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Evaluation of Warm Mix Asphalt Mixtures with Foaming Technology and Additives Using New Simple Performance Testing Equipment

새로운 Simple Performance Testing 장비를 이용한 중온형 폼드 아스팔트 혼합물의 공용성 평가

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요지

최근에 135℃ 이하의 온도에서 생산되는 중온형 아스팔트 혼합물의 새로운 생산 기술이 전세계적으로 개발되고 있다. 본 연구에서는 가열 아스팔트보다 낮은 온도에서 아스팔트를 효과적으로 골재에 분산시켜 코팅할 수 있는 폼드 아스팔트 기술을 이용하여 중온형 아스팔트 혼합물을 생산하였으며, 최근 개발된 새로운 Simple Performance Testing 장비를 이용하여 다양한 온도와 하중조건 하에서 중온형 폼드 아스팔트 혼합물의 공용성 특성을 평가하였다. 중온형 폼드 아스팔트 혼합물은 PG 64-22의 아스팔트를 거품상태로 만들어 중온으로 가열된 골재에 뿌려서 제조하였으며, 중온형 아스팔트 혼합물은 중온의 골재에 PG 64-22의 아스팔트를 액상 상태로 첨가하여 제조하였다. 중온형 폼드 아스팔트 혼합물은 중온형 아스팔트 혼합물보다 높은 동탄성계수와 Flow Number를 나타내었다. 따라서, 100℃로 가열된 골재를 사용하여 생산된 중온형 폼드 아스팔트 혼합물은 중온형 아스팔트 혼합물에 비하여 피로균열 및 소성변형 저항에 우수한 것으로 평가되었다.

핵심용어 : 중온형 아스팔트 혼합물, 폼드 아스팔트, 동탄성계수, 플로우 넘버

Abstract

To produce asphalt mixtures at temperature significantly below 135℃, called "Warm Mix Asphalt (WMA)", new technologies are currently being developed worldwide. To produce WMA mixtures in this research, foaming technology is adopted to effectively disperse asphalt binder at lower temperature than hot mix asphalt (HMA) in the field. The main objectives of this study are to develop WMA process using foaming technology (WMA-foam) and evaluate its performance characteristics under various temperatures and loading conditions. WMA-foam mixtures were produced by injecting PG 64-22 foamed asphalt into warm aggregates whereas WMA mixtures were produced by adding PG 64-22 asphalt (without foaming) in the warm aggregates. Both dynamic modulus and flow number of WMA-foam mixtures were higher than those of WMA mixtures. Based on the limited dynamic modulus and repeated load test results, it is concluded that the WMA-foam mixtures using warm aggregates at 100℃ are more resistant to fatigue cracking and rutting than WMA mixtures.

Keywords: warm mix asphalt, foamed asphalt, dynamic modulus, flow number

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1. INTRODUCTION

Since the first asphalt plant was built in Cambridge, Massachusetts in 1901, hot mix asphalt (HMA) has been produced and discharged at elevated temperatures above 135℃, normally up to 160℃. To reduce CO_2 emission per Kyoto agreement on reducing greenhouse gases produced by all manufacturers, however, it is critical for HMA manufacturers to produce asphalt mixtures at lower temperatures. New technologies are currently being developed worldwide to produce asphalt mixtures at temperatures significantly below 135℃. Warm mix asphalt (WMA) entails the use of foaming technology and/or additives to soften the asphalt binder, allowing workability and compactability at lower temperatures than HMA in the field (CTC, 2005). New WMA technologies allow asphalt mixes to be produced at lower mixing and compaction temperatures, addressing the prominent environmental and economic factors currently faced by industry.

There are several benefits for using WMA such as the extension of the construction season and reduced aging of the asphalt binder. Reduction of the short term aging (oxidation and volatilization) of the asphalt binder during conventional construction could potentially enhance pavement performance through reduced thermal and fatigue cracking, thus decreasing the life cycle cost of the facility. Particularly, warm mix asphalt using foaming technology (WMA-foam) presents an opportunity for the asphalt industry to improve its product performance, construction efficiency and environmental stewardship. Its potential benefits include reduction in energy consumption, emissions, fumes, and odors while improving its performance. Due to its production and compaction at the lower temperatures, WMA-foam pavements can be opened to traffic earlier than HMA pavements.

The main objectives of this research are to: 1) develop new environmentally friendly WMA process using foaming technology and additives at lower production and compaction temperatures and 2) to evaluate its performance characteristics under various temperatures and loading conditions using new simple performance testing (SPT) equipment. The laboratory evaluation was performed on four different WMA mixtures by conducting dynamic modulus and repeated load tests. In this paper, the findings from laboratory tests are presented and the recommendations are made regarding the warm mix asphalt process utilizing foamed asphalt and additives.

2. LITERATURE REVIEW

The traditional HMA is normally produced at temperature between 140℃ and 180℃ and compacted at temperatures between 80℃ to 160℃ The temperature of the asphalt mix has a direct impact on the viscosity of the asphalt binder and compaction efforts. The goal of the WMA technology is to lower the temperature at which traditional HMA are produced and placed without adversely affecting these properties (FHWA 2007). In the past, a limited number of WMA technologies have been developed to reduce the mixing and compaction temperatures without sacrificing the quality of the resulting pavement. Apart from the obvious advantages such as reduced fuel consumption and reduced emissions in the plant, there are several other advantages of using warm asphalt, including longer paving 'seasons', longer hauling distances, reduced wear and tear of the plants, reduced aging of binders, reduced oxidative hardening of binders and thus reduced cracking in the pavements, ability of opening the site to traffic sooner, etc. (Hurley and Powell, 2006).

From the previous researches done so far, it seems that the quality of WMA is quite comparable to HMA but the mix design procedure and performance in various field conditions remain to be researched (Koenders et al., 2000). WAM-foam was originally developed jointly by Shell Global Solutions and Kolo Veidekke in Norway, where two different bitumen grades, soft bitumen and hard bitumen, are combined with the mineral aggregate. This process makes it possible to produce the asphalt mixture at temperatures between 100℃ and 120℃ and compact it at 80 to 110℃(Koenders et al., 2000). Recently, Astec Inc. (2007) developed a double barrel green system, where a multi-nozzle device is fitted to a double barrel drum plant. Romier et al. (2006) developed the low energy asphalt process, which is based on a global re-assessment of the basic thermo-dynamics of hot-mix asphalt production in order to minimize or eliminate the most energy-consuming/pollution-producing phases. They used mixing temperatures of 80℃ for the low energy asphalt mix design and the heating energy of HMA plant was reduced by more than 50%.

Gaudefroy et al. (2007) investigated the influence of the aggregate temperature on the mix treated with foam bitumen and presented a new coating process. Diefenderfer et al. (2007) evaluated the installation of WMA and compiled experiences and future use. Ólöf K. et al. (2007) examined the costs, benefits and risks associated with WMA technologies in an attempt to determine the most promising implementation path for WMA technologies. Nazimuddin et al. (2007) reported that Sasobit® decreased the mixing and compaction temperatures and upgraded the binder without increasing the viscosity of the binder. They also reported that Sasobit® decreased the rut depth significantly which justifies the improvement in high temperature binder grading. Kunnawee et al. (2007) reported AC 60/70 binder modified with 3.0% Sasobit® improved the compactability of asphalt mixture and resulted in acceptable density at temperature of 20℃~40℃ below normal compaction temperatures. In addition, the mixtures modified with Sasobit® exhibited a greater resistance to densification under simulated traffic. Prowell et al. (2007) evaluated the rutting potential of WMA mixes using the Evotherm® process under accelerated loading at the test track. They reported that in-place densities of the WMA surface layers were equal to or better than the HMA surface layers even when compaction temperatures were reduced by 8℃ to 42℃. They also reported that WMA test sections showed excellent field performance in terms of rutting after the application of traffic level of 515,333 ESALs in 43 days.

3. THEORY OF DYNAMIC MODULUS AND FLOW NUMBER

3.1 Dynamic Modulus

The dynamic modulus test is to determine the stiffness of asphalt mixtures on the response to loading and various temperature conditions. The fundamental concept behind the dynamic modulus test is a linear visco-elasticity of asphalt mixtures. The stress to strain relationship under a continuous sinusoidal loading for linear visco-elastic materials is defined as 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 shown in Eq. 1.

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

The measured dynamic modulus at different temperatures can be then shifted relative to the frequency so that several curves can be aligned to form a single master curve. In constructing the master curve, as shown in Figure 1, the measured dynamic moduli at test temperatures higher than the reference temperature are horizontally shifted to lower frequencies and those measured at test temperatures lower than the reference temperature are shifted to the higher frequencies. A master curve can be constructed using the time-temperature correspondence principle, which uses the equivalency between frequency and temperature. The master curve of an asphalt mixture allows comparisons to be made over extended ranges of frequencies and temperature. To construct the master curve of WMA mixtures, Williams-Landel-Ferry (WLF) equation was used to obtain a shift factor and a nonlinear sigmoidal function is fitted using the Excel's optimization solver function as shown in Eq. 2 (NCHRP 2006).

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log f_r}} \qquad (2)$$

$\log|E^*|$ = log of dynamic modulus(kPa),

δ = minimum modulus value,

fr = reduced frequency(Hz),

α = span of modulus value,

β, γ = shape parameters.

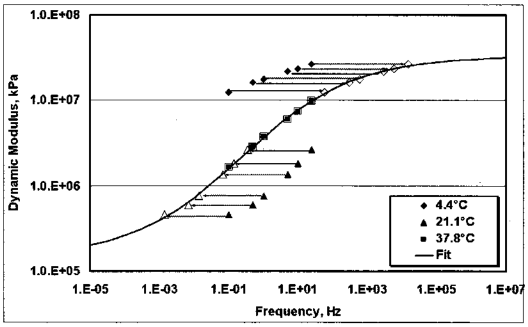


Fig. 1 Construction of Master Curve Represented by Nonlinear Sigmoidal Model

3.2 Flow Number

The repeated load test was originally developed to identify the permanent deformation characteristics of HMA mixtures by applying several thousand repetitions of a dynamic 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 2, results from the repeated load test are normally presented in terms of the cumulative permanent strai(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 (El-Basyoung et al. 2005). 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.

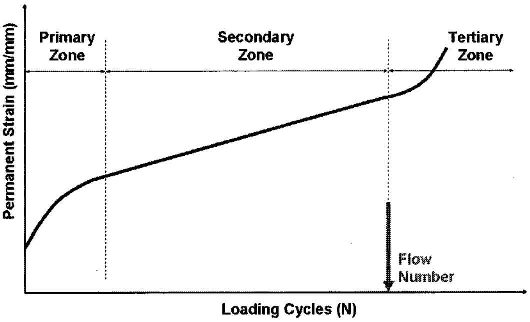
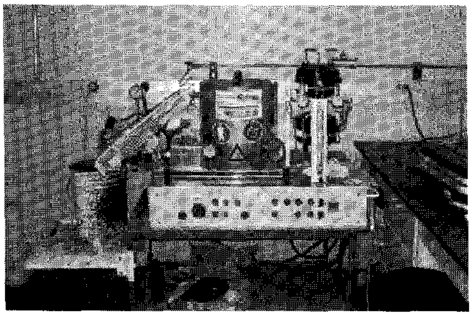


Fig. 2 Permanent Deformation Behavior under Loading Cycles

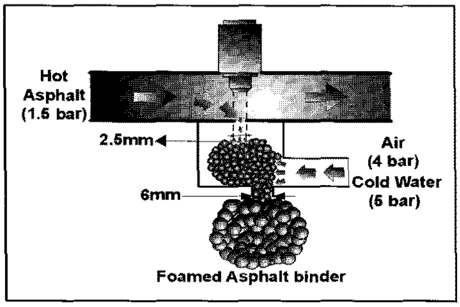
4. PREPARATION OF WMA SPECIMENS

4.1 Foaming Technology

The foamed asphalt technology was developed by Professor Csanyi (1960) at Iowa State University in 1956, which consisted of injecting steam into hot asphalt. In 1968, Mobil Oil Australia modified the original process by adding cold water rather than steam for the practical foaming operations in the field. To create the foamed asphalt, a controlled flow of cold water was injected to the hot asphalt between 160℃ to 180℃ in the expansion chamber. Figure 3 (a) shows the laboratory foaming asphalt equipment developed by Wirtgen, Inc and Figure 3 (b) illustrates the production process of foamed asphalt in the expansion chamber. Hot asphalt is injected into the expansion chamber through a 2.5mm nozzle and cold water is introduced into the chamber under air pressure simultaneously. Foamed asphalt is then immediately released into the mixer through the 6mm nozzle. The created foamed asphalt was sprayed on virgin aggregates or RAP materials through nozzles. During the foaming process, the asphalt binder's original volume could increase up to twenty times and the foamed asphalt with a low viscosity in a temporary state can be mixed with aggregate materials at room temperature.



(a) WLB 10 foaming equipment (University of Iowa)



(b) Foaming process

Fig. 3 Laboratory Foaming Asphalt Equipment and Foaming Process

4.2 Mix Design Parameters

First, aggregates were divided into ten stockpiles, which were retained on the following sieves: 19mm, 12.5mm, 9.5mm, 4.75mm, 2.38mm, 0.5mm, 0.3mm, 0.15mm, 0.075mm and passing 0.075mm. As shown in Figure 4, each stockpile was combined to produce a design gradation using WC-3 gradation specification. Table 1 summarizes the design parameters used for WMA-foam mixtures where PG 64-22 asphalt binder was used to create the foamed asphalt at 170℃. WMA-foam mixtures were prepared using at 5.0% foamed asphalt content with 165 gyrations. Zeolite and lime were used as an additive for WMA-foam mixtures. For this study, four types of WMA mixtures were prepared: 1) WMA with 5.0% foamed asphalt (WMA-foam) and 2) WMA using 5.0% foamed asphalt and 0.3% Zeolite (WMA-foam/zeolite), and 3) WMA using 5.0% foamed asphalt and 1.5% lime (WMA-foam/lime), and 4) using 5.0% virgin asphalt without foaming (WMA).

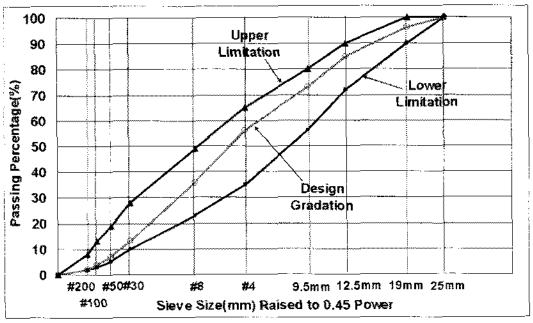


Fig. 4 Gradation Plots of Aggregates Used in Warm Mix Aspalt Mixtures

Table 1. Design Parameters Used for Warm Mix Asphalt Mixtures

Binder Grade	PG 64-22
Foaming Temperature (℃)	170℃
Foamed Asphalt Content (%)	5.0%
Foaming Water Content (%)	1.5%
Aggregate Temperature (℃)	100℃
Compaction Method	Gyratory compaction at 165 gyrations
Additives	1) Aspha-min Zeolite (0.3% of total mix weight) 2) Lime (1.5% of total mix weight)
Mixing Time	1) Pre-mixing for 30 seconds and 2) additional mixing with foamed asphalt for 60 seconds
Performance Test	1) dynamic modulus test and 2) repeated load test

4.3 Mix Design Procedure

To prepare WMA-foam mixture, as shown Figure 5, foaming quality was evaluated under various combinations of foaming water contents and asphalt binder temperatures. A foaming temperature of 170℃ and water content of 1.5% were selected as the optimum mix design condition for an expansion ratio of 11 and a half-life of 8 seconds. Second, to produce a batch of 2 SPT specimens, aggregates were heated at temperature of 100℃ for 6 hours in the oven. Third, the heated aggregates were pre-mixed for 30 seconds and, after a required amount of foamed asphalt was sprayed to the aggregates, mixed for 60 seconds. Finally, the produced WMA-foam mixtures were added in a preheated gyratory mold at 100℃ and compacted by 165 gyrations.

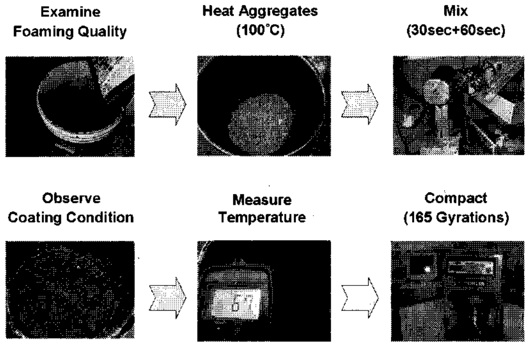
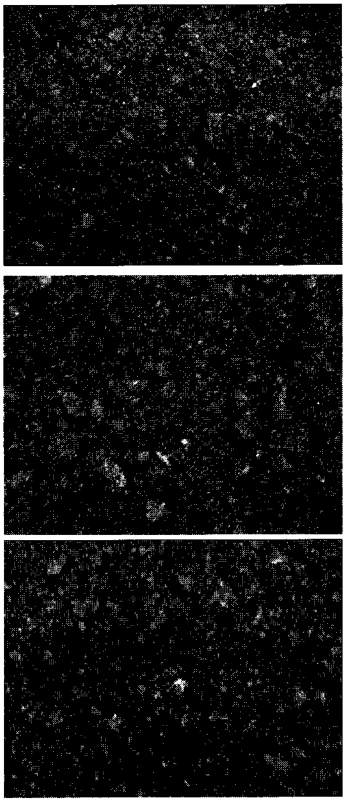


Fig. 5 Mix Design Process of WMA-Foam Mixtures

4.4 Visual Observation and Temperature Variations of WMA Mixtures

Based upon the visual observation of three WMA mixtures, as shown in Figure 6, the heated aggregate materials at 100℃ were coated well with the foamed asphalt. No mixing or coating problems of WMA mixtures were observed during the mix design process in the laboratory. It appears that WMA-foam mixtures have a slightly better coating of aggregates than others.


(a) WMA-foam

(b) WMA-foam/zeolite

(c) WMA

Fig. 6 Visual Observation of Warm Mix Asphalt Mixtures

Temperatures were measured from the mixtures for two times: right after mixing and right before compaction. The temperature measured right after mixing ranged from 102℃ and 107℃ and temperature right before compaction ranged 82℃ and 97℃. With aggregates heated at 100℃, the test specimens were produced without any problem during the mixing and compaction process.

4.5 Compaction Characteristics

The bulk specific gravities were determined in accordance with AASHTO T 166 by measuring the dry, SSD, wet mass (AASHTO 2007). Figure 7 shows average densities of the gyratory compacted test specimens. As shown in Figure 7, WMA-foam specimens exhibited higher density than WMA specimens.

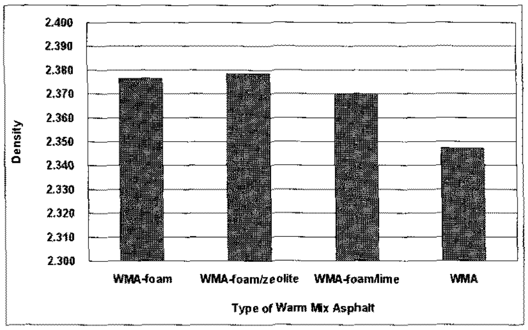


Fig. 7 Average Densities of Warm Mix Asphalt Mixtures

5. SIMPLE PERFORMANCE TESTS OF WMA MIXTURES

Four types of warm mixture specimens were prepared and tested to evaluate their fatigue crack and rutting resistances under various temperatures and loading conditions using new Simple Performance Testing (SPT) equipment. Dynamic modulus and repeated load tests were performed on the WMA-foam, WMA-foam/zeolite, WMA-foam/lime, and WMA mixtures following ASHTO TP 62 (2007) and NCHRP 9-29 protocols (2002, 2003), respectively. The gyratory compacted specimens with 100-mm diameter and 150-mm height were prepared for dynamic modulus and repeated load tests. The test specimens were compacted using the gyratory compactor at 165 gyrations. The compacted test specimens were cured in the room temperature at 25℃ for one day before the test. The dynamic modulus and repeated load test results were analyzed to evaluate the fatigue crack and rutting resistances of the warm mixtures.

5.1 New Simple Performance Equipment

Witczak et al. (2002) and Bonaquist et al. (2003) described the development of the new SPT equipment, which can perform dynamic modulus, static creep and repeated load tests at the various loading and temperature conditions. As shown in Figure 8, the test specimen can be accessed from all sides when the temperature and pressure vessel is lifted. Also, this system utilizes a

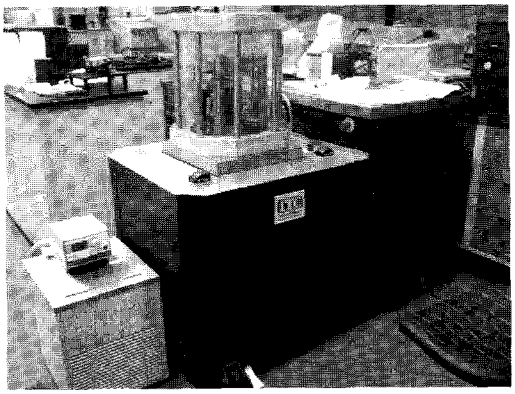


Fig. 8 Simple Performance Testing Equipment
at the University of Iowa

magnetic mounted extensometer, which snaps on the test specimen with a minimum disruption to temperature control. A stand-alone environmental unit can provide heated and refrigerated air to the environmental test chamber, which ranges from 4℃ to 60℃.

5.2 Dynamic Modulus Test

The existing AASHTO protocol 62-03: Determining Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures (ASSHTO 2007) was modified to be performed on warm mixtures at three temperatures of 4.4℃, 21.1℃, and 37.8℃ and six frequencies of 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz. 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. To begin testing, two linear variable displacement transducers (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 test specimens. A sinusoidal axial compressive load was applied to the specimen while maintaining the axial strain at 100 microstrain. The test results during the last ten cycles were recorded for each frequency and the dynamic modulus was measured from each specimen twice. The dynamic moduli for three different warm mix types are plotted against six loading frequencies at three temperatures of 4.4℃, 21.1℃, and 37.8℃ in Figure 9. At 4.4℃, WMA-foam mixtures exhibited the highest dynamic modulus values, WMA-foam/zeolite mixtures were second and WMA mixtures were the lowest for nearly all loading frequencies. At 21.1℃ and 37.8℃, dynamic modulus of WMA-foam mixtures was the highest followed by WMA mixtures and WMA-foam/zeolite mixtures.

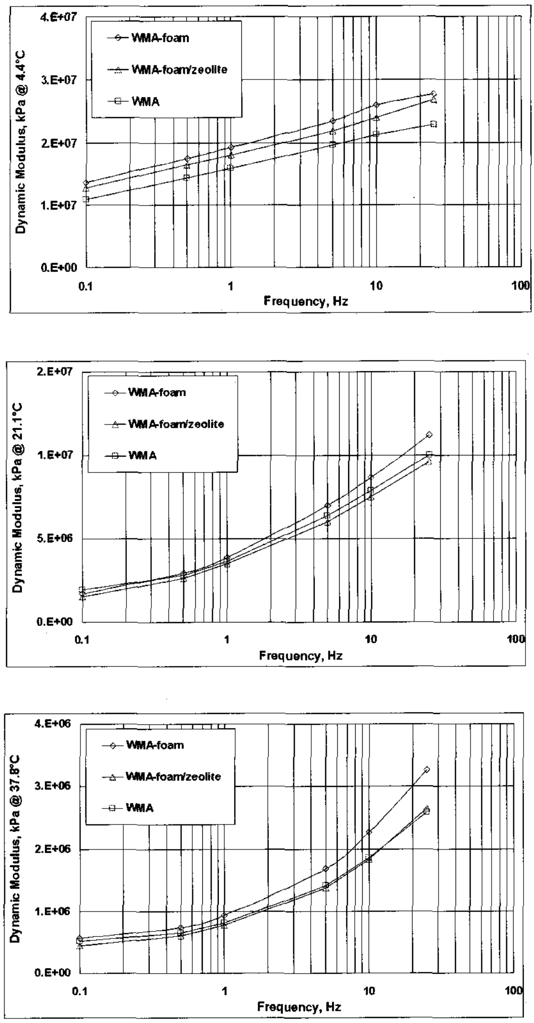


Fig. 9 Plots of Dynamic Moduli against Loading Frequencies

Using the dynamic modulus test results measured at three different temperature and six different frequencies, as shown in Figure 10, the master curves were constructed for a reference temperature of 21℃ for each of three WMA mixtures. 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

Sigmoid model using the Excel's Optimization Solver function. As can be seen from Figure 10, the best fit master curves match the measured moduli quite well. Overall, the master curves were relatively flat compared with ones constructed for HMA materials, which indicate that the WMA mixture is less susceptible to the loading frequencies.

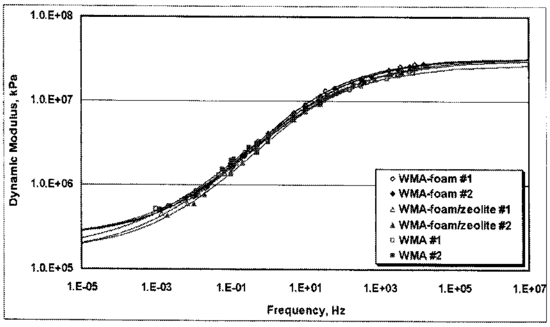


Fig. 10 Master Curves of Three Different Warm Mix Asphalt Mixtures

5.3 Repeated Load Test

The uniaxial compression load without confinement was applied to obtain a loading stress level of 138kPa at 40℃. 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 55℃ was selected to represent the temperature of a surface layer in the field. The loading stress was applied in the form of a haversine curve with a loading time of 0.1 second with a rest period of 0.9 second in one cycle. The test was conducted up to 10,000 cycles or until achieving 5.0% of cumulative permanent stain. Figure 11 shows plots of cumulative strain against the number of loading cycles measured from three different WMA types. It should be noted that, due to the failed specimens during the sample preparation process, only one specimen was tested for WMA-foam and WMA-foam/lime whereas two specimens were tested for WMA. As shown in Figure 11, the flow number of WMA-foam/lime mixtures is the highest followed by WMA-foam mixtures and WMA mixtures. Based on the limited test results, it can be concluded that lime may improve characteristics of WMA mixtures by increasing its resistance to rutting.

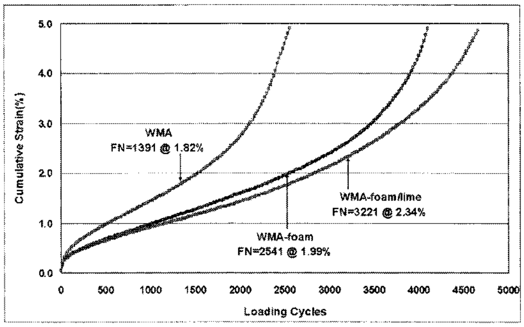


Fig.11 Plots of Cumulative Permanent Deformation against Loading Cycles

6. SUMMARY AND CONCLUSIONS

Rising energy prices, global warming and more stringent environmental regulations have triggered a significant interest in the warm mix asphalt (WMA) technologies as a means to decrease the energy consumption and emissions associated with conventional hot mix asphalt (HMA) production. Warm Mix Asphalt using foaming technology (WMA-foam) presents an opportunity for the asphalt industry to improve its performance while maintaining their environmental stewardship. First, the mix design process of WMA-foam mixtures was developed, where foamed asphalt is injected to the heated aggregates at 100℃. It is interesting to note that, with the 100℃-aggregates, no mixing or coating problems of warm mixtures were observed during the mixing and compaction process in the laboratory.

Overall, WMA-foam exhibited higher density than WMA, which confirms its better compactability. Four types of warm mixture, which include 1) WMA-foam, 2) WMA-foam/zeolite, 3) WMA-foam/lime and 4) WMA, were prepared and tested to measure: 1) dynamic modulus to predict a fatigue crack resistance and 5) flow number to predict a rutting resistance. The dynamic modulus of WMA-foam mixtures was slightly higher than WMA-foam/zeolite and WMA mixtures at all test temperatures. The master curves of warm mixtures were relatively flat compared with ones constructed for HMA materials, which indicate that the WMA mixture is less susceptible to the loading frequencies. WMA-foam/lime mixture exhibited a highest flow number followed by WMA-foam and WMA mixtures. Based on the limited test results, it can be concluded that the WMA-foam and WMA-foam/lime using the heated aggregates at 100℃ is more compactable, slightly stiffer and rutting resistant than WMA mixtures using virgin asphalt without foaming.

7. ACKNOWLEDGMENTS

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