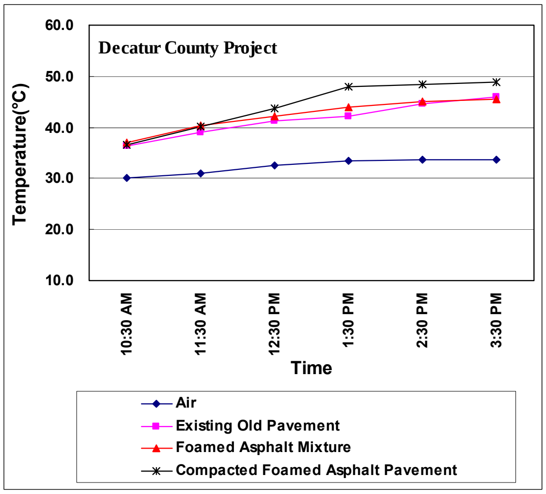
Figure 10-11. Locations of measured temperatures from CIR-foam process

Temperatures measured at different time periods throughout the day are summarized in Table 10-4 and plotted in Figure 10-12. Decatur and Harrison County projects were conducted on June 6, 2005 and June 18, 2005 in the middle of summer whereas Johnson County project were conducted on September 28, 2005 in the beginning of fall. All temperatures were measured in the time periods between 11:30 a.m. and 3:30 p.m. in Decatur and Harrison County projects whereas all temperatures were measured from 8:30 a.m. and 11:30 a.m. in Johnson County project.

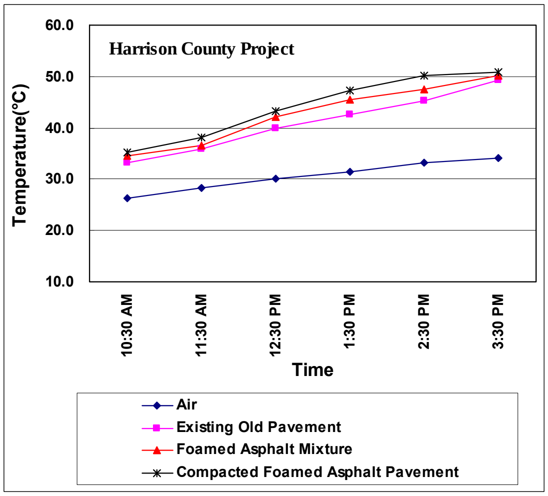
Air temperatures in Decatur and Harrison County projects ranged between 26.2°C and 34.2°C from 11:30 a.m. and 3:30 p.m. As shown in Figure 10-12, for Decatur and Harrison County projects, the temperature of the existing pavements ranged between 33.2°C and 49.2°C, the temperatures of the foamed asphalt mixtures ranged between 34.6°C and 50.2°C and the temperatures of the compacted foamed asphalt pavement ranged between 35.3°C and 50.8°C. Temperatures of the existing pavements in Johnson County project ranged between 16.7°C and 19.8°C from 8:30 a.m. and 10:30 p.m.

Table 10-4. Measured temperatures form three CIR-foam project sites

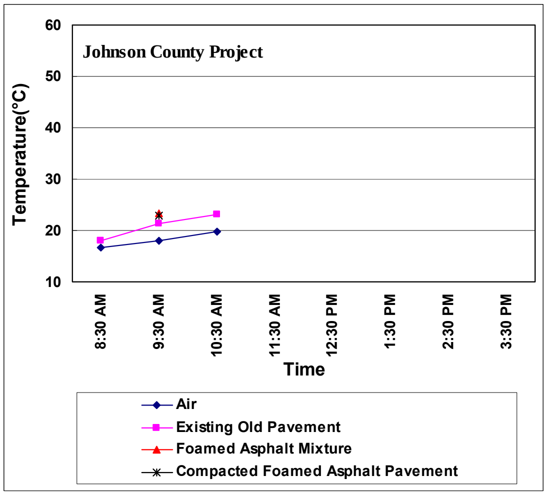
Time	Decatur County	Harrison County	Johnson County
	Measured Temperature in the Air		
8:30 a.m.	-	-	16.7 °C
9:30 a.m.	-	-	17.9 °C
10:30 a.m.	30.0 °C	26.2 °C	19.8 °C
11:30 a.m.	31.0 °C	28.4 °C	20.7 °C
12:30 p.m.	32.5 °C	30.0 °C	-
1:30 p.m.	33.5 °C	31.4 °C	-
2:30 p.m.	33.7 °C	33.4 °C	-
3:30 p.m.	33.7 °C	34.1 °C	-
Time	Measured Temperature from the Existing Old Pavement		
8:30 a.m.	-	-	18.1 °C
9:30 a.m.	-	-	21.4 °C
10:30 a.m.	36.3 °C	33.2 °C	23.2 °C
11:30 a.m.	39.1 °C	35.8 °C	24.3 °C
12:30 p.m.	41.3 °C	40.0 °C	-
1:30 p.m.	42.1 °C	42.7 °C	-
2:30 p.m.	44.5 °C	45.3 °C	-
3:30 p.m.	46.0 °C	49.2 °C	-
Time	Measured Temperature from Foamed Asphalt Mixture		
8:30 a.m.	-	-	-
9:30 a.m.	-	-	23.4 °C
10:30 a.m.	37.1 °C	34.6 °C	23.7 °C
11:30 a.m.	40.3 °C	36.6 °C	24.8 °C
12:30 p.m.	42.2 °C	42.2 °C	-
1:30 p.m.	44.0 °C	45.5 °C	-
2:30 p.m.	45.0 °C	47.5 °C	-
3:30 p.m.	45.6 °C	50.2 °C	-
Time	Measured Temperature from Compacted Foamed Asphalt Pavement		
8:30 a.m.	-	-	-
9:30 a.m.	-	-	22.0 °C
10:30 a.m.	36.5 °C	35.3 °C	23.1 °C
11:30 a.m.	40.1 °C	38.1 °C	-
12:30 p.m.	43.8 °C	43.3 °C	-
1:30 p.m.	48.0 °C	47.2 °C	-
2:30 p.m.	48.4 °C	50.1 °C	-
3:30 p.m.	48.9 °C	50.8 °C	-



(a) Decatur County



(b) Harrison County



(c) Johnson County

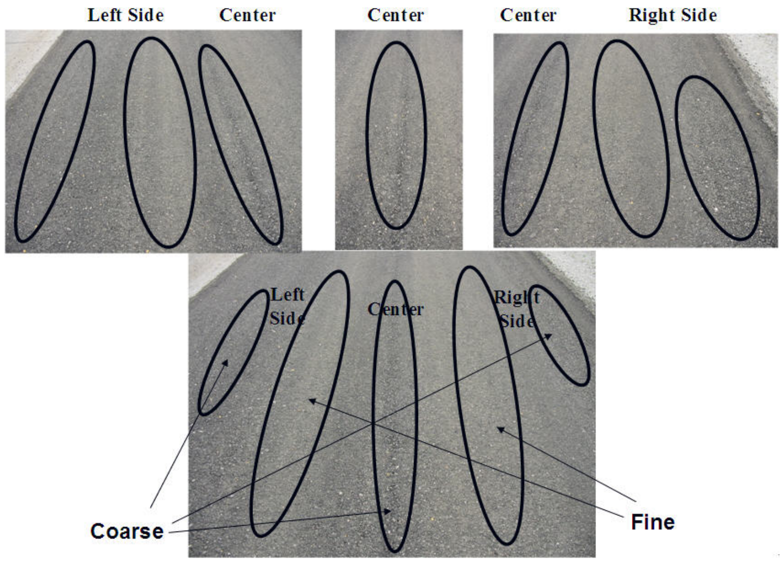
Figure 10-12. Changes of measured temperatures in CIR-foam project sites

10.5 Visual Observation of CIR-foam Quality

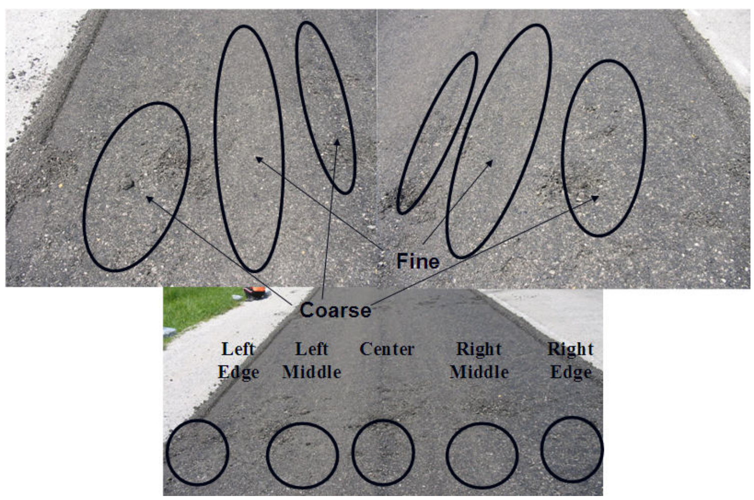
The foamed asphalt content in the field was adjusted by contractor based on the visual field observation. The original foamed asphalt content determined for the CIR-foam projects in Decatur and Johnson Counties were adjusted during the construction process.

As shown in Figure 10-13, the paved foamed asphalt mixtures before compaction did not seem to be distributed evenly across the lane such that coarser mixtures were placed in the left side, center and right side across the lane whereas finer mixtures were placed in the left middle and right middle.

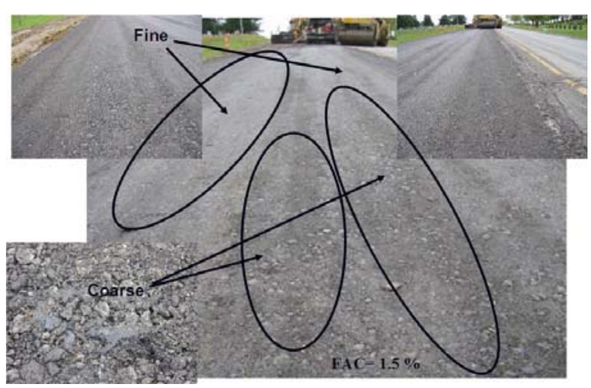
To determine the distribution of foamed asphalt, foamed asphalt mixtures were collected across and along the lane. The collected mixtures were tested for: 1) foamed asphalt content using burn-off test and 2) gradation analysis from extracted RAP aggregate.



(a) Decatur County project



(b) Harrison County project



(c) Johnson County project

Figure 10-13. Pictures of paved foamed asphalt mixtures observed from CIR-foam field projects

In the CIR-foam compaction process, as shown in Figure 10-14, 7-pass of tire roller and 6-pass of steel roller with vibration were normally applied to achieve the field density based upon the empirical method because there was no standard compaction procedure in the field.


(a) tire roller


(b) steel roller

Figure 10-14. Pictures of tire and steel rollers used in CIR-foam compaction process

For Johnson County project, the surface condition of the CIR-foam pavement was surveyed by visual observation and AICS before HMA overlay. As show in Figure 10-15, the raveling and thin cracks were observed throughout the project site. The raveling seemed to have been caused by low foamed asphalt content and inadequate compaction and traffic allowed for the curing period. As shown in Figure 10-16, the increased foamed asphalt content reduced raveling. As shown in Figure 10-17, it is interesting to note that the traffic lane is better compacted than the shoulder due to the traffic allowed during the curing period.

(a) Visual observation (b) Captured image from AICS

Figure 10-15. Pictures of surface problems at the rehabilitated CIR-foam pavement

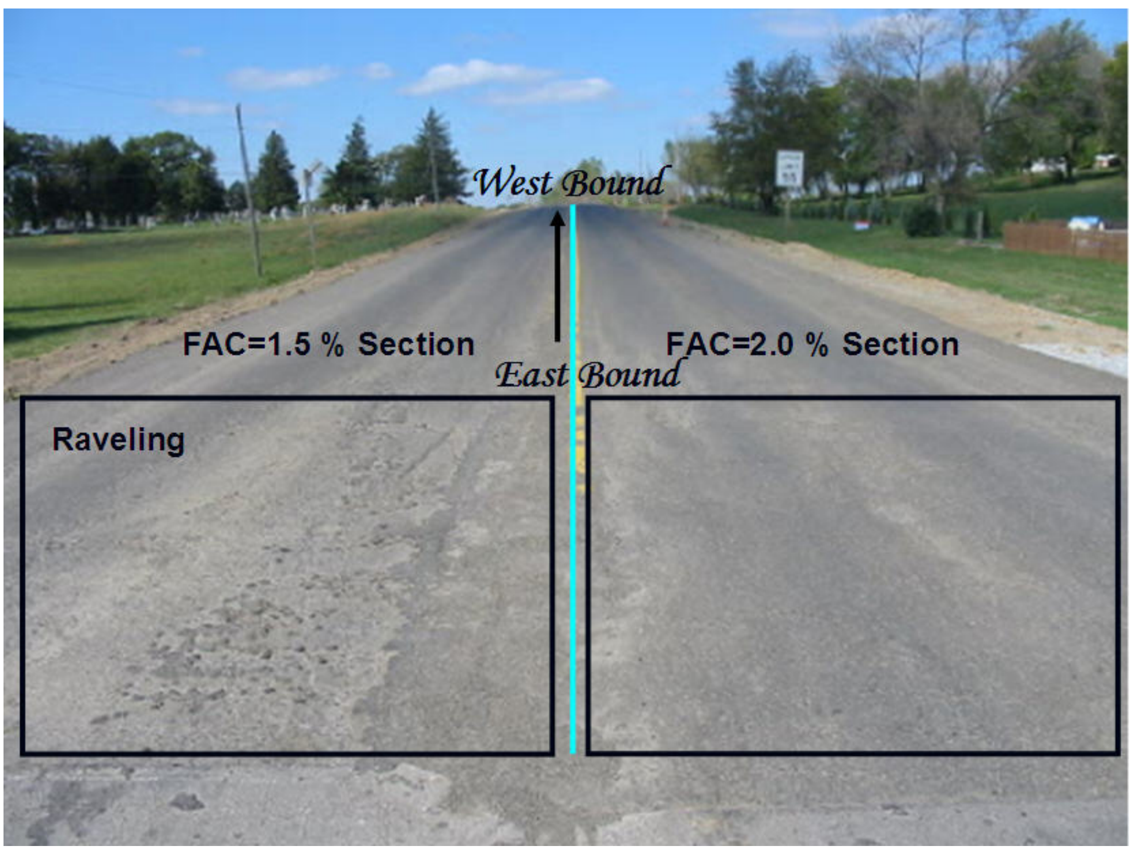


Figure 10-16. Comparison of CIR-foam pavement raveling at two different FAC

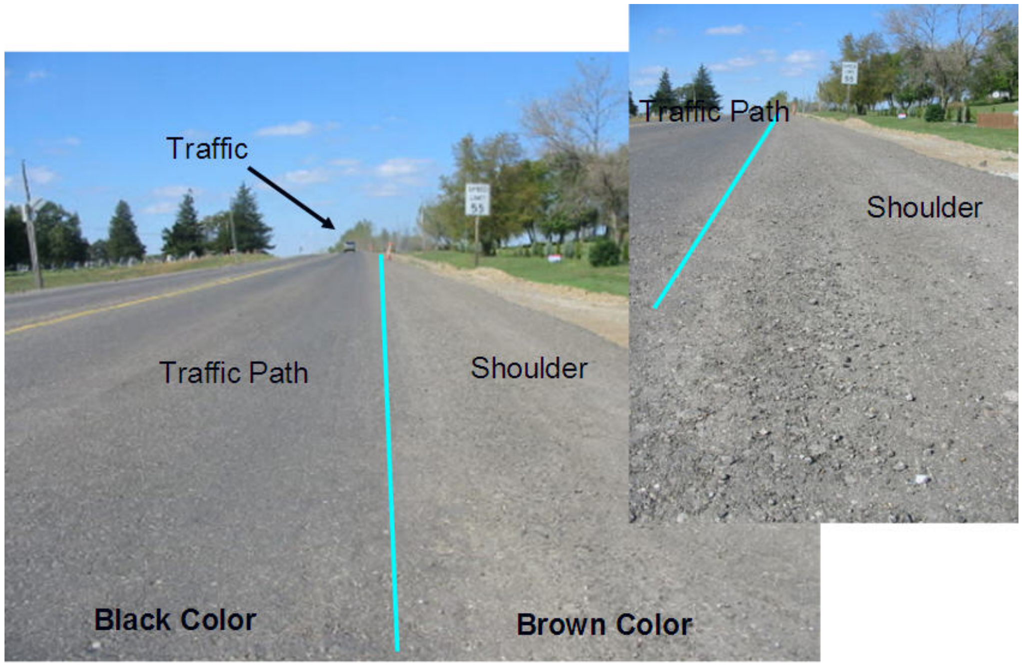


Figure 10-17. Comparison of CIR-foam pavement between traffic path and shoulder

10.6 Evaluation of RAP Materials and CIR-foam Mixtures

CIR-foam construction process was observed to see if there is a variation in the foamed asphalt mixtures and milled RAP materials due to the milling time and weather condition. The following tests were performed using milled RAP materials and foamed asphalt mixtures collected from three CIR-foam project sites:

(1) Gradations of RAP materials

(2) Gradations of extracted aggregates

(3) Residual asphalt content

(4) Wet indirect tensile strength of field CIR-foam mixtures

Gradation analysis of collected RAP materials were conducted to evaluate their field gradations at different milling time and indirect tensile strength test of foamed asphalt mixtures were conducted to evaluate uniformity of foamed asphalt mixtures over time. Burn-off tests of the milled RAP materials and paved foamed asphalt mixtures were performed at Iowa DOT.

10.6.1 Description of Sampling Locations

(1) Decatur County Project

As illustrated in Figure 10-18, both milled RAP materials and foamed asphalt mixtures were collected from five different locations from 10:30 a.m. and 3:30 p.m. with one hour interval in order to see if there is a variation RAP materials and foamed asphalt mixtures due to the milling time and field temperature.

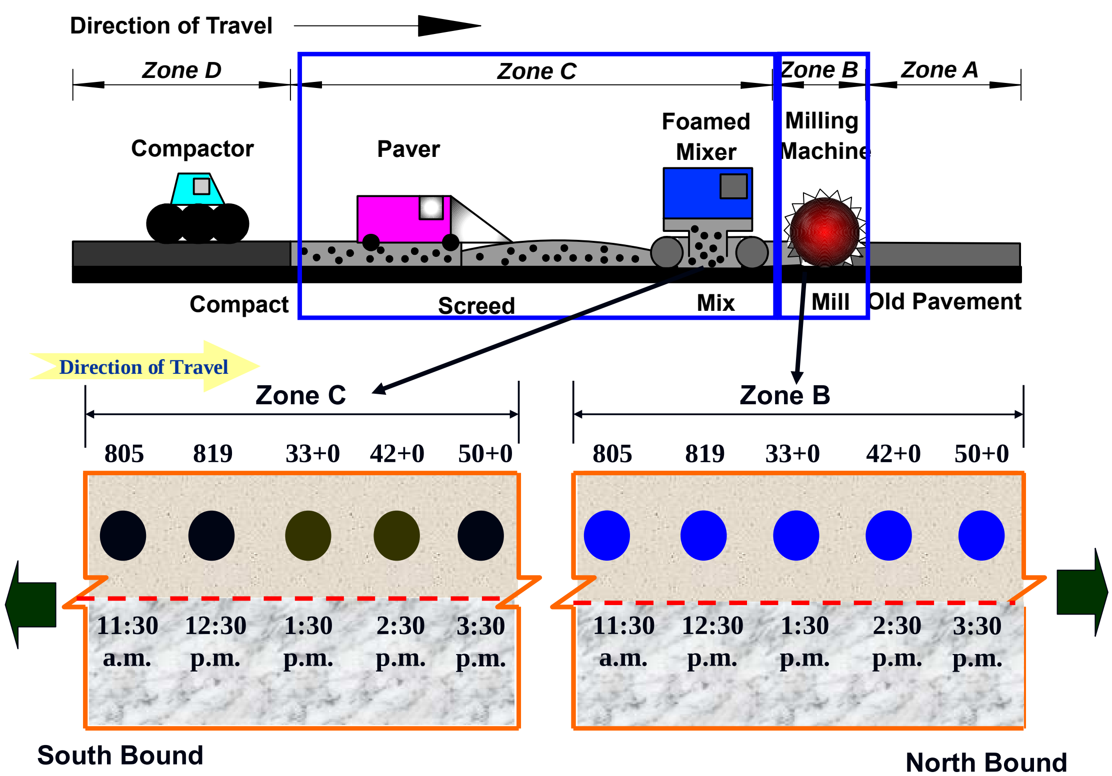


Figure 10-18. Location of collected RAP materials and foamed asphalt mixtures in Decatur County project sites

As shown in Figure 10-19 (a), RAP materials were collected from milling machine directly and as shown in Figure 10-19 (b), foamed asphalt mixtures were collected from the stockpiles behind the foamed asphalt mixer.

(a) RAP

(b) Foamed asphalt mixtures

Figure 10-19. Pictures of field sampling methods in Decatur County project

(2) Harrison County Project

As shown in Figure 10-20, both RAP materials and foamed asphalt mixtures were collected from five different locations between 10:30 a.m. and 3:30 p.m. at one-hour interval in order to see if there is a variation in milled RAP materials and foamed asphalt mixtures due to the milling time and field temperature. To evaluate uniformity of foamed asphalt distribution across the lane, paved foamed asphalt mixtures were collected from five different spots, which include left side, left center, center, right center, and right side.

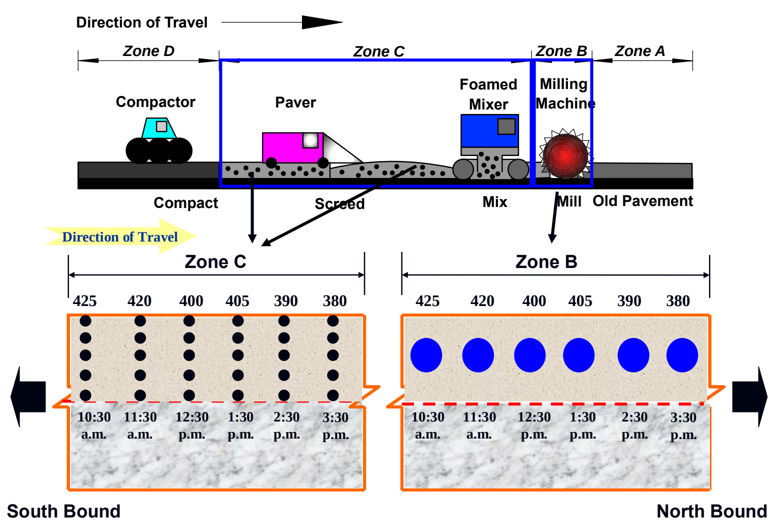
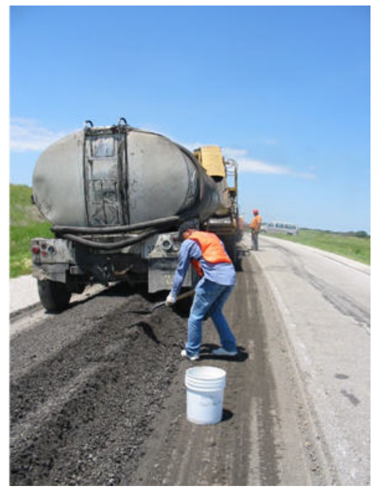


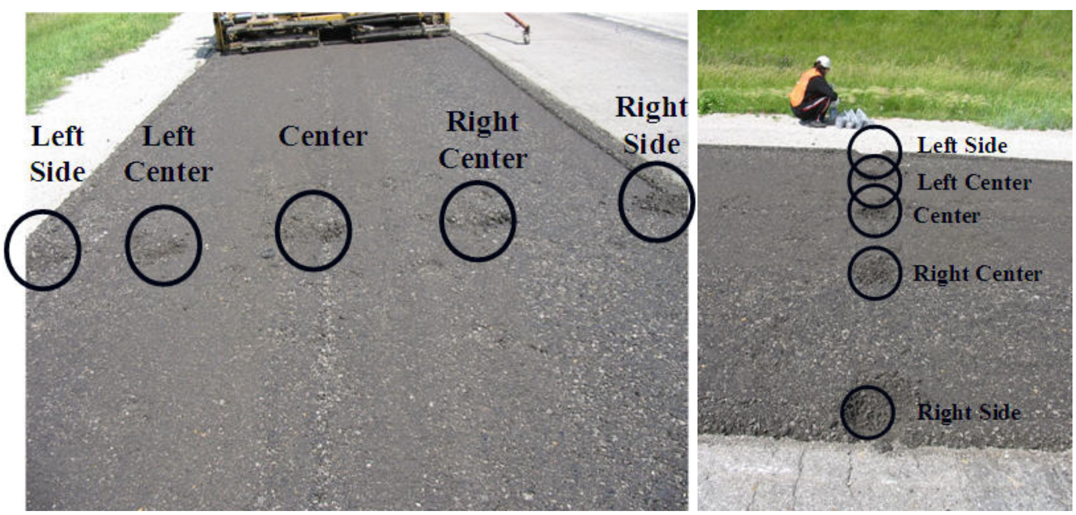
Figure 10-20. Location of collected RAP materials and paved foamed asphalt mixtures in Harrison County project sites

As shown in Figure 10-21 (a), RAP materials were collected from milling machine directly, as shown in Figure 10-21 (b), foamed asphalt mixtures were collected from the stockpiles behind the foamed asphalt mixer and as shown in Figure 10-21 (c), paved foamed asphalt mixtures were collected from five different spots, which include left side, left center, center, right center, and right side.

(a) RAP



(b) Foamed asphalt mixtures



(c) Paved foamed asphalt mixtures

Figure 10-21. Pictures of field sampling methods in Harrison County project site

(3) Johnson County Project

As shown in Figure 10-22, RAP materials and foamed asphalt mixtures were collected at beginning point of CIR-foam construction from 8:30 a.m. and 9:30 p.m. because the foaming equipment was broke down in the beginning of the CIR-foam construction. RAP materials were collected from the ground before a paver finishes the surface while spraying foamed asphalt on them and foamed asphalt mixtures were collected from the paved foamed asphalt pavements.

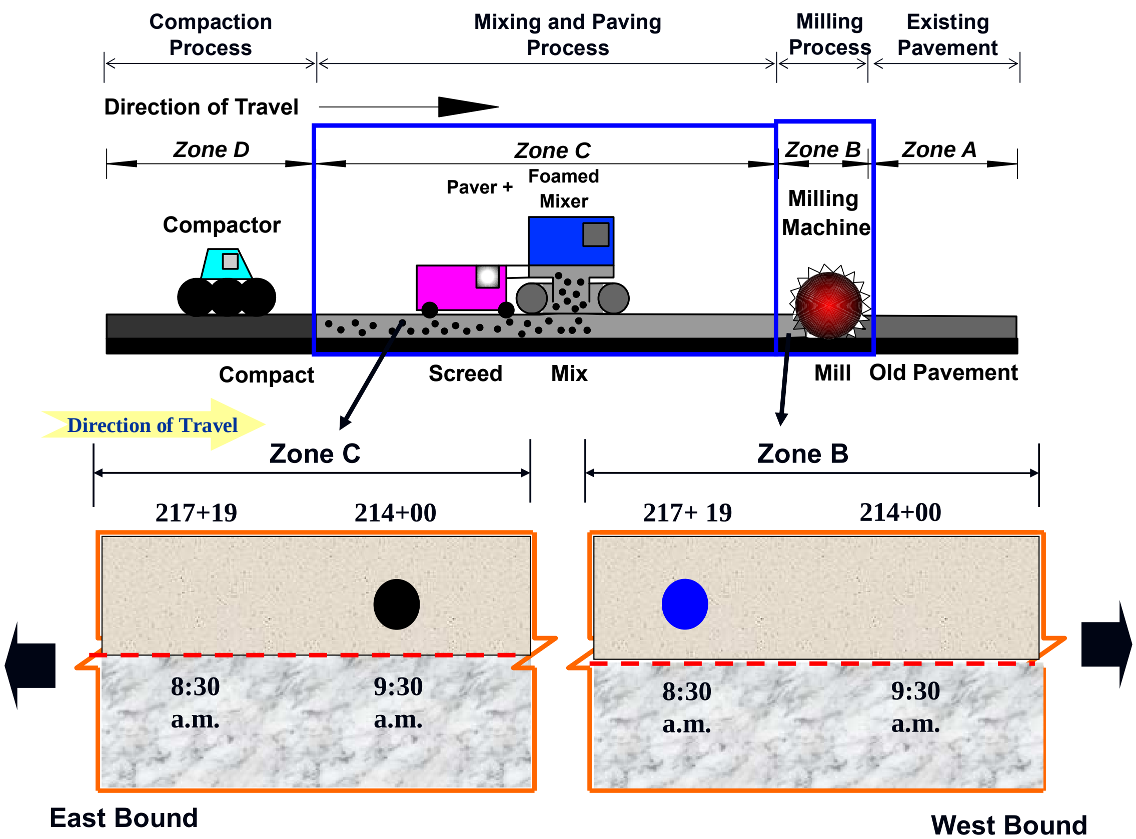


Figure 10-22. Locations of collected RAP materials and foamed asphalt mixtures in Johnson County project sites

10.6.2 RAP Gradations

The collected RAP materials were brought to laboratory and they were dried in the air (24°C - 27°C) for 20 days. The moisture contents of the dried RAP materials were 0.1% to 0.2%. Figure 10-23 shows RAP materials being dried on the floor of the laboratory and their storage in the carts.

Figure 10-23. Drying process of the RAP materials at the laboratory

First, dried RAP materials, were divided into six stockpiles which were retained on the following sieves: 25 mm, 19 mm, 9.5 mm, 4.75 mm, 1.18 mm and ones of passing the 1.18 mm. As shown in Figure 10-24, divided RAP materials were stored in 5-gallon bucket holding about 50 lbs of RAP materials. A total of 12 gradation analyses were conducted for the RAP materials collected from five different time periods in Decatur County, the RAP materials collected from six different time periods in Harrison County, and the RAP materials collected from one time period in Johnson County.

Figure 10-24. Sorted RAP materials in 5-gallon buckets

The sorted RAP materials from three different sources were weighed and their relative proportions were computed as shown in Table 10-5, Table 10-6 and Table 10-7.

Table 10-5. Gradation summary of RAP materials collected from Decatur County

RAP Size	Time Periods of RAP Collection									
	A (11:30 a.m.)		B (12:30 p.m.)		C (1:30 p.m.)		D (2:30 p.m.)		E (3:30 p.m.)	
	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)
38 mm - 25 mm	1283.2	3.2	282.0	0.7	427.1	1.2	180.8	0.4	237.8	0.6
25 mm - 19 mm	5436.0	13.7	2335.2	5.9	3452.9	9.7	1403.8	3.3	1739.5	4.5
19 mm - 9.5 mm	11724.0	29.5	9900.3	25.2	10815.1	30.3	8768.2	20.5	10455.5	26.8
9.5 mm - 4.75 mm	9324.0	23.5	11574.2	29.5	9441.1	26.4	13261.7	31.0	11266.8	28.9
4.75 mm - 1.18 mm	9067.3	22.8	10997.9	28.0	8741.3	24.5	13737.8	32.1	11426.1	29.3
Below 1.18 mm	2847.9	7.2	4208.9	10.7	2868.7	8.0	5478.0	12.8	3878.7	9.9
Total	39682.4	100.0	39298.5	100.0	35746.2	100.0	42830.3	100.0	39004.4	100.0

Table 10-6. Gradation summary of RAP materials collected from Harrison County project site

RAP Size	Time Periods of RAP Collection											
	A (10:30 a.m.)		B (11:30 a.m.)		C (12:30 p.m.)		D (1:30 p.m.)		E (2:30 p.m.)		F (3:30 p.m.)	
	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)
38 mm - 25 mm	701.3	1.9	2641.4	7.8	1827.7	4.2	1379.6	4.0	664.9	1.5	652.4	2.3
25 mm - 19 mm	1147.5	3.1	2701.2	8.0	2581.9	6.0	1868.2	5.4	1696.7	3.8	2468.0	8.5
19 mm - 9.5 mm	7521.9	20.3	11135.6	32.9	12376.7	28.6	9540.2	27.4	11130.1	24.8	9777.6	33.8
9.5 mm - 4.75 mm	10021.8	27.1	8169.1	24.2	10248.3	23.7	7757.4	22.3	11937.8	26.6	7861.3	27.2
4.75 mm - 1.18 mm	13245.6	35.8	6914.8	20.5	10095.9	23.4	9405.4	27.1	13752.9	30.6	4907.0	16.9
Below 1.18 mm	4340.8	11.7	2238.6	6.6	6072.5	14.1	4819.4	13.9	5729.5	12.8	3284.7	11.3
Total	36978.9	100.0	33800.7	100.0	43203.0	100.0	34770.2	100.0	44911.9	100.0	28951.0	100.0

Table 10-7. Gradation summary of RAP materials collected from Johnson County

RAP Size	RAP Collection Time Periods			
	A (8:30 a.m.)		B (8:30 a.m.)	
	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)
38 mm - 25 mm	608.1	2.86	610.9	3.33
25 mm - 19 mm	1071.8	5.05	887.7	4.84
19 mm - 9.5 mm	4402.8	20.73	3737.0	20.36
9.5 mm - 4.75 mm	4119.9	19.40	3644.9	19.86
4.75 mm - 1.18 mm	5671.8	26.71	4929.4	26.86
Below 1.18 mm	5363.9	25.26	4540.8	24.74
Total	21238.3	100.00	18350.7	100.00

After discarding RAP materials bigger than 25 mm, gradations are summarized in Table 10-8, Table 10-9 and Table 10-10 and plotted on a 0.45 power chart in Figure 10-25, Figure 10-26 and Figure 10-27.

For Decatur County project, as shown in Table 10-8 and Figure 10-25, RAP materials can be considered from dense to coarse with a very small amount of fine RAP materials passing 0.075 mm sieve. All RAP materials passed 38.1mm sieve and less than 1.0% was retained on the 25mm sieve except RAP materials collected at 11:30 a.m. and 1:30 p.m. RAP materials collected at 11:30 a.m. can be considered the most coarse and those collected from 1:30 p.m. as coarse. RAP materials collected at 2:30 p.m. can be considered the most dense and those collected from 12:30 p.m. and 3:30 p.m. as dense. There seems to be a significant variation among RAP materials collected at different times, which could have been affected by pavement temperatures.

For Harrison County project, , as shown in Table 10-9 and Figure 10-26, RAP materials can be considered from dense to coarse with a very small amount of fine RAP materials passing 0.075 mm sieve. All RAP materials passed 38.1mm sieve and 1.5% to 7.8% of RAP materials were retained on the 25mm sieve. RAP materials collected at 11:30 a.m. can be considered the most coarse, those collected from 3:30 p.m. as coarse, and those collected from 10:30 p.m., 12:30 p.m., 1:30 p.m., and 2:30 p.m. as dense. There seems to be a significant variation among RAP materials collected at different times but the gradation did not correlate well with the pavement temperatures.

For Johnson County project, as shown in Table 10-10 and Figure 10-27, RAP materials can be considered fine with a small amount of fine RAP materials passing 0.075 mm sieve. All RAP materials passed 38.1mm sieve and 3.0% of RAP materials were retained on the 25mm sieve. RAP materials can be considered the most fine compared to RAP materials from the other two project sites. As shown in Figure 10-27, the two sets of RAP materials collected at the same time show consistency in their gradations.

Table 10-8. Gradation summary of RAP materials passing 25 mm sieve collected from Decatur County

RAP Size	RAP Collection Time Periods									
	A (11:30 a.m.)		B (12:30 p.m.)		C (1:30 p.m.)		D (2:30 p.m.)		E (3:30 p.m.)	
	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)
38 mm - 25 mm	0	0	0	0	0	0	0	0	0	0
25 mm - 19 mm	5436.0	14.2	2335.2	6.0	3452.9	9.8	1403.8	3.3	1739.5	4.5
19 mm - 9.5 mm	11724.0	30.5	9900.3	25.4	10815.1	30.6	8768.2	20.6	10455.5	27.0
9.5 mm - 4.75 mm	9324.0	24.3	11574.2	29.7	9441.1	26.7	13261.7	31.1	11266.8	29.1
4.75 mm - 1.18 mm	9067.3	23.6	10997.9	28.2	8741.3	24.7	13737.8	32.2	11426.1	29.5
Below 1.18 mm	2847.9	7.4	4208.9	10.8	2868.7	8.1	5478.0	12.8	3878.7	10.0
Total	38399.2	100.0	39016.5	100.0	35319.1	100.0	42649.5	100.0	38766.6	100.0

Table 10-9. Gradation summary of RAP materials passing 25 mm sieve collected from Harrison County

RAP Size	RAP Collection Time Periods											
	A (10:30 a.m.)		B (11:30 a.m.)		C (12:30 p.m.)		D (1:30 p.m.)		E (2:30 p.m.)		F (3:30 p.m.)	
	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)
38 mm - 25 mm	0	0	0	0	0	0	0	0	0	0	0	0
25 mm - 19 mm	1147.5	3.2	2701.2	8.7	2581.9	6.2	1868.2	5.6	1696.7	3.8	2468.0	8.7
19 mm - 9.5 mm	7521.9	20.7	11135.6	35.7	12376.7	29.9	9540.2	28.6	11130.1	25.2	9777.6	34.6
9.5 mm - 4.75 mm	10021.8	27.6	8169.1	26.2	10248.3	24.8	7757.4	23.2	11937.8	27.0	7861.3	27.8
4.75 mm - 1.18 mm	13245.6	36.5	6914.8	22.2	10095.9	24.4	9405.4	28.2	13752.9	31.1	4907.0	17.3
Below 1.18 mm	4340.8	12.0	2238.6	7.2	6072.5	14.7	4819.4	14.4	5729.5	12.9	3284.7	11.6
Total	36277.6	100.0	31159.3	100.0	41375.3	100.0	33390.6	100.0	44247.0	100.0	28298.6	100.0

Table 10-10. Gradation summary of RAP materials passing 25 mm sieve collected from Johnson County

RAP Size	RAP Collection Time Periods			
	A (8:30 a.m.)		B (8:30 a.m.)	
	Weight (g)	Prop. (%)	Weight (g)	Prop. (%)
38 mm - 25 mm	0	0	0	0
25 mm - 19 mm	1071.8	5.20	887.7	5.00
19 mm - 9.5 mm	4402.8	21.34	3737.0	21.07
9.5 mm - 4.75 mm	4119.9	19.97	3644.9	20.55
4.75 mm - 1.18 mm	5671.8	27.49	4929.4	27.79
Below 1.18 mm	5363.9	26.00	4540.8	25.60
Total	20630.2	100.00	17739.8	100.00

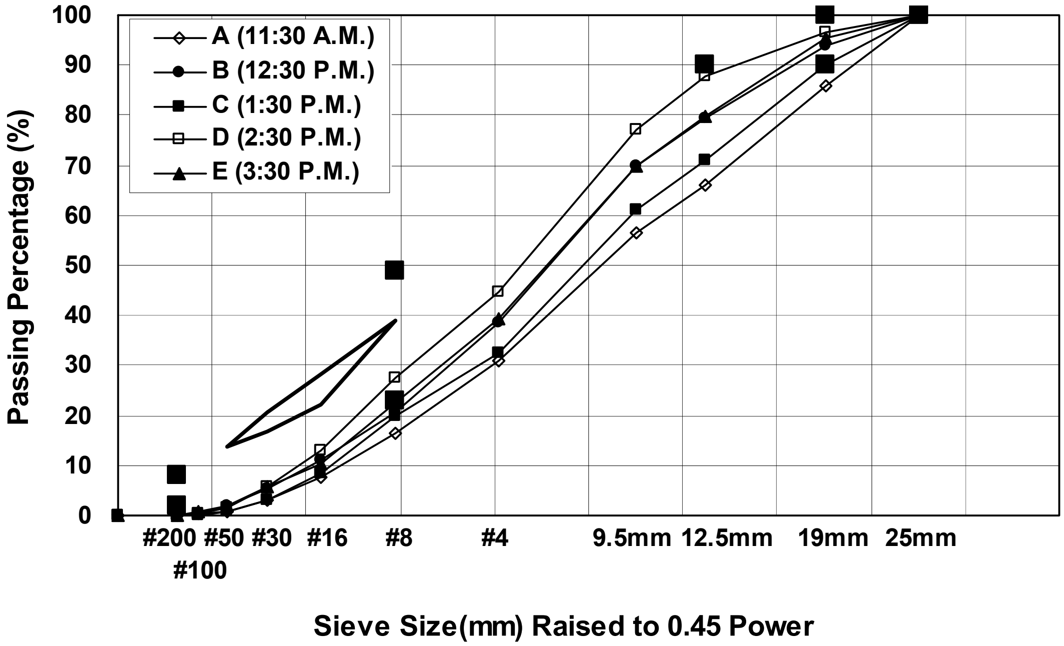


Figure 10-25. Gradation plots of RAP materials passing 25 mm sieve colleted at five different time periods in Decatur County project

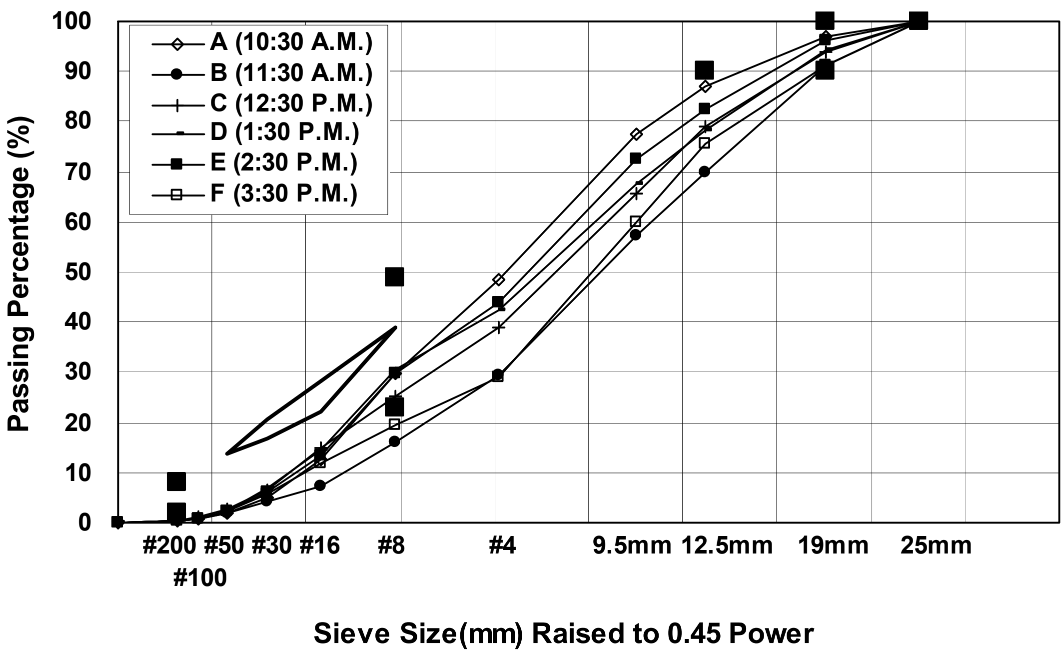


Figure 10-26. Gradation plots of RAP materials passing 25mm colleted at six different time periods in Harrison County project

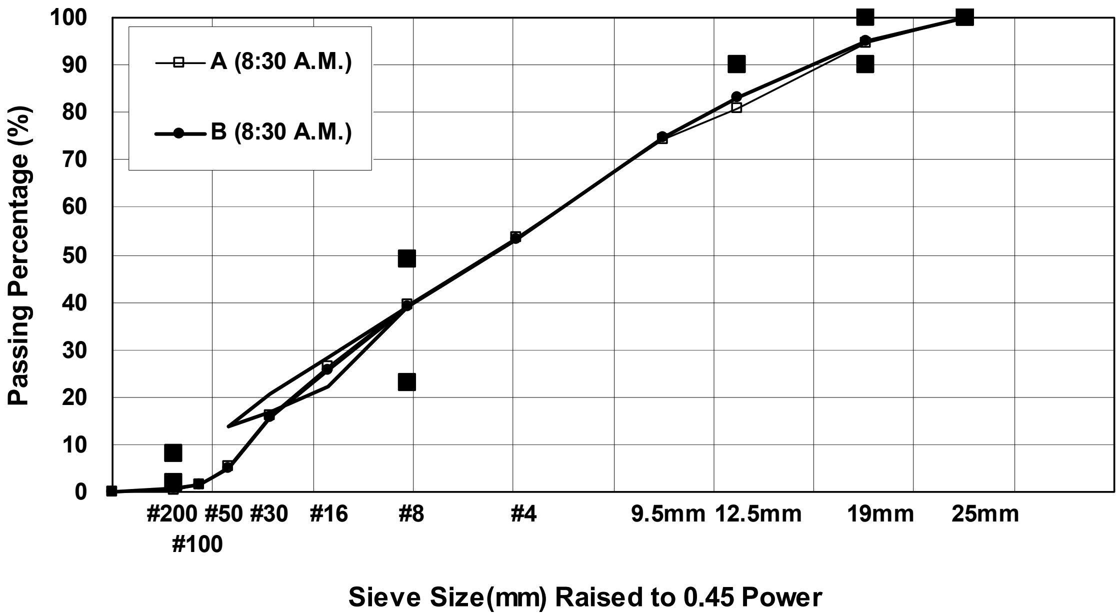


Figure 10-27. Gradation plots of RAP materials passing 25 mm colleted at one time period in Johnson County project

10.6.3 RAP Aggregate Gradations and Asphalt Contents Using Burn-Off Oven

Foamed asphalt mixtures were collected at five different spots across lane and RAP materials were collected from the conveyor belt as a reference at four different times at 10:30 a.m., 12:30 p.m., 1:30 a.m., and 3:30 p.m. from Harrison County project. Collected samples were then sent to Iowa DOT to determine the variation of foamed asphalt content and gradation across the lane at four different time frames. The residual asphalt contents of foamed asphalt mixtures and RAP materials were measured using the burn-off oven.

Tables 10-11, 10-12, 10-13 and 10-14 show the aggregate gradation test results and residual asphalt contents of the extracted RAP materials and foamed asphalt mixtures collected at 10:30 a.m., 12:30 p.m., 1:30 a.m., and 3:30 p.m., respectively, from the Harrison County project. The aggregate gradations of the extracted foamed asphalt mixtures collected from five spots across the lane are plotted in Figures 10-28, 10-29, 10-30, and 10-31, respectively. There was no significant variation observed among gradations depending on the locations across the lane and different milling times during the day.

As shown in Figure 10-32, the residual asphalt contents of the foamed asphalt mixtures varied across the lane and different time frames. Particularly, at 12:30 p.m., the residual asphalt content from the foamed asphalt mixtures collected from the left-hand side of the lane was much less than that of center and right-hand side of the lane. As can be seen in Figure 10-33, the foamed asphalt contents are computed by subtracting the residual asphalt content from RAP materials form that of the foamed asphalt mixture and they are plotted against the locations across the lane. This plot confirms that the variations in the residual asphalt contents of the foamed asphalt mixtures were caused by the variations in foamed asphalt sprayed during the CIR-foam construction process. Overall, the applied foamed asphalt contents ranged from 2.64% to 2.94%, which is consistently higher than 2.5% originally specified by Iowa DOT.

Table 10-11. Gradations and residual asphalt contents of foamed asphalt mixture and RAP materials collected at 10:30 a.m.

Sieve Size (mm)	Foamed Asphalt Mixture Collected at 10:30 a.m.										RAP Materials Collected at 10:30 a.m.	
	Left side		Left Center		Center		Right Center		Right Side			
	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2
25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	99.8	99.5	98.1	98.4	98.5	98.6	98.8	97.4	99.3	99.5	99.3	99.8
9.5	97.3	97.2	95.5	95.6	96.0	96.9	96.4	94.5	97.3	97.2	97.5	98.0
4.75 (No.4)	81.6	79.9	79.2	80.1	80.1	79.8	80.3	79.4	81.8	79.9	82.5	83.9
2.36 (No.8)	63.8	61.5	62.7	63.4	62.8	63.1	63.0	63.5	64.0	61.5	64.2	65.1
1.18 (No.16)	48.7	46.6	48.4	48.9	47.9	48.9	47.7	49.4	49.1	46.6	49.5	48.5
0.6 (No. 30)	34.6	36.0	34.8	35.5	35.1	35.4	37.0	35.3	35.5	36.0	35.6	33.3
0.3 (No.50)	18.8	20.0	19.8	20.0	20.4	20.3	20.4	19.3	20.3	20.0	19.1	16.7
0.15 (No.100)	9.5	10.3	10.1	10.7	11.6	11.7	10.2	9.9	11.6	10.3	9.1	8.5
0.074 (No.200)	3.1	4.5	5.6	7.1	7.9	7.9	5.8	4.9	7.1	4.5	5.5	4.4
Residual AC (%)	8.42	8.24	8.63	8.96	8.39	8.86	9.15	9.41	8.75	8.91	5.90	5.90
Average (%)	8.33		8.80		8.63		9.28		8.83		5.90	
	8.77											

Table 10-12. Gradations and residual asphalt contents of foamed asphalt mixture and RAP materials collected at 12:30 p.m.

Sieve Size (mm)	Foamed Asphalt Mixture Collected at 12:30 p.m.										RAP Materials Collected at 12:30 p.m.	
	Left side		Left Center		Center		Right Center		Right Side			
	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2
25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	99.1	98.4	98.9	99.1	99.2	99.2	99.0	98.8	99.3	98.9	99.3	98.4
9.5	96.7	96.1	96.9	97.8	96.9	97.2	95.6	95.2	96.9	97.3	97.1	96.1
4.75 (No.4)	84.4	83.4	84.1	85.1	84.5	83.7	82.2	80.7	85.5	84.8	82.9	81.3
2.36 (No.8)	68.0	66.6	67.7	68.1	68.3	67.4	66.4	65.5	67.7	67.6	65.7	64.5
1.18 (No.16)	51.9	49.7	51.3	51.6	52.4	51.5	51.0	50.9	50.9	51.4	49.9	49.7
0.6 (No. 30)	37.2	34.4	36.2	36.7	37.3	36.5	36.2	36.0	36.1	36.7	35.3	35.3
0.3 (No.50)	21.2	18.4	19.8	20.6	20.1	19.8	19.9	19.8	19.8	20.6	18.2	19.6
0.15 (No.100)	11.6	8.6	10.1	11.1	9.9	10.5	10.4	10.5	10.3	11.2	9.4	10.7
0.074 (No.200)	7.7	4.1	4.9	5.2	4.0	5.5	5.4	5.6	4.8	6.1	5.0	6.6
Residual AC (%)	7.91	7.75	7.89	8.06	9.05	9.01	9.21	9.33	8.98	8.94	5.96	5.97
Average (%)	7.83		7.98		9.03		9.28		8.96		5.97	
	8.61											

Table 10-13. Gradations and residual asphalt contents of foamed asphalt mixture and RAP materials collected at 1:30 p.m.

Sieve Size (mm)	Foamed Asphalt Mixture Collected at 1:30 p.m.										RAP Materials Collected at 1:30 p.m.	
	Left side		Left Center		Center		Right Center		Right Side			
	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2
25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	98.0	98.6	99.0	98.5	98.7	97.8	98.5	97.2	98.6	98.5	98.2	98.1
9.5	94.2	95.6	95.4	95.0	95.7	94.2	94.1	93.7	96.1	96.5	94.2	94.6
4.75 (No.4)	79.7	80.7	79.8	79.8	80.8	78.3	79.8	78.3	81.9	82.4	77.6	78.6
2.36 (No.8)	63.0	64.0	63.7	64.2	65.3	63.4	64.1	63.6	64.8	65.0	61.1	63.3
1.18 (No.16)	48.8	49.1	49.2	50.6	50.6	49.5	49.9	50.1	49.0	49.4	46.5	48.7
0.6 (No. 30)	34.8	34.8	35.5	36.2	36.1	35.1	35.5	35.9	34.8	35.3	31.7	33.9
0.3 (No.50)	19.5	19.1	19.6	20.1	19.6	18.5	19.6	19.1	19.2	19.9	15.7	17.8
0.15 (No.100)	10.1	10.3	9.7	10.5	10.3	8.6	10.4	9.5	10.4	10.8	8.1	9.2
0.074 (No.200)	5.6	6.7	4.9	5.6	5.8	3.9	6.6	5.5	6.6	7.2	5.0	5.9
Residual AC (%)	8.25	8.3	8.36	8.69	9.07	8.87	8.74	8.87	8.7	8.63	5.95	6.03
Average (%)	8.28		8.53		8.97		8.81		8.67		5.99	
	8.65											

Table 10-14. Gradations and residual asphalt contents of foamed asphalt mixture and RAP materials collected at 3:30 p.m.

Sieve Size (mm)	Foamed Asphalt Mixture Collected at 3:30 p.m.										RAP Materials Collected at 3:30 p.m.	
	Left side		Left Center		Center		Right Center		Right Side			
	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2
25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	97.7	99.1	98.7	98.0	98.4	98.7	97.1	98.3	98.2	98.7	97.8	97.5
9.5	93.4	96.4	96.0	94.0	94.8	95.1	93.3	95.1	95.2	95.7	94.3	94.7
4.75 (No.4)	78.3	81.7	81.1	78.8	80.8	81.6	79.4	79.4	80.8	82.0	78.5	80.1
2.36 (No.8)	62.7	64.7	65.7	62.7	65.1	65.6	64.7	64.4	64.3	65.7	62.6	64.6
1.18 (No.16)	47.6	49.0	50.4	48.3	50.0	50.2	49.9	50.0	49.4	50.4	48.2	49.8
0.6 (No. 30)	33.4	34.9	35.7	34.2	35.6	36.1	35.4	35.9	35.1	36.0	33.4	34.9
0.3 (No.50)	17.8	19.6	19.7	18.4	19.4	20.5	19.1	20.4	18.5	20.5	17.0	18.3
0.15 (No.100)	9.1	10.9	11.0	10.1	10.7	11.9	10.1	11.7	9.6	10.0	8.4	10.0
0.074 (No.200)	4.5	7.3	7.0	6.6	5.0	7.9	6.3	5.3	3.9	1.5	4.5	5.7
Residual AC (%)	8.47	8.66	9.00	8.87	9.31	8.85	9.17	9.15	9.07	9.20	5.99	6.08
Average (%)	8.57		8.94		9.08		9.16		9.14		6.04	
	8.98											

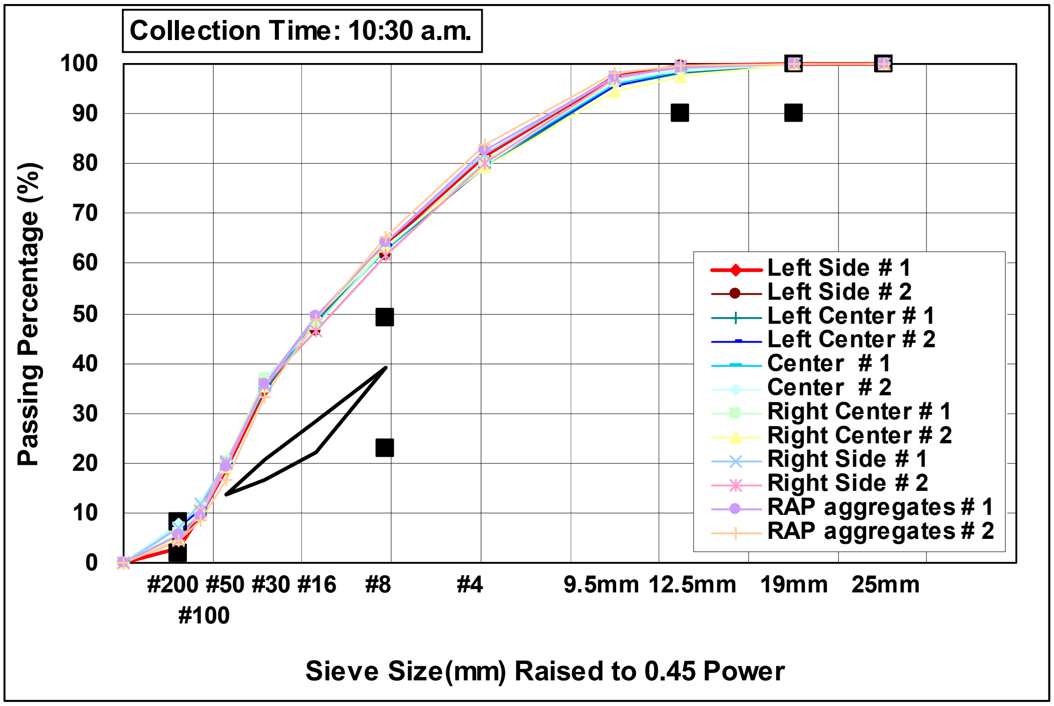


Figure 10-28. Gradations of burned foamed asphalt mixture aggregates collected at 10:30 a.m. across the lane

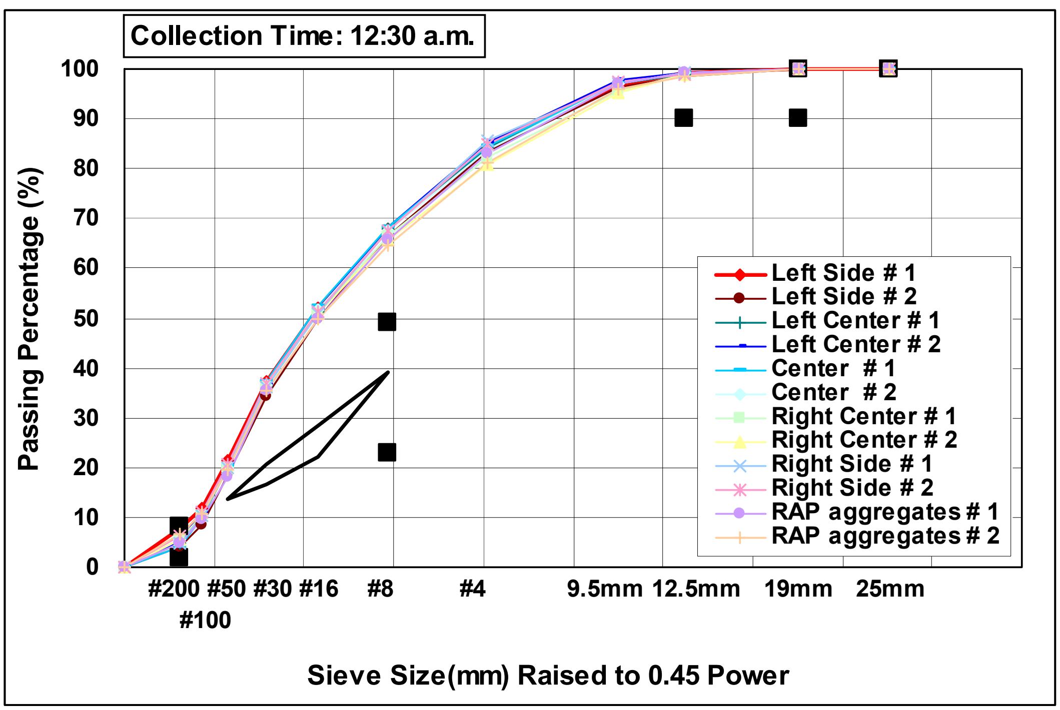


Figure 10-29. Gradations of burned foamed asphalt mixture aggregates collected at 12:30 p.m. across the lane

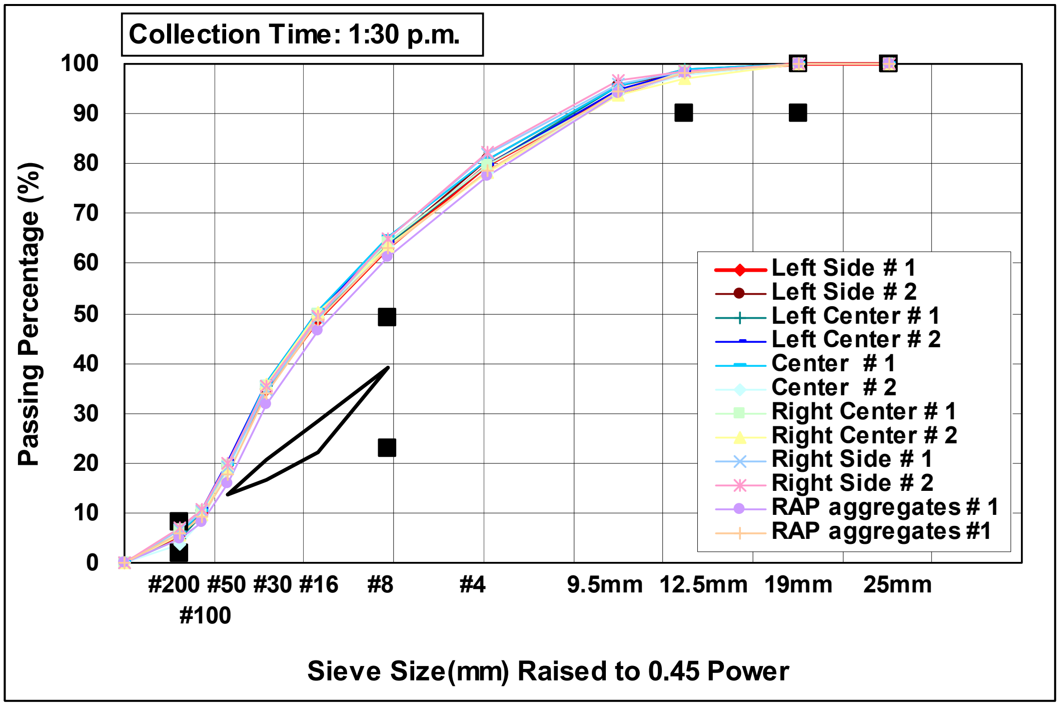


Figure 10-30. Gradations of burned foamed asphalt mixture aggregates collected at 1:30 p.m. across the lane

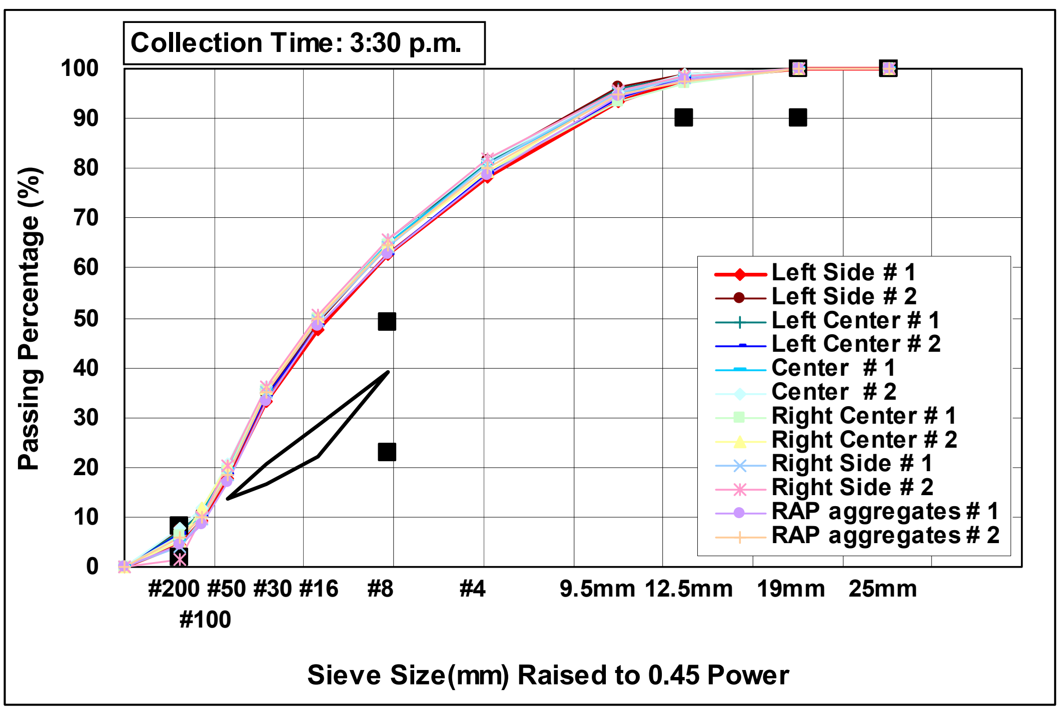


Figure 10-31. Gradations of burned foamed asphalt mixture aggregates collected at 3:30 p.m. across the lane

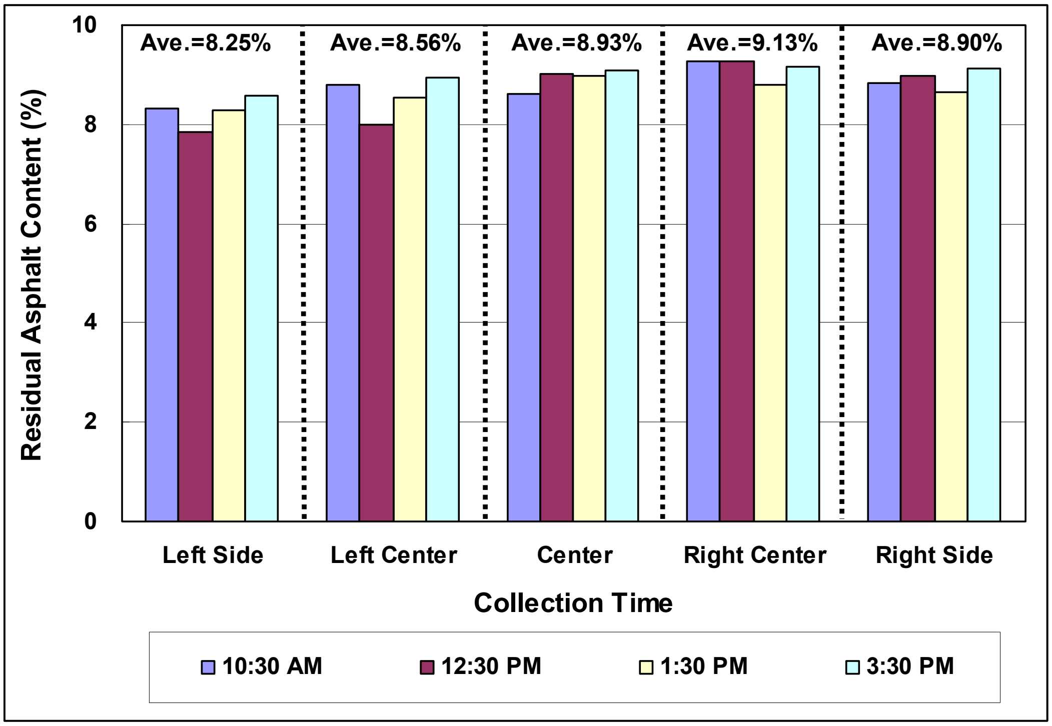


Figure 10-32. Residual asphalt contents of foamed asphalt mixtures across the lane

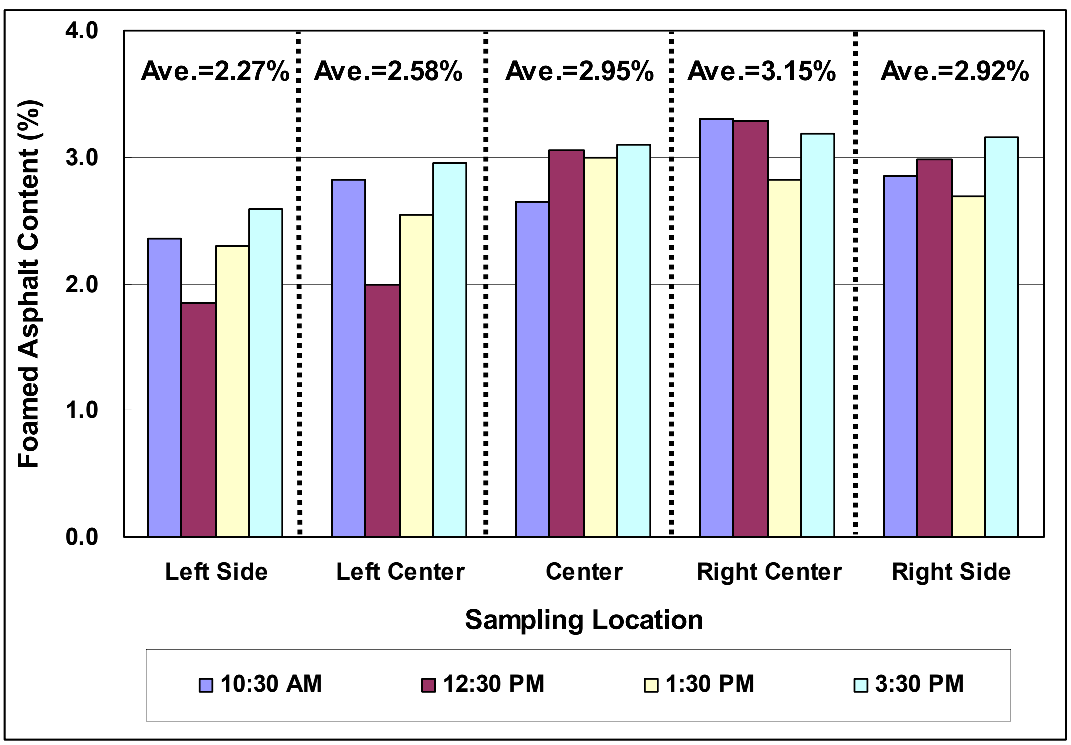


Figure 10-33. Foamed asphalt contents against five different spots across lane

10.6.4 Evaluation of CIR-foam Mixtures

As summarized in Table 10-15, the foamed asphalt mixtures from three different Counties were compacted at 30 gyrations and were cured at 40°C oven for three days and at 60°C oven for two days. The cured specimens were placed in 25˚C water bath for a total of 1.5 hours, 30 minutes without vacuum, 30 minutes with 20-mm Hg vacuum, and 30 minutes without vacuum. Saturated specimens were tested to determine their "wet" indirect tensile strengths. Bulk specific gravities (G_{mb}) of the foamed asphalt mixtures were estimated by measuring volume of the compacted specimens. The maximum specific gravities were measured at each of collection time.

Table 10-15. Number of specimens for evaluation of field foamed asphalt mixtures

Decatur County						
Curing Temperature	Testing Condition	Collection Time				
		11:30 a.m.	12:30 a.m.	1:30 p.m.	2:30 p.m.	3:30 p.m.
40 °C	Wet	3	3	3	3	3
60 °C	Wet	3	3	3	3	3

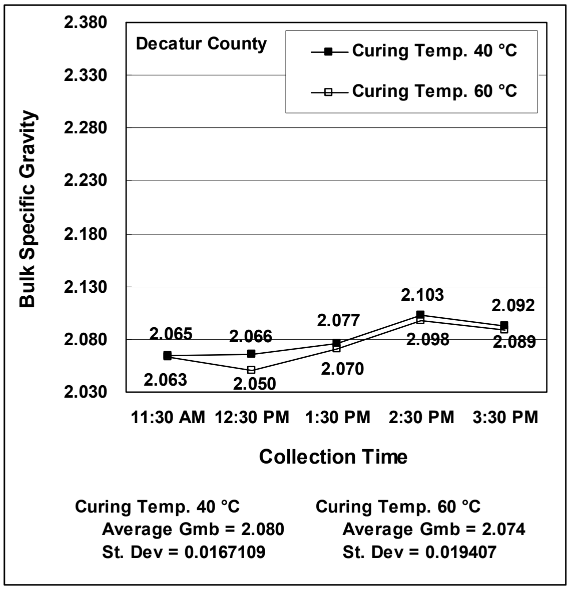
Harrison County							
Curing Temperature	Testing Condition	Collection Time					
		10:30 a.m.	11:30 a.m.	12:30 a.m.	1:30 p.m.	2:30 p.m.	3:30 p.m.
40 °C	Wet	2	2	2	2	2	2
60 °C	Wet	2	2	2	2	2	2

Johnson County		
Curing Temperature	Testing Condition	Collection Time
		9:30 a.m.
40 °C	Wet	3
60 °C	Wet	3

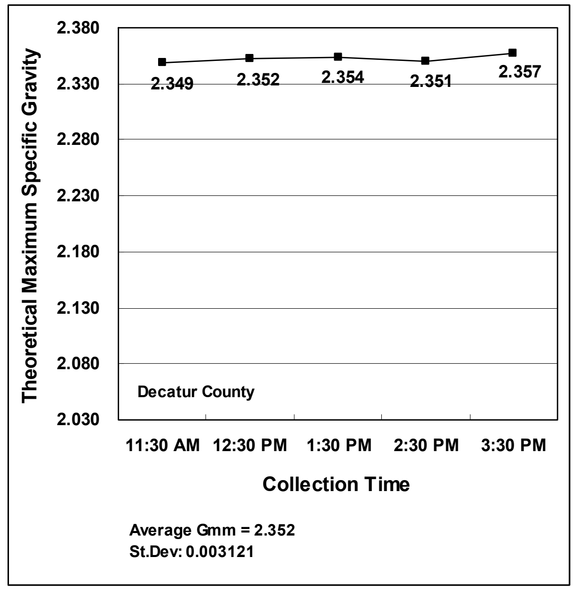
(1) Decatur County Project

Figure 10-34 shows volumetric characteristics and ITS of foamed asphalt mixtures collected from Decatur County at five different collection periods, 11:30 a.m., 12:30 p.m., 1:30 p.m., 2:30 p.m. and 3:30 p.m. As shown in Figure 10-34, specimens cured at 40°C exhibited little higher bulk specific gravity than specimens cured at 60°C. Specimens collected at 12:30 p.m. shows lower bulk specific gravity at both curing temperatures. Theoretical maximum specific gravity exhibits very similar over the time from 11:30 a.m. to 3:30 p.m. Air void also exhibited a very similar trend over time except 12:30 p.m. to 2:30 p.m.

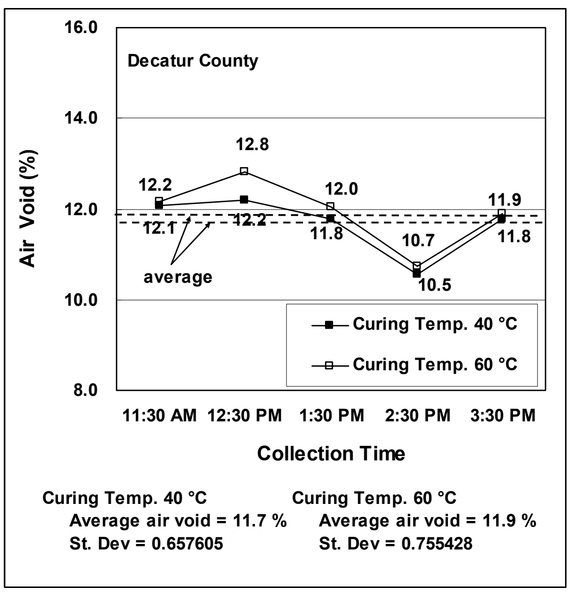
As shown in Figure 10-34 (d), indirect tensile strength of CIR-foam specimens cured at 60°C exhibits higher that that of CIR-foam specimens cured at 40°C. Foamed asphalt specimens collected at 11:30 a.m., 1:30 p.m., and 3:30 p.m. exhibited the similar indirect tensile strength but foamed asphalt specimens collected at 12:30 a.m. and 2:30 p.m. exhibited significantly lower than others. The lower indirect tensile strength could have been caused by their relatively fine gradations obtained at 12:30 p.m. and 2:30 p.m. It is interesting to note that foamed asphalt specimens with both the highest and the lowest air void exhibits lower indirect tensile strength, which indicates that the optimum air void may lead to the higher indirect tensile strength.



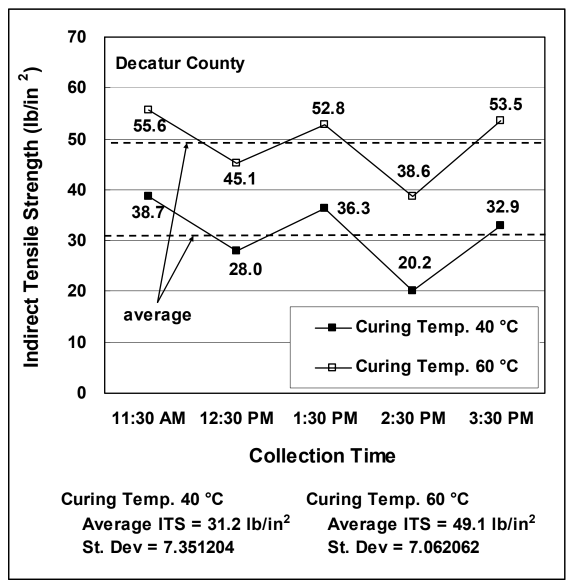
(a) Estimated G_{mb}



(b) G_{mm}



(c) Air void



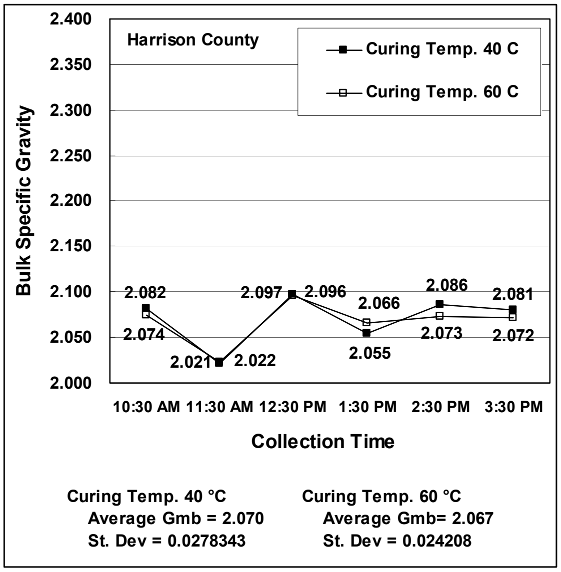
(d) ITS

Figure 10-34. Volumetric characteristics and ITS of foamed asphalt mixture collected from Decatur County project

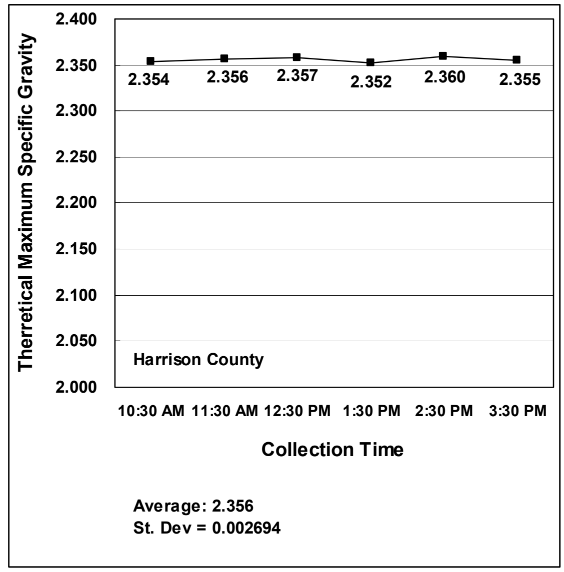
(2) Harrison County Project

Figure 10-35 shows volumetric characteristics and ITS of foamed asphalt mixtures collected from the Harrison County project at six different collection periods, 10:30 a.m., 11:30 a.m., 12:30 p.m., 1:30 p.m., 2:30 p.m. and 3:30 p.m. As shown in Figure 10-35, specimens cured at 40°C exhibited little higher bulk specific gravity than those cured at 60°C. The specimens collected at 11:30 a.m. shows lower bulk specific gravity at both curing temperatures because RAP gradation collected at 11:30 a.m. exhibited the most coarse gradation. Theoretical maximum specific gravity exhibited very similar over time from 10:30 a.m. to 3:30 p.m. Air void were also very consistent over time except 11:30 a.m.

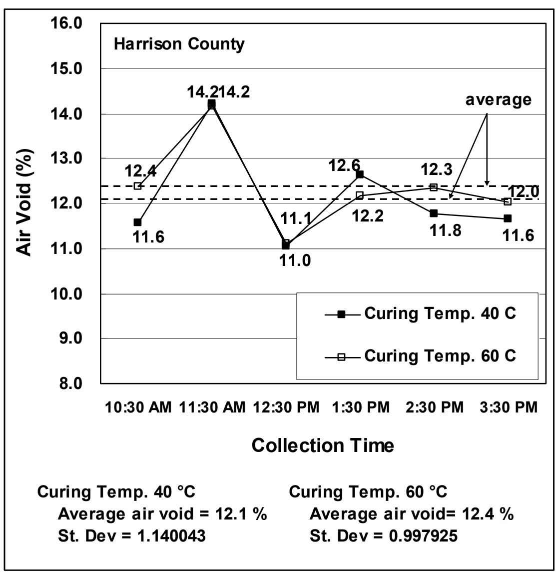
As shown in Figure 10-35 (d), indirect tensile strength of CIR-foam specimens cured at 60°C exhibited higher that that of CIR-foam specimens cured at 40°C. Foamed asphalt specimens collected at 11:30 a.m. exhibited the lowest indirect tensile strength at both curing temperatures. It is interesting to note that the gradation at 11:30 a.m. was the coarsest.



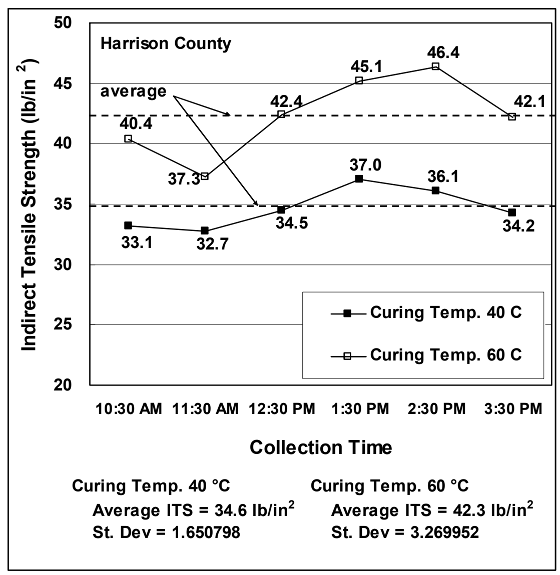
(a) Estimated G_{mb}



(b) G_{mm}



(c) Air void



(d) ITS

Figure 10-35. Volumetric characteristics and ITS of foamed asphalt mixture collected from Harrison County project

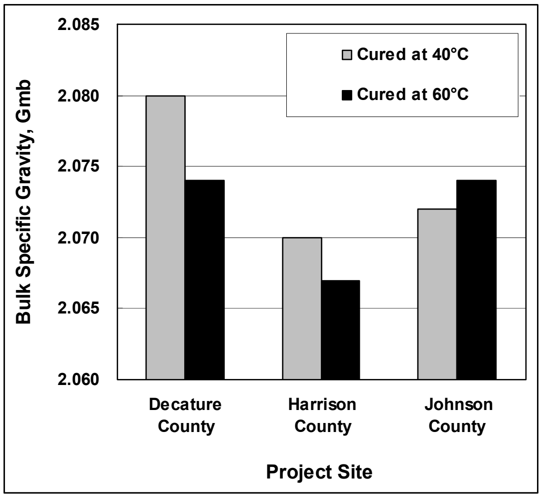
(3) Johnson County Project

Table 10-16 shows volumetric characteristics and ITS of foamed asphalt mixtures collected from the Johnson County project collected at 9:30 a.m. The specimens cured at 40°C and 60°C exhibited the similar bulk specific gravity and air void. Indirect tensile strength of CIR-foam specimens cured at 60°C exhibited higher that that of CIR-CIR-foam specimens cured at 40°C.

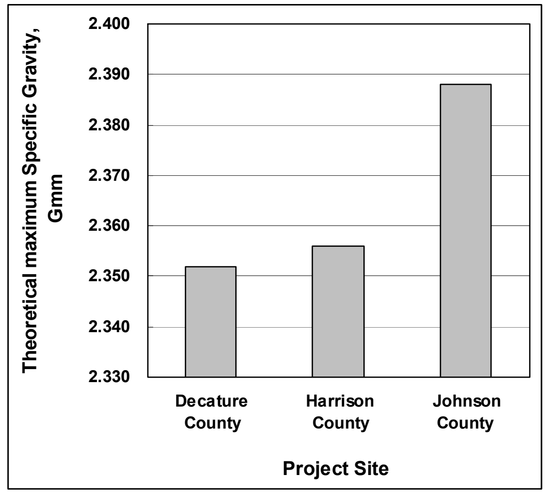
Table 10-16. Volumetric characteristics and ITS of foamed asphalt mixtures collected in the Johnson County project

Curing Condition : 40°C for 3days				
Collection Time	Bulk Specific Gravity	Theoretical Maximum Specific Gravity	Air Void (%)	ITS (lb/in^2)
9:30 a.m.	2.072	2.388	13.2	24.0
Curing Condition : 60°C for 2days				
Collection Time	Bulk Specific Gravity	Theoretical Maximum Specific Gravity	Air Void (%)	ITS (lb/in^2)
9:30 a.m.	2.074	2.388	13.2	40.9

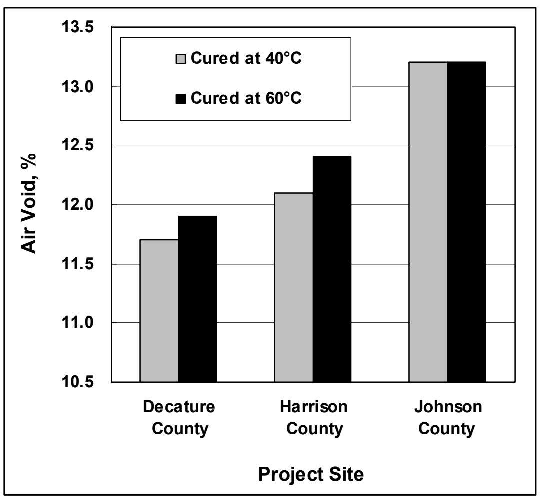
Figure 10-36 shows volumetric characteristics and ITS of foamed asphalt mixtures collected from three CIR-foam project sites. The RAP materials from the Johnson County exhibited the highest maximum specific gravity mainly due to its low foamed asphalt content. The low foamed asphalt content lead to the high air voids due to its lack of compatibility. As a result, the indirect tensile strength was the lowest among them.



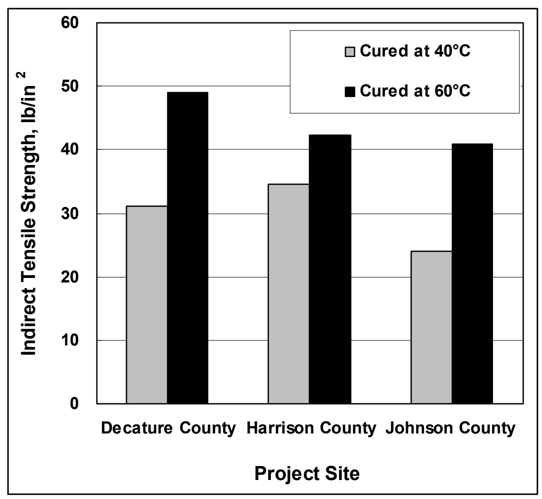
(a) G_{mb}



(b) G_{mm}



(c) Air void



(d) ITS

Figure 10-36. Comparisons of volumetric characteristics and ITS of foamed asphalt mixture collected from three CIR-foam project sites

11. CONCLUSIONS AND RECOMMENDATIONS

Asphalt pavement recycling has grown dramatically over the last few years as the preferred way to rehabilitate existing asphalt pavements. Rehabilitation of existing asphalt pavements has employed different techniques; one of them, Cold In-place Recycling with foamed asphalt (CIR-foam), has been effectively applied in Iowa. However, the current CIR-foam practice utilizes a generic recipe specification without a mix design, where a contractor is given latitude to adjust the proportions of the foamed asphalt content to achieve a specified level of density. Therefore, this study was conducted to develop a new laboratory mix design process for CIR-foam in consideration of its predicted field performance.

First, the findings, conclusions, and recommendations obtained from phase I study are summarized. The developed mix design procedure was then validated using different sources of RAP materials. The simple performance tests, which include dynamic modulus test, dynamic creep test and raveling test, were conducted to evaluate the consistency of a new CIR-foam mix design process to ensure reliable mixture performance over a wide range of traffic and climatic conditions. Pavement surface conditions of seven CIR projects were evaluated after one year since construction, where the RAP materials had been collected in the summer of 2004. Finally, the CIR-foam construction processes from milling to compaction were observed.

Conclusions

Based on the extensive laboratory experiments the following conclusions are derived:

1. Gyratory compactor produces the more consistent CIR-foam laboratory specimen than Marshall hammer.

2. Indirect tensile strength of gyratory compacted specimens is higher than that of Marshall hammer compacted specimens
3. 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.
4. Dynamic modulus of CIR-foam is affected by a combination of the RAP sources and foamed asphalt contents.
5. The coarse RAP materials with a small amount of residual asphalt content may be more resistant to fatigue cracking but less resistant to rutting.
6. CIR-foam is not as sensitive to temperature or loading frequency as HMA.
7. Based on the dynamic creep tests performed at 40˚C, CIR-foam with 1.0% foamed asphalt is more resistant to rutting than CIR-foam with 2.0% or 3.0%.
8. Based on the dynamic creep tests performed at 40C, RAP aggregate structure has a predominant impact on its resistant to rutting.
9. 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.
10. CIR-foam specimens with 2.5% foamed asphalt content are more resistant to raveling than ones with 1.5%.
11. There is a significant variation in distribution of foamed asphalt across the lane during the CIR-foam construction, which could affect its field performance.

Recommendations

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

1. 30 gyrations are recommended for producing the equivalent laboratory specimens produced by 75-blow Marshall hammer.

2. Laboratory specimens should be cured in the oven at 60°C for 2 days.
3. To determine the optimum foamed asphalt content, indirect tensile strength test should be performed on vacuum saturated specimen.
4. Gyratory compacted specimens should be placed in 25˚C water for 20 minutes, vacuumed saturated at 20 mm Hg for 30 minutes and left under water for additional 30 minutes without vacuum.
5. 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 increases from 28 to 15.
6. The proposed mix design procedure should be implemented to assure the optimum performance of CIR-foam pavements in the field.

Future Studies

1. CIR-foam pavements should be constructed following the new mix design process and their long-term field performance should be monitored and verified against the laboratory performance test results.
2. New mix design and laboratory simple performance tests should be performed on the CIR-foam mixtures using stiffer asphalt binder grade, i.e., PG 58-28 or 64-22.
3. Static creep test should be evaluated for a possible addition to the performance test protocol.
4. New mix design and laboratory performance tests should be evaluated for CIR-emulsion mixtures.
5. To better simulate the field performance as a base, performance tests should be performed on both CIR-foam and CIR-emulsion specimens with a horizontal confined pressure.
6. A comprehensive database of mix design, dynamic modulus, flow number and

raveling for both CIR-foam and CIR-emulsion should be developed to allow for an input to the Mechanistic-Empirical Pavement Design Guide (MEPDG).

REFERENCES

AASHTO-AGC-ARTBA Joint Committee Task Force 38. (1999). "Report on Cold Recycling of Asphalt Pavements". Washington, DC: AASHTO.

Asphalt Recycling and Reclamation Association (ARRA). (2001). Basic Asphalt Recycling Manual.

AASHTO (2001). "Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens." AASHTO T 166.

AASHTO, (2003). "Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures." AASHTO TP-62-03.

ASTM (2005). "Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate." ASTM D 4791.

Brennen, M., M. Tia, A. Altschaeffl, and L. E. Wood. (1970)."Laboratory Investigation of the Use of Foamed Asphalt for Recycled Bituminous Pavements." Washington, DC: TRB, National Research Council, pp. 80-87.

Bonaquist, R. F., Christensen, D. W. and Stump, W. (2003). "Simple Performance Tester for Superpave Mix Design Development and Evaluations." Transportation Research Record, NCHRP Report 513.

Brown, E. R., Cooley, A., Prowell, B. amd Powell, B. (2004) "Evaluation of Rutting Performance at the 2000 NCAT Test Track." Journal of the Association of Asphalt Pavement Technologist, Volume 73.

Brown, E. R., Powell, B., West, R. and Timm, David. (2005) "NCAT Test Track Findings." National Center for Asphalt Technology.

Birgisson, B., Roque, R., Kim, J. and Pham, L. V. (2004) "The Use of Complex Modulus to Characterize the Performance of Asphalt Mixtures and Pavements in Florida." Final Report, 4910-4501-784-12, Florida Department of Transportation.

Clyne, T. R., Li, X., Marasteanu, M. O. and Engene, K. (2003) "Dynamic Modulus and Resilient Modulus of Mn/DOT Asphalt Mixtures." Minnesota Department of Transportation, MN/RC-2003-09.

Ekingen, E. R. (2004). "Determining Gradation and Creep Effects in Mixtures Using the Complex Modulus Test." Thesis of Mater Degree, University of Florida.

EI-Basyoung, M. M, Witczck, M., Kaloush, K. (2005) "Development of the Permanent Deformation Models for the 2002 Design Guide." CD-ROM of TRB 84th Annual Meeting, Washington. D.C.

Guide for Mechanical-Empirical Design of New and Rehabilitated Pavement Structures. NCHRP Project 1-37A, www.trb.org/mepdg/. Accessed July 15, 2006..

Kaloush, K.E., Witczak, M.W. and Quintus, H.V. (2002) "Pursuit of the Simple Performance Test for Asphalt Mixture Rutting," Journal of the Association of Asphalt Paving Technologists, Vol.71, pp.783-810.

Kim Y. and Lee, H. (2006). "Development of Mix Design Procedure for Cold In-Place Recycling with Foamed Asphalt" The Journal of Materials in Civil Engineering, ASCE, Vol. 18, No1, ISSN 0899-1561, pp 116-124.

Lee, H., and Kim Y. (2003). "Development of a Mix Design Process for Cold In-Place Rehabilitation using Foamed Asphalt", Iowa Department of Transportation, Iowa Highway research board, Final report.

Lee. K.W., T. E. Brayton, and J. Harrington. (2003). "New Mix-Design Procedure of

Cold In-Place Recycling for Pavement Rehabilitation." Washington, DC: CD-ROM of TRB 82th Annual Meeting.
Lundy, J. R., Sandoval-Gil, J., Brickman, A. and Patterson, B. (2005) "Asphalt Mix Characterization Using Dynamic Modulus and APA Testing" Final Report, FHWA-OR-RD-06-09, Oregon Department of Transportation and Federal Highway Administration.
Mohammad, L. N., Wu, Z., Obulareddy, S., Cooper, S. and Abadie, C. (2006). "Permanent Deformation Analysis of HMA Mixtures Using Simple Performance Tests and The 2002 Mechanistic-Empirical Pavement Design Software." CD-ROM of TRB 85th Annual Meeting, Washington. D.C.
Nataatmadja, A. (2001). "Some Characteristics of Foamed Bitumen Mixes." Transportation Research Record 1767. Washington, DC: TRB, National Research Council, pp. 120-125.
Pan, T., Tutumluer, E. and Carpenter, S. H., (2006). "Effect of Coarse Aggregate Morphology on Pavement Deformation Behavior of Hot Mix Asphalt." Journal of Transportation Engineering, ASCE, Vol. 132, No. 7, pp580-589.
Salomon, A., and D.E. Newcomb. (2001). "Cold In-Place Recycling Literature Review and Preliminary Mixture Design Procedure." Minnesota Department of Transportation, MN/RC-2000-21.
Stephen A. C. (2002). "Determination of N design for CIR mixtures using the Superpave Gyratory Compactor". University of Kansas Center for Research.
Thomas, T., and Kadrmas, A. (2003). "Performance-Related Tests and Specifications for Cold In-Place Recycling: Lab and Field Experience". CD-ROM of TRB 82th Annual Meeting, Washington. D. C.
Williams, M. L., Landel, R. F. and Ferry, J. D. (1955). "The Temperature Dependence of Relaxation Mechanism in Amorphous Polymers and other Glass Forming Liquids." Journal of the American Chemical Society, Vol. 77, pp 3701-3706.
Witczak, M. W., Kaloush, K., Pellinen, T., El-Basyouny, M. and Von Quintus, H. (2002). ''Simple performance test for superpave mix design.'' NCHRP Rep. No. 465, Transportation Research Board, National Research Council, National Academy Press, Washington D.C.

GLOSSARY OF ACRONYMS

AADT: Average annual daily traffic

CIR: Cold in-place recycling

CIR-foam: Cold in-place recycling using foamed asphalt

CIR-ReFlex: Cold in-place recycling using ReFlex Emulsion

CIR-Emulsion: Cold in-place recycling using Emulsion

FAC: Foamed asphalt content

G_{mb}: Bulk specific gravity

G_{mm}: Theoretical maximum specific gravity

HMA: Hot mix asphalt

ITS: Indirect tensile strength

MC: Moisture content

PG: Performance grade

SPT: Simple performance test

RAP: Reclaimed asphalt pavement