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Determination of Dynamic Modulus of Cold In-place Recycling Mixtures with Foamed Asphalt

폼드아스팔트를 이용한 현장 상온 재생 아스팔트 혼합물의 동탄성계수 결정

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요 지

폼드아스팔트를 이용한 현장 상온 재생아스팔트 혼합물에 대한 배합설계법이 아이오아 주 교통국에서 사용하기 위해 개발되었다. 상온 재생 폼드아스팔트 혼합물의 배합설계를 위한 실내시험절차를 개선하기 위하여 배합설계에 영향을 미치는 중요한 배합설계변수들을 결정하여 상온 재생 폼드아스팔트 혼합물의 특성을 반영할 수 있는 새로운 배합설계절차를 개발하였다. 개발된 배합설계법의 검증을 위한 한 가지 방법으로 상온 재생 폼드아스팔트 혼합물의 동탄성계수를 측정하였다. 본 연구에서는 새로운 simple performance testing 장비를 이용한 상온 재생 폼드아스팔트 혼합물의 동탄성계수 측정을 위한 표준시험절차를 정립하고, 7가지 재생 아스팔트 골재를 사용하여 생산된 상온 재생 폼드아스팔트 혼합물의 동탄성계수를 측정하여 마스터곡선을 작성하였다. 또한, 재생 아스팔트 골재의 특성이 상온 재생 폼드아스팔트 혼합물의 동탄성 계수에 미치는 영향을 조사하였다. 3가지 온도와 6가지의 하중주기에서 측정된 상온 재생 폼드아스팔트 혼합물의 동탄성계수는 7가지 재생 아스팔트 골재에서 일관된 값을 나타내었으며, 작성된 상온 재생 폼드아스팔트 혼합물의 마스터곡선은 가열 아스팔트 혼합물의 마스터곡선에 비해 하중주기에 대해 덜 민감한 것으로 평가되었다. 저온에서는 재생 아스팔트 골재의 잔골재 함유량이 상온 재생 폼드아스팔트 혼합물의 동탄성계수에 영향을 미치는 것으로 나타났으며, 고온에서는 재생 아스팔트 골재의 잔류 아스팔트 특성이 상온 재생 폼드아스팔트 혼합물의 동탄성계수에 영향을 미치는 것으로 나타났다.

핵심용어 : 현장 상온 재생, 폼드아스팔트, 재생 아스팔트 골재, 동탄성계수, 마스터곡선

Abstract

A new mix design procedure for cold in-place recycling using foamed asphalt (CIR-foam) has been developed for Iowa Department of Transportation. Some strengths and weaknesses of the new mix design parameters were considered and modified to improve the laboratory test procedure. Based on the critical mixture parameters identified, a new mix design procedure was developed and validated to establish the properties of the CIR-foam mixtures. As part of the validation effort to evaluate a new CIR-foam mix design procedure, dynamic moduli of CIR-foam mixtures made of seven different reclaimed asphalt pavement (RAP) materials collected throughout the state of Iowa were measured and their master curves were constructed. The main objectives of this study are to provide: 1) standardized testing procedure for measuring the dynamic modulus of CIR-foam mixtures using new simple performance testing (SPT) equipment; 2) analysis procedure for constructing the master curves for a wide range of RAP materials; and 3) impacts of RAP material characteristics on the dynamic modulus. Dynamic moduli were measured at three different temperatures and six different loading frequencies and they were consistent among different RAP sources. Master curves were then constructed for the CIR-foam mixtures using seven different RAP materials. Based upon the observation of the constructed master curves, dynamic moduli of CIR-foam mixtures were less sensitive to the loading frequencies than HMA mixtures. It can be concluded that at the low temperature, the dynamic modulus is affected by the amount of fines in the RAP materials whereas, at the high temperature, the dynamic modulus is influenced by the residual binder characteristics.

Keywords : cold in-place recycling, foamed asphalt, reclaimed asphalt pavement, dynamic modulus, and master curve

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1. INTRODUCTION

A desire to maintain a safe, efficient, and cost-effective roadway system has led to a significant increase in the demand to rehabilitate the existing pavements. The asphalt pavement recycling has grown dramatically over the last few years as preferred way to rehabilitate the existing pavements. The rehabilitation of existing asphalt pavements has been done using various techniques; one of these, the cold in-place recycling with foamed asphalt (CIR-foam), is discussed in this paper.

As cold in-pace recycling (CIR) continues to evolve, the desire to place CIR mixtures with specific engineering properties requires the use of a mix design process. Both Marshall stability and indirect tensile strength test procedures were evaluated as part of the CIR-foam mix design procedure using reclaimed asphalt pavement (RAP) materials collected from US-20 highway in Iowa (Lee and Kim 2003). The critical mix design parameters were identified and the laboratory test procedure was modified to improve the consistency of the existing CIR-foam mix design process. Based on the critical mixture parameters identified, a new mix design procedure was developed and validated to establish the properties of the CIR-foam mixtures (Kim and Lee 2006; Kim et al. 2007).

As part of the validation effort to evaluate the consistency of the new CIR-foam mix design procedure, the dynamic moduli of CIR-foam mixtures, which were made of seven different reclaimed asphalt pavement (RAP) materials collected throughout the state of Iowa, were measured using new simple performance testing (SPT) equipment. The SPT system can perform the dynamic modulus test, static creep test, and repeated load test following the NCHRP 9-29 test standards. Although the concept of using dynamic modulus has been adopted for evaluating the performance characteristics of hot mix asphalt (HMA) materials, there has been little research performed on the use of dynamic modulus for the evaluation of the performance characteristics of CIR mixtures.

This paper presents a standardized testing procedure for measuring the dynamic modulus of CIR-foam mixtures using new SPT equipment, an analysis procedure for constructing the master curves for a wide range of RAP materials, and the impacts of RAP material characteristics on the dynamic modulus. CIR-foam specimens with RAP materials from seven different sources were prepared using the gyratory compactor at 25 gyrations with the foamed asphalt content (FAC) of 2.0% and the moisture content of 4.0%. The 25-gyration was selected because the test specimens compacted by 25 gyrations produced the equivalent bulk specific gravity as the specimens compacted by 75 blows of Marshall hammer (Lee and Kim 2003). Dynamic modulus was measured from the 25-gyration compacted CIR-foam specimens with 100-mm diameter and 150-mm height at three different temperatures, 4.4℃, 21.1℃ and 37.8℃ and six different loading frequencies, 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz and 0.1Hz. The master curves were then constructed based on the nonlinear Sigmoidal model using the Excel Optimization Solver function. Impacts of RAP characteristics such as gradation, residual asphalt content, and residual asphalt stiffness on the dynamic modulus are discussed in this paper.

2. LITERATURE REVIEW

Over the decades, numerous studies have been conducted to develop various foamed asphalt mix design procedures for full-depth reclamation (FDR) and they were thoroughly reviewed and summarized by Kim and Lee (2006). FDR is a reclamation technique in which an asphalt pavement and layer and predetermined portion of the underlying base materials are crushed, pulverized and blended, resulting in a stabilized base course. Cold in-place recycling (CIR) is a surface recycling technique that mills a surface asphalt pavement layer, blend with stabilizing agents such as emulsified asphalt and foamed asphalt, resulting in a stabilized base course (Marquis et al. 2003). AIPCR and PIARC (2002) published a report on CIR applications with emulsion (CIR-emulsion) or foamed bitumen (CIR-foam), which was not intended as a specification; it rather provided information on the applications in different countries. However, none of these CIR design methods considered the dynamic modulus as a design parameter.

Since 1960's, many studies have been conducted in the area of improving the dynamic modulus test procedures. Witczak and Rott (1974) presented that the tension-compression test that better predicted asphalt pavement behavior under the field loading conditions. Bonnaure et al. (1977) selected a bending test to determine the dynamic modulus. Stroup-Gardiner and Newcomb (1997), Drescher et al. (1997) and Zhang et al. (1997) conducted complex modulus tests on both tall cylindrical specimens and indirect tensile specimens and reported that tests on the same material with the different setups yielded different dynamic moduli and phase angles. Recently, Witczak et al. (2002) and Bonaquist et al. (2003) proposed new guidelines for the dynamic modulus test with respect to the proper specimen geometry and size, specimen preparation, testing procedure, loading pattern, and empirical modeling.

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 binder exhibited the lower dynamic modulus than those with stiffer asphalt binder. Ekingen (2004) also found that the dynamic modulus was sensitive to the asphalt viscosity of mixtures. Brown et al. (2004) 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. Birgisson et al. (2004) reported that there was a significant effect of gradation on dynamic modulus measurements. Tran and Hall (2006) reported that the variability of the test results was larger for HMA mixtures having larger aggregate sizes and was more pronounced for extreme high and low temperatures. Lundy et al. (2005) found that the dynamic modulus would be similar if the aggregate structures are similar. They also reported that the mixtures with PG 76-22 binder consistently exhibited the highest dynamic modulus, PG 70-28 was next and PG 64-22 was the lowest.

Although the performance characteristics have been applied to characterize the HMA materials, there has been little research performed on the use of dynamic modulus to evaluate CIR mixtures. Currently, due to a lack of research effort in CIR materials, the mechanical-empirical pavement design guide (M-E PDG) treats CIR mixtures same as HMA base course. However, they significantly vary in terms of stress-strain behavior where that of CIR materials is influenced by stabilizing agents and the quality of RAP materials. Thomas and Richard (2007) reported the dynamic modulus of FDR-emulsion was influenced by the mix composition, quantity of RAP and binder type. It was found that default constant modulus of 69MPa for FDR was an unrealistically low value because it showed the dynamic modulus of 4415MPa at 21℃ and 10Hz.

3. MASTER CURVE CONSTRUCTION PROCEDURE

The purpose of the dynamic modulus test is to determine the stiffness of asphalt mixtures in response to loading and various temperature conditions. The stress to strain relationship under a continuous sinusoidal loading for linear visco-elastic materials is defined by a complex number called complex modulus, where its absolute value is defined as the dynamic modulus. The dynamic modulus is mathematically defined as the maximum dynamic stress (σ_0) divided by peak recoverable axial strain (ε_0) as Eq. 1:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (1)$$

The measured dynamic modulus at different temperatures can be then shifted relative to the loading frequency so that the various curves can be aligned to form a single master curve as shown in Eq. 2. The master curve of an asphalt mixture allows comparisons to be made over extended ranges of frequencies and temperatures. Master curve 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.

$$\log(f_r) - \log(f) = \log\ \alpha(T) \quad (2)$$

f_r = reduced frequency (Hz)
f = loading frequency (Hz)
$\alpha(T)$ = 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 $\alpha(T)$ is defined as Eq. 3:

$$\log\ \alpha(T) = -\frac{C_1(T - T_{ref})}{C_2 + T - T_{ref}} \quad (3)$$

T_{ref} = reduced frequency (℃)
T = tst temperature (℃)
C_1, C_2 = empirical constants

The frequency where the master curve should be read f_r is defined as Eq. 4:

$$f_r = \alpha(T) \times f \quad (4)$$

A master curve represented by a nonlinear Sigmoidal function is defined in AASHTTO 2002 Design Guide (NCHRP 1-37A, 2006) as Eq. 5:

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log f_r}} \quad (5)$$

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

In constructing the master curve, as shown in Figure 1, the measured dynamic moduli at test temperatures higher than the reference temperature are horizontally shifted to lower frequencies and those at test temperatures lower than the reference temperature are shifted to the higher frequencies.

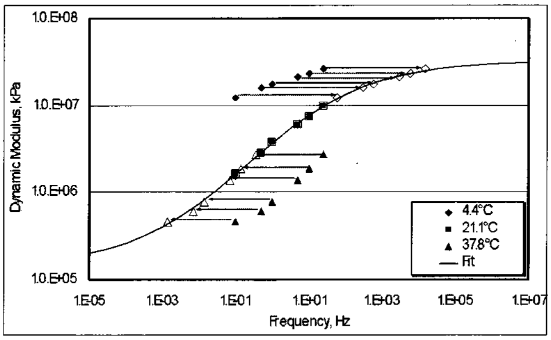


Fig. 1 Construction of Master Curve Represented by a Nonlinear Sigmoidal Model

4. DYNAMIC MODULUS TESTING PROCEDURE FOR CIR-FOAM MIXTURES

In order to prepare the CIR-foam specimens for dynamic modulus test, as shown in Figure 2, RAP materials were collected from seven different CIR construction sites: three CIR-foam sites and four CIR-ReFlex® emulsion sites.

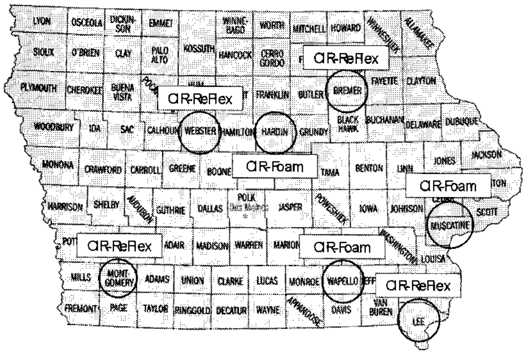


Fig. 2 Locations of CIR Construction Sites where RAP Materials were Collected

The collected RAP materials were dried in the air (25℃~27℃) for 10 days. Dried RAP materials were divided into five stockpiles which were retained on the following four sieves: 19.0mm, 9.5mm, 4.75mm, 1.18mm and passing 1.18mm sieve. The divided RAP stockpiles were then weighted and their relative proportions were computed. As shown in Figure 3, gradations of seven RAP sources are plotted on a 0.45 power chart. Overall, the gradation of RAP materials from all seven Counties can be considered coarse with a very small amount of fines passing No. 200 sieve.

As summarized in Table 1, the characteristics of RAP materials from seven different sources were analyzed in terms of 1) amount of fines passing No.4 sieve, 2) residual asphalt content, and 3) residual asphalt stiffness in penetration index. RAP materials from Muscatine County are the coarsest, followed by those from Montgomery, Webster Counties whereas the ones from Bremer, Lee, and Hardin Counties can be considered as densely graded. The residual asphalt was recovered by the Abson method from a solution (ASTM 2003). The residual asphalt stiffness of the recovered asphalt were evaluated by the penetration test, which measures the penetration of a standard needle into the asphalt binder sample under the loading of 100g at 25℃ for 5 seconds (ASTM 2006). The residual asphalt contents ranged from 4.6% for RAP materials collected from Wapello County to 6.1% from Hardin County. The residual asphalt of RAP materials from Montgomery County exhibited the highest penetration of 28 whereas that from Lee County showed the lowest penetration of 15.

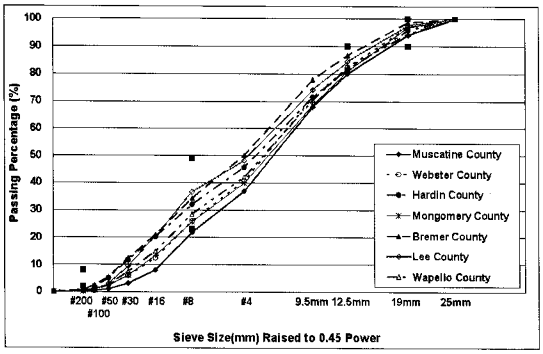


Fig. 3 Gradation Plots of Seven Different RAP Materials Passing 25mm Sieve

Table 1. Extracted Binder and Aggregates Tests

RAP Source	RAP Characteristics		
	% Passing No.4 Sieve	Residual AC (%)	Stiffness (Pen.)
Bremer County	Fine (50.1%)	Middle (5.0%)	Hard (17)
Lee County	Fine (48.3%)	Middle (5.4%)	Hard (15)
Hardin County	Fine (45.7%)	High (6.1%)	Hard (15)
Wapello County	Middle (42.0%)	Low (4.6%)	Soft (21)
Webster County	Coarse (40.6%)	High (6.0%)	Hard (17)
Montgomery County	Coarse (39.8%)	High (5.7%)	Soft (28)
Muscatine County	Coarse (36.8%)	Low (4.7%)	Middle (19)

4.1 Simple Performance Testing Equipment

Witczak et al. (2002) and Bonaquist et al. (2003) described the development of the simple performance testing (SPT) equipment, which can conduct dynamic modulus test, static creep test and repeated load test at various loading and temperature conditions. As shown in Figure 4, the SPT system installed at the University of Iowa utilizes a magnetic mounted extensometer, which snaps on the test specimen with a minimum disruption to the temperature control. It is equipped with an environmental chamber, where the CIR-foam specimens can be tested at 4.4℃, 21.1℃ and 37.8℃, where 37.8℃ can be considered as the highest temperature of CIR-foam endured as a base material in the field.

Fig. 4 Interlaken Simple Performance Testing Equipment

4.2 Preparation of Dynamic Modulus Test Specimens

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

Table 2 summarizes mix design parameters, which were adopted to prepare CIR-foam specimens to measure the dynamic modulus using seven different RAP sources. For each RAP source, two test specimens were prepared with 2.0% of foamed asphalt content and 4.0% of moisture content. CIR-foam specimens were compacted by gyratory compactor at 25 gyrations and were cured in the oven at 40℃ for 3 days. The cured specimens were allowed to cool to a room temperature for 24 hours before testing.

Table 2. Mix Design Parameters of CIR-foam Specimens for Dynamic Modulus Test

Number of Specimen	2 specimens
Asphalt Binder	PG 52 - 34
Foaming Temperature (℃)	170℃
Foaming Water Content (%)	1.3 %
Foamed Asphalt Content (%)	2.0 %
Moisture Content of RAP (%)	4.0 %
Compaction Method	Gyratory Compactor (25 gyrations)
Curing Condition	In the oven at 40℃ for 72 hours

The bulk specific gravities of each CIR-foam specimen were determined following the AASHTO T 166 by measuring the dry mass and height (AASHTO 2001). As

Table 3. Bulk Specific Gravity of CIR-foam Specimens for Dynamic Modulus Test

RAP Source	Number of Specimen		Average
	# 1	# 2	
Hardin County	2.032	2.022	2.022
Lee County	2.071	2.074	2.072
Webster County	2.080	2.080	2.080
Muscatine County	2.079	2.082	2.081
Montgomery County	2.077	2.092	2.085
Bremer County	2.108	2.108	2.108
Wapello County	2.119	2.123	2.121

summarized in Table 3, RAP materials from Hardin County showed the lowest bulk specific gravity whereas those from Wapello County showed highest bulk specific gravity.

4.3 Dynamic Modulus Testing Procedure

In order to perform dynamic modulus test on CIR-foam mixtures, the standard "AASHTO TP 62-07 protocol: Determining Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures" was modified to be performed at three temperatures of 4.4℃, 21.1℃, and 37.8℃ 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 limiting axial strain of 100 microstrain. At the high temperature, however, CIR-foam specimens become too soft and it is very difficult to control the applied axial force to obtain the axial strain of 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 70mm ± 1mm at the middle of the specimen. As shown in Figure 5, 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 5.0% of the dynamic load was applied to the specimen. A sinusoidal axial compressive load was then 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.

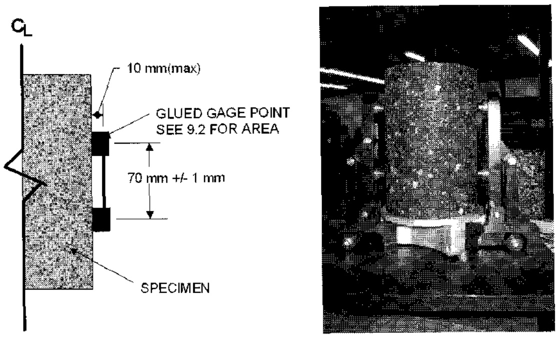
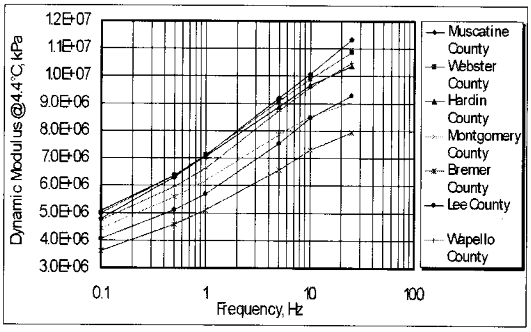


Fig. 5 Glued Magnetic Gauge Points Placed on Both Sides of the SPT Specimens

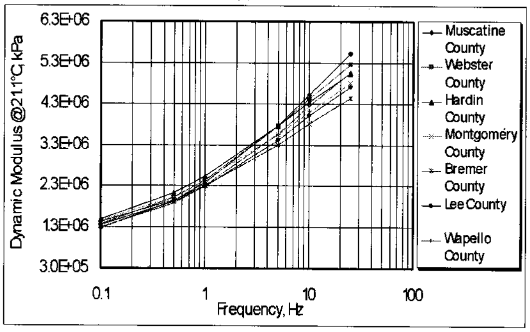
5. DYNAMIC MODULUS TEST RESULTS

The dynamic modulus tests were performed on CIR-foam specimens at six frequencies and three different temperatures. As shown in Figure 6, the dynamic moduli for seven different RAP sources are plotted against six loading frequencies at 4.4℃, 21.1℃, and 37.8℃. As expected, the dynamic modulus decreased as the testing temperature increased and the loading frequency decreased. The dynamic modulus values of CIR-foam were smaller but less sensitive to the test temperature than HMA. Overall, the dynamic moduli of CIR-foam were considered reasonable and consistent across seven different RAP sources.

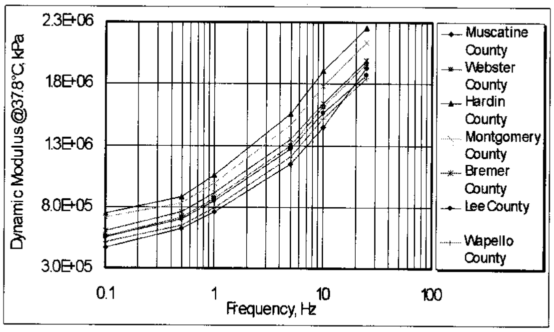
At 4.4℃ and 21.1℃, RAP materials from Muscatine County exhibited the highest dynamic modulus values. However, at 37.8℃, they exhibited the lowest dynamic modulus. They were the coarsest with a least amount of residual asphalt content. On the other hand, fine RAP materials with a large amount of hard residual asphalt content like the one from Hardin County exhibited the highest dynamic modulus at 37.8℃.



(a) 4.4℃



(b) 21.1℃



(c) 37.8℃

Fig. 6 Plots of Dynamic Moduli against Loading Frequencies at Three Different Test Temperatures

5.1 Construction of Mater Curves

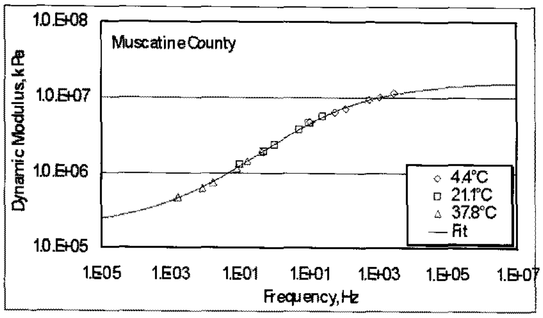
Using the dynamic modulus test results measured at three different temperatures and six different loading frequencies, a master curve was constructed for the reference temperature of 21℃ for each of seven RAP sources. Figure 7 shows measured dynamic modulus data and a master curve constructed for each of seven RAP sources. As shown in Figure 7, the constructed mater curves match the measured moduli quite well. Overall, master curves are relatively flat compared to HMA mixtures, which supports that foamed asphalt mixtures are not as visco-elastic as HMA.

6. IMPACTS OF RAP CHARACTERISTICS ON DYNAMIC MODULUS

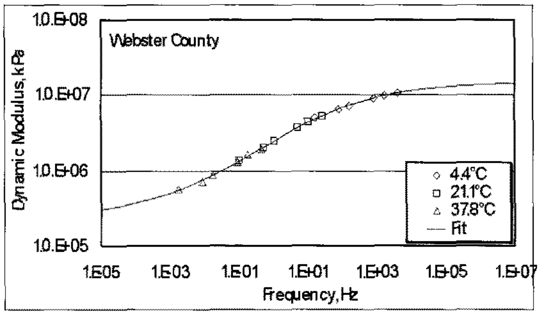
To identify the impacts of RAP characteristics on dynamic modulus values, the following RAP characteristics were measured: 1) amount of fines passing No.4 sieve, 2) residual asphalt content, and 3) residual asphalt stiffness in penetration index. The dynamic moduli measured at 10 Hz were used to identify their correlations with these RAP characteristics.

Figure 8 (a) and (b) show plots of dynamic modulus values measured at 4.4℃ against residual asphalt content of RAP materials and the percentage of passing No. 4 sieve in the RAP materials, respectively. As can be seen from these figures, the residual asphalt content of RAP materials did not influence the dynamic modulus values measured at 4.4℃. However, as the amount of fine RAP materials passing No. 4 sieve increased, the dynamic modulus value decreased.

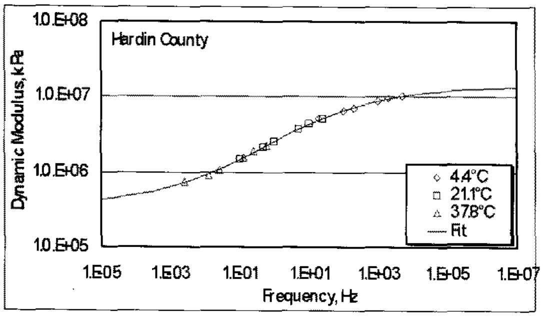
Figure 8 (c) and (d) show plots of dynamic modulus values measured at 37.8℃ against residual asphalt content of RAP materials and the percentage of passing No. 4 sieve in the RAP materials, respectively. As can be seen from these figures, the amount of fine RAP materials passing No. 4 sieve did not influence the dynamic modulus values measured at 37.8℃. However, as the residual asphalt content increased, the dynamic modulus value increased.



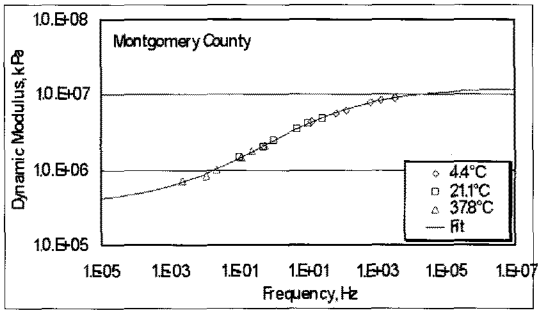
(a) Muscatine County



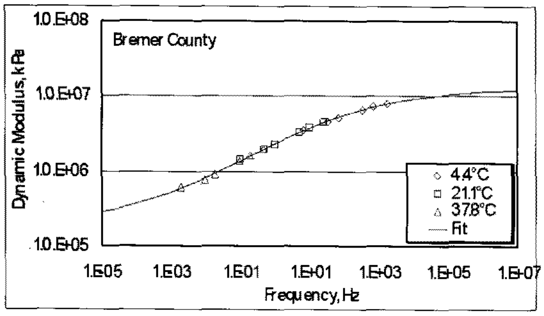
(b) Webster County



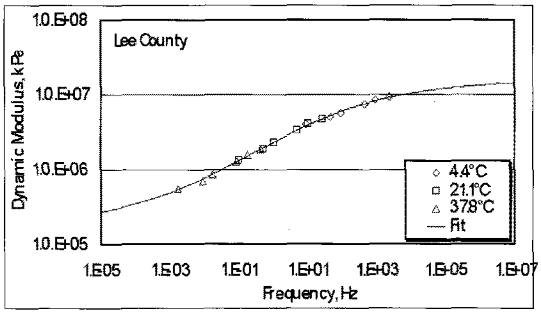
(c) Hardin County



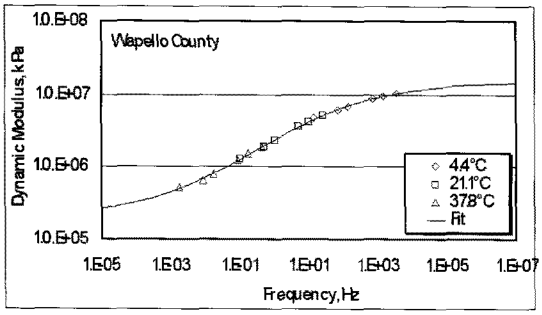
(d) Montgomery County



(e) Bremer County

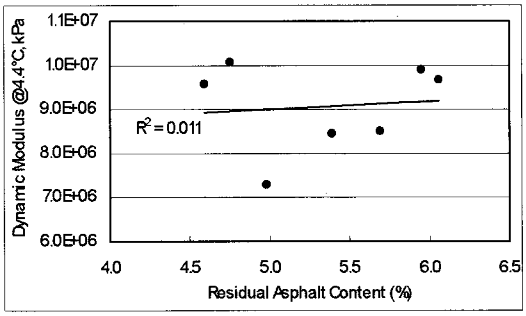


(f) Lee County

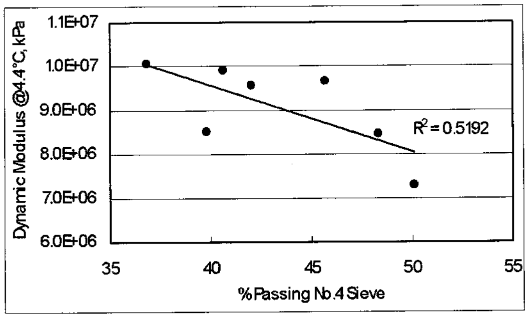


(g) Wapello County

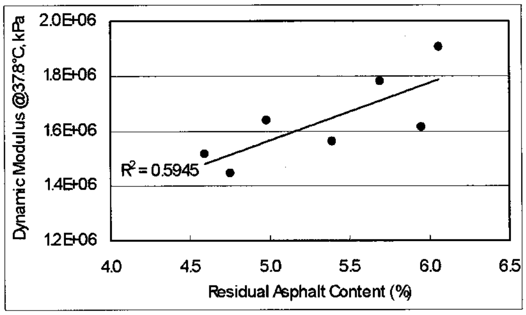
Fig. 7 Master Curves at T=21℃ Using the Sigmoidal Model



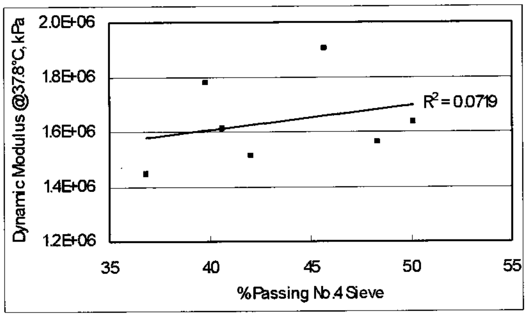
(a) dynamic modulus @ 4.4℃ vs. residual asphalt content



(b) dynamic modulus @ 4.4℃ vs. % passing No.4 sieve



(c) dynamic modulus @ 37.8℃ vs. residual asphalt content



(d) dynamic modulus @ 37.8℃ vs. % passing No.4 sieve

Fig. 8 Plots of Dynamic Modulus against RAP Characteristics

7. SUMMARY AND CONCLUSIONS

To validate the new CIR-foam mix design procedure, dynamic moduli of CIR-foam mixtures made of seven different RAP materials were measured and their master curves were constructed. The main objectives of this study are to provide 1) standardized testing procedure for measuring the dynamic modulus of CIR-foam using new SPT equipment; 2) analysis procedure for constructing the master curves for a wide range of RAP materials; and 3) impacts of RAP material characteristics on the dynamic modulus.

In order to perform dynamic modulus test on CIR-foam mixtures, the standard AASHTO TP 62-03 protocol was modified to be performed at three temperatures of 4.4℃, 21.1℃ and 37.8℃ and six frequencies of 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz and 0.1 Hz. At both 4.4℃ and 21.1℃, overall, the coarser RAP materials exhibited the higher dynamic modulus. At 37.8℃, however, the dynamic modulus of the coarsest RAP materials with the least amount of residual asphalt content became the lowest. Overall, the dynamic moduli of CIR-foam mixtures were very reasonable and consistent across seven different RAP sources. This result indicates that the dynamic modulus testing can be applied to consistently characterize the CIR mixtures.

Master curves were then constructed for the CIR-foam mixtures using seven different RAP materials. The constructed master curves by a nonlinear Sigmoidal model matched well with the measured dynamic modulus. Dynamic moduli of CIR-foam mixtures were less sensitive to the loading frequencies and temperatures than those of HMA mixtures.

Based on the limited test results, the increased amount of fine RAP materials passing No. 4 sieve seemed to decrease the dynamic modulus values measured at 4.4℃. The increased amount of residual asphalt content seemed to increase the dynamic modulus values measured at 37.8℃. In the future, a comprehensive database of dynamic modulus for both CIR-foam and CIR-emulsion using different PG-grade binders and RAP gradations should be developed to allow for an accurate input to the mechanistic-empirical pavement design guide (M-E PDG).

8. ACKNOWLEDGEMENTS

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