Technical paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 1(1):34-40
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Laboratory Evaluation of Warm Mix Asphalt: A Preliminary Study

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Abstract: The asphalt industry has been assisting in the improvement of energy savings and the reduction of emissions to create more environmentally friendly paving construction for decades. Use of Warm Mix Asphalt (WMA) is an example of the industry's efforts toward improvement. WMA is produced in the temperature range from 17 to 56°C (30 to 100°F) lower than the traditional Hot Mix Asphalt (HMA). WMA's benefits include reducing energy consumption and emissions from burning fuels and volatiles generated from heated asphalt binder at the production plant and the paving site. Several technologies used in WMA are available today, such as Aspha-Min®, Sasobit®, Evotherm, and WAM-Foam. New technologies continue to be developed. Results found from a laboratory evaluation of WMA made with synthetic zeolite were presented in this study. An asphalt mixture with the nominal maximum size of 12.5mm (1/2 inch) and PG64-22 binder was used in the laboratory evaluation. A control HMA mixture, WMA with 0.3% of synthetic zeolite, and WMA with 0.5% of synthetic zeolite, were used in the laboratory evaluation. The characteristics of asphalt and asphalt mixtures were examined using viscosity, dynamic shear modulus, and bending beam creep stiffness. Asphalt mixes were compacted via the Superpave gyratory and a simple performance test, the dynamic modulus test, was conducted to evaluate design purpose. Tests conducted found that the addition of the synthetic zeolite in the binder slightly decreased the binder's viscosity. Overall performance of WMA in terms of dynamic modulus has increased when compared to the control mix.

***Key words**: Dynamic modulus; Dynamic shear modulus; Master curve; Simple performance test; Superpave; Synthetic zeolite; Viscosity; Warm mix asphalt.*

Introduction

Traditionally, Hot Mix Asphalt (HMA) has been produced by batch or drum plants at a discharge temperature between 138 and 160°C (280 and 320°F). During the HMA production, aggregate was heated to temperature in order to dry it, coat with the asphalt binder, and achieve desired workability. In HMA production, cost of the energy (fuel) is significantly large due to the high demand of fuel needed to continue heating the aggregate and thus increasing the energy cost. Environmental awareness has been increasing rapidly over the past years and extensive measures such as air pollution reduction targets set by the European Union with the Kyoto Protocol have encouraged efforts to reduce pollution.

Goals for Warm Mix Asphalt (WMA) include use of existing HMA plants, and existing standards of the HMA specifications, and focus on dense graded mixes for wearing courses. Europeans are using WMA technologies, which allow significant reduction in temperatures when asphalt mixes are produced and placed. A typical compaction temperature range is 121 to 135°C (250 to 275°F). As shown in Fig. 1, the WMA temperature is between HMA and Cold Asphalt Mix. Based on research done in Europe and North America, there are several technologies used to produce WMA [1]. They are as follows:

1. The addition of a synthetic zeolite called Aspha-Min® used during mixing at the plant creates a foaming effect in the binder.
2. A two-component binder system called WAM-Foam® introduces a soft and hard foamed binder at different stages during production.
3. Use of organic additives includes Sasobit®, a Fischer-Tropsch paraffin wax.
4. Application of Asphaltan B®, a low molecular weight esterified wax.
5. Use of Evotherm®, a technology based on a chemistry package that includes additives to improve coating and workability, adhesion promoters, and emulsification agents.

These technologies reduce the viscosity of the asphalt binder at a given temperature and allow the aggregate to be fully coated at a lower temperature. Such technologies have a significant impact on pavement projects in and around non-attainment areas. Manufacturers and materials suppliers have reported energy savings on the order of 30%, with a reduction in CO_2 emissions of 30%. The mixture production and placement temperature could create costs, environmental, and performance benefits [2, 3, 4]. Advantages of WMA are briefly summarized:

- Lower energy consumption (reduce fuel costs)
- Reduce mixing and compaction temperature
- Early site opening
- Lower plant wear
- Slow binder aging potential by reducing the temperatures
- Lower fumes and emissions
- Cool weather paving
- Improve workability
- Extend paving window

Literature Review

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Note: Submitted August 30, 2007; Revised October 23, 2007; Accepted November 1, 2007.

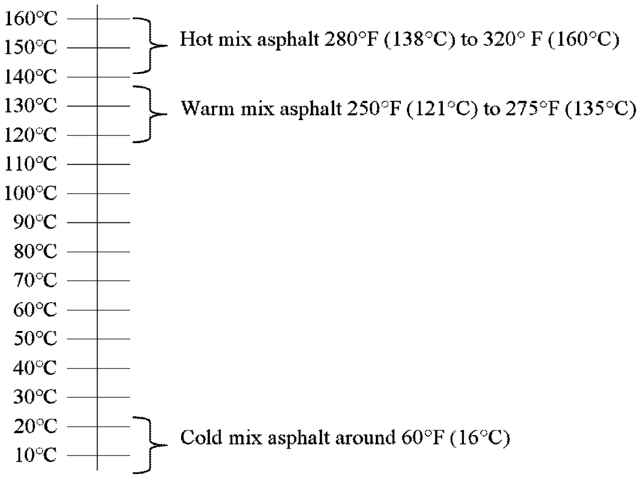

Fig. 1. Typical Mixing Temperature Range.

Several types of WMA technologies were used in European countries and the USA based on literature review and internet sources. This study is an evaluation of asphalt and asphalt mixtures with Aspha-min®, a product of Eurovia Services GmBH Bottrop, Germany [5], called Eurovia, available in a very fine white powder form in 25 or 50kg bags or in bulk for silos. It is a manufactured synthetic zeolite (Sodium Aluminum Silicate), which has been hydro-thermally crystallized. The percentage of water held internally by the Aspha-Min® is 21% by mass and is released in the temperature range from 85 to 182°C (185 to 360°F). By adding Aspha-Min® to the mix at the same time as the binder, a very fine water spray is created. Release of water creates a volume expansion of the binder that results in asphalt foam and increases workability and aggregate coating at lower temperatures [3, 4 ,6, 7]. Eurovia recommends adding Aspha-Min® at the rate of 0.3% of the mass of the mix, which can result in a potential 30°C (54°F) reduction in typical HMA production temperatures. This reduction in temperature was reported to lead to a 30% reduction in fuel energy consumption. Eurovia stated that all commonly known asphalt and polymer-modified binders can be used with Aspha-Min®. Also, the addition of recycled asphalt is compatible with Aspha-Min® [6, 7].

A combination of field and laboratory studies on Sasobit® and Aspha-Min® was conducted by researchers [8] to evaluate the performance of WMA. Field sections with and without Aspha-Min® additive were placed on the entrance road to Hookset Crushed Stone in November 2005. Samples and cores were tested using the third-scale Model Mobile Load Simulator to evaluate performance with and without moisture. Laboratory tests using the Tensile Strength Ratio (TSR) showed WMA had higher moisture sensitivity than typical HMA. This project is currently ongoing and further study will be conducted to evaluate the performance of WMA.

A laboratory study was conducted by the National Center for Asphalt Technology (NCAT) to determine the applicability of Aspha-Min® to typical paving operations and environmental conditions [9]. Two aggregates, granite and limestone, were used for the test. The Superpave gyratory compactor was used for mix preparation and a vibratory compactor was used to determine the mixes' compaction ability over a range of temperatures. Mixes were compacted at 149, 129, 110, and 88°C (300, 264, 230, and 190°F) and the mixing temperature was about 19°C (34°F) above the compaction temperature. The main results from NCAT indicated additional Aspha-Min® lowered the air void in the gyratory compactor, increased the potential of moisture damage, and lowered the TSR as compared to the control mixture. Also found was that additional Aspha-Min® did not affect the resilient modulus and rutting potential. However, results indicated that the resilient modulus decreased as compaction temperature decreased and air void would increase. Furthermore, rut depth increased as the temperature decreased for all the factors in combination.

A study of field performance of WMA was conducted at the NCAT test track [10]. Results indicated that HMA and WMA sections showed excellent field performance in terms of rutting after the application of 515,333 ESALs in a 43-day period. One of the WMA sections, also evaluated for quick turn over to traffic, showed good performance.

Researchers [11] have studied the rut depth and the rheological properties of binders with the addition of Aspha-Min® and Sasobit®. Results show that Aspha-Min® did not give any beneficial effect in temperature reduction in PG64-22 based on rotational viscometer. The rutting potential decreases in mixing and compaction temperature for Sasobit® and Aspha-Min® mixture; however there was no significant direct decrease in production temperature with Aspha-Min®. In addition, a field demonstration project in Florida indicated that addition of Aspha-Min® in the mix improved the workability compared to the control mix and was equally resistant to moisture damage as the control mix [9].

Several Aspha-Min® comparison tests done by Eurovia resulted in field tests that indicated after three years no significant changes were observed in surface characteristics. The Aspha-Min® section was comparable to the traditional HMA comparison section [5]. A field demonstration test was conducted by Hubbard Group at Orlando, Florida on February 2004 [7]. Objectives for the field demonstration were to compare the conventional HMA with mix containing Aspha-Min® additive at the reduced temperature in a typical paving setting and to compare the workability, compactability, elevator drag strain, and mix volumetric properties. Compaction temperatures used during the test were 154°C (310°F) for control and 132°C (270°F) for the Aspha-Min® additive. Aspha-Min® was added at the rate of 0.3% of the total weight of mixture during this test. Main results obtained from Hubbard Group were: 1) for additional Aspha-Min®, there were no changes for maximum specific gravity and bulk specific gravity from Marshall and Superpave performance test; 2) for additional Aspha-Min®, there was a significant increase in air voids before and after aging process; 3) and for additional Aspha-Min®, there was slight decrease in stability when running the Marshall Stability test.

Conclusions and recommendations drawn from Hubbard Group on adding Aspha-Min® to the mixture are: 1) comparison of laboratory tests is favorable with almost no change in volumetric properties and Marshall Stability; 2) the amperage meter dropped from 34 to 32amps on the mix elevator, possibly indicating better workability in the WMA; 3) the nuclear density was 44.85kg/m^3 (2.8pcf) higher after initial compaction in the WMA; 4) and the lower temperature did not change the workability and the material texture was the same.

Aspha-Min®, a relatively new technology, shows a significant promise in energy saving and emission reduction; Currently only a few laboratory experiments were conducted and more detailed studies and tests are needed to evaluate the performance of Aspha-Min® in terms of mixture volumetric design and asphalt binder properties. This paper evaluates the performance of the mixtures and the binder properties using synthetic zeolite as an additive.

Scope and Objectives

In this paper, the WMA with synthetic zeolite was studied in the laboratory. Synthetic zeolite was added to the mixture at the rate of 0.3 and 0.5% of the total weight of the mixture. Binder properties and mixture volumetric properties were determined. Two compacting temperatures, 100 and 120°C (212 and 248°F), were chosen to evaluate the performances of synthetic zeolite volumetric design. The WMA performance was evaluated and compared with traditional HMA where compacting temperature is 142°C (288°F).

Objectives of this study are: 1) evaluate performance of synthetic zeolite binder property through the viscosity, the change in $G^*/\sin(\delta)$ on original, Rolling Thin Film Oven (RTFO) aged and Pressure Aging Vessel (PAV) aged binder, and creep stiffness using bending beam rheometer; 2) evaluate the performance of synthetic zeolite through the change in dynamic modulus (E^*).

Materials Description and Experiment Design

In this section, the asphalt binder, asphalt mixtures, and synthetic zeolite are discussed. Asphalt binder PG64-22 was used as the control binder obtained in a local highway project. Both the control mixture (HMA) and WMA mixture were prepared in lab. Synthetic zeolite was introduced for the WMA at the rate of 0.3 and 0.5% based on total weight of the mixture, respectively. For the asphalt binder, the synthetic zeolite was added to the binder at the rate of 0.3 and 0.5% of the total weight of asphalt binder, respectively.

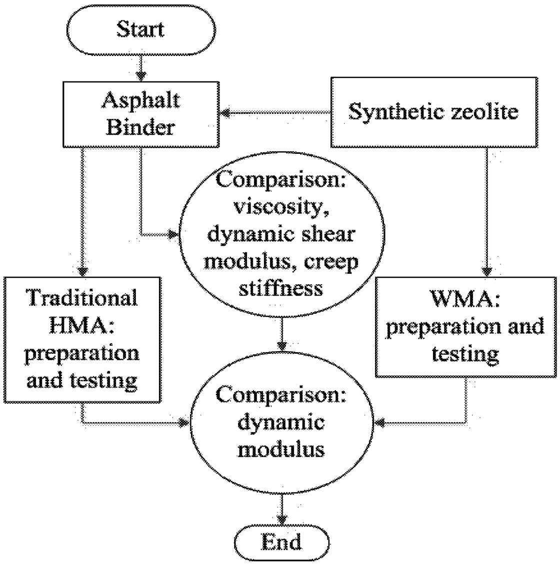

Fig. 2. The General Test Flow Chart for the Asphalt Binder and Mixtures.

Synthetic zeolite is the framework silicates with large vacant spaces in their structure. This allows space for large cations such as sodium, potassium, barium, and calcium, and relatively large molecules and cation groups such as water. In more useful synthetic zeolite, spaces are interconnected and form several long, wide channels of varying sizes depending on the mineral. These channels allow easy movement of resident ions and molecules in and out of the synthetic zeolite structure. The most common use for synthetic zeolite is in water softeners. Synthetic zeolite, characterized by its ability to lose and absorb water without damage to its crystal structures, can have water in their structures driven out by heat and other solutions pushed through the structure. It can then act as a delivery system for the new fluid [1, 12].

Experiments in this study included two parts: one for asphalt binder, the other for asphalt mixtures. For asphalt binder, viscosity, dynamic shear modulus, and creep stiffness of the asphalt before and after applied synthetic zeolite were measured. For asphalt mixtures, dynamic modulus for traditional HMA and WMA were measured. The general test flow chart is illustrated in Fig. 2.

Experiment Results and Discussions

Asphalt and asphalt mixture performance laboratory tests were conducted based on the Superpave mix design method. Laboratory experiments performed in this study include tests of rotational viscosity, dynamic shear modulus, creep stiffness, and dynamic modulus. Three samples were used in each of four tests. An average test result from three samples was applied for analyzing. The results were analyzed using statistical method and some discussions were included in this study.

Effect of Synthetic Zeolite on Viscosity at Production Temperatures

Rotational viscosity was run at six temperatures on three types of binders. The temperatures were 80, 100, 140, 135, 150, and 175°C (176, 212, 266, 275, 302, and 347°F). The types of binder were control binder, 0.3% synthetic zeolite by weight, and 0.5% synthetic zeolite by weight. Fig. 3 depicts test results for binder with 0.3 and 0.5% synthetic zeolite additive compared to the control binder. Test results indicated that binder with synthetic zeolite additive slightly reduced the binder viscosity compared to the control binder. To determine whether the synthetic zeolite significantly affects the binder, a statistical method, a paired t-test with 95% confidence level, was performed. Results of 95% confidence interval for the mean difference between the control binder and the binder with 0.3% synthetic zeolite is located in a small range (-90.148, 693.349), and the range for control binder and the binder with 0.5% synthetic zeolite is located at (-362.867, 1,355.878). Synthetic zeolite slightly reduced the viscosity of the binder, however the statistical test result indicates that additional 0.3 and 0.5% did not have significant effect.

Typically, mixing and compacting temperatures were evaluated from the viscosity/temperature graph. However, it is not clear if engineers should follow the traditional rule. The reason is that water spray will be released when the synthetic zeolite is added during the mixing process [5], which allows a lower mixing temperature. Also, adding synthetic zeolite into the binder may change the binder's

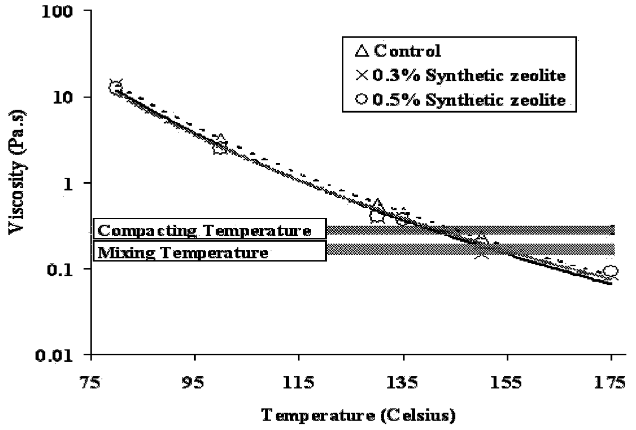

Fig. 3. Comparing Viscosity Test Results of Control and Synthetic zeolite Binder.

characteristic. Therefore, it may be inappropriate to determine the mixing and compacting temperatures for the WMA mixture using 0.3 and 0.5% synthetic zeolite additive binder through the viscosity/temperature chart.

Effect of Synthetic Zeolite on Complex Modulus at Service High and Low Temperatures

Dynamic Shear Rheometer (DSR) test was performed to evaluate the effect of additional synthetic zeolite in the binder. Based on the test results, one can identify whether the synthetic zeolite will give either positive or negative effect to the asphalt.

Three states of asphalt binder condition were used in the DSR tests. These states are original binder, binder after the short-term aging process, and long-term aging process. The short-term aging process is known as the asphalt binder condition after the pavement construction, and it is stimulated using the RTFO in the lab. The long-term aging process is prepared via the PAV, where the PAV is used to stimulate in-service oxidative aging of asphalt binder by exposure to elevated temperature in a pressurized environment in the laboratory setup.

Table 1 shows the results of DSR test for the original binder, binder after RTFO, and binder after RTFO and PAV process. DSR test results for high temperature (64°C) were obtained from original binder and after RTFO process. The result for low temperature (22°C) was obtained after the RTFO and PAV process. It is observed that the control binder has a higher G*/sin(δ) value of 1.1766kPa for original binder test, where the binders with additional synthetic zeolite show the value below 1.00kPa. Superpave specification requires a minimum value of 1.10kPa is needed to pass the high temperature (64°C) grade requirement and the additional synthetic zeolite has shown the value below the limit. This also indicated that the binder has bumped down by one performance grade after adding the synthetic zeolite. Previous literature review of the research from NCAT [9] and WMA for Cold Weather Paving [12] indicated that additional synthetic zeolite may decrease the production temperature by bumping one grade down on high temperature.

Table 1. Dynamic Shear Test Results for High And Low Temperatures.

	G*/sin(δ) (kPa)		G*·sin(δ) (kPa)
	High Temperature, 64°C		Low Temperature, 22°C
	Original Binder	RTFO	PAV
Control	1.1766	2.6195	2064.3
0.3% Synthetic zeolite	0.9018	2.0523	2639.2
0.5% Synthetic zeolite	0.7820	2.0258	2813.8

Note: G* is dynamic shear modulus
δ is phase angle

Table 2. Results from Creep Stiffness Test.

Sample Description	Average Stiffness (MPa)	Average m-value
Control	210.50	0.315
0.3% Synthetic zeolite	193.75	0.317
0.5% Synthetic zeolite	191.83	0.321

Note: m-value is the slope of BBR creep stiffness versus time at the time of 60 seconds.

From Table 1, as expected, the value of G*/sin(δ) for the control binder after the short-term aging process is higher than the binders with the additional synthetic zeolite. Test results for control binder for G*/sin(δ) is 2.6195kPa and both values for binder with addition of synthetic zeolite is below 2.10kPa. The binder with the additional synthetic zeolite did not qualify for the Superpave binder specification, because they did not meet the minimum requirement value after the short-term aging process of 2.20kPa. Results of DSR for original and for short-term aging process have shown that additional synthetic zeolite has increased the rutting potential.

DSR test results on the binder after long-term aging, G*·sinδ for the control binder shows 2,064.3kPa; the binders with the addition of synthetic zeolite are 2,639.2 and 2,813.8kPa with the addition of 0.3 and 0.5% synthetic zeolite, respectively. This indicates that the additional synthetic zeolite slightly increases the fatigue potential and still falls under the limitation of Superpave specification of maximum 5,000kPa.

Effect of Synthetic zeolite on Binder Creep Stiffness Using Bending Beam Rheometer

The Bending Beam Rheometer (BBR) test was performed to evaluate the stiffness of the binder by applying the constant creeping load on the asphalt binder. All binders underwent the short-term aging process (RTFO) and the long-term aging process (PAV) prior to this test.

Table 2 shows the BBR test results for both control and synthetic zeolite modified binder. It is noticeable that the additional Synthetic zeolite has slightly decreased the value of the flexural creep stiffness of the binder while the m-value increased slightly. Similar to DSR test result, a lower value in BBR test result indicates that additional synthetic zeolite increases the fatigue potential of the binder.

Effect of Synthetic zeolite on Dynamic Modulus

Dynamic modulus is the ratio of stress to strain under haversine (or sinusoidal) loading conditions. The greatest advantage of the dynamic modulus (E*) is it can be used in developing a series of prediction models through Mechanistic- Empirical Pavement Design

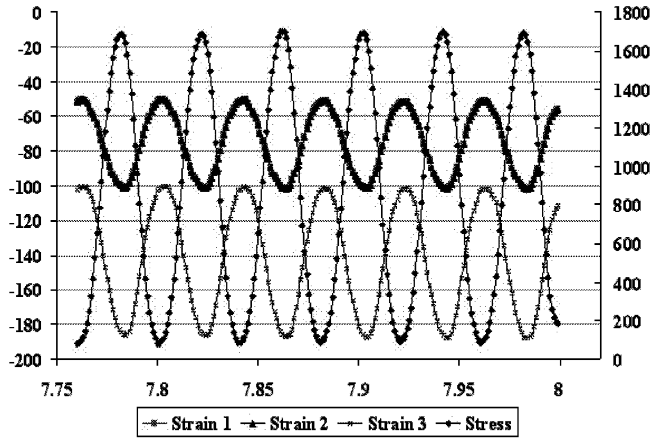

Fig. 4. Dynamic Modulus Test Result Obtained from the UTM 100 Machine.

Guide (MEPDG). In this paper, the dynamic modulus test was conducted according to AASHTO TP62-03. Temperatures used to measure E* are -5, 4, and 21.1°. Frequencies used for each individual in this test were 0.1, 0.5, 1, 5, 10, and 25Hz. Five types of mixture were used: a control mixture, 0.3% synthetic zeolite mixture compacted at 100 and 120°C, and 0.5% synthetic zeolite mixture compacted at 100 and 120°C. The recoverable axial micro-strain in this test was adjusted to values between 50 and 100 so the material is in the viscoelastic range. Fig. 4 shows an example of a typical stress input from a sinusoidal load and the strain output from three Linear Variable Displacement Transducers (LVDTs) of the dynamic modulus test using the UTM 100 (a Universal Testing Machine) at Michigan Technological University.

Results of the dynamic modulus test are presented in Figs. 5, 6, and 7. The legend for the graph is as follows: "Control" for the control mixture, "0.3%AM_100C" for the asphalt mixture with 0.3% synthetic zeolite and compacted at 100°C, "0.3%AM_120C" for the asphalt mixture with 0.3% synthetic zeolite compacted at 120°C, "0.5%AM_100C" for the asphalt mixture with 0.5% synthetic zeolite compacted at 100°C, and "0.5%AM_120C" for asphalt mixture with 0.5% synthetic zeolite compacted at 120°C.

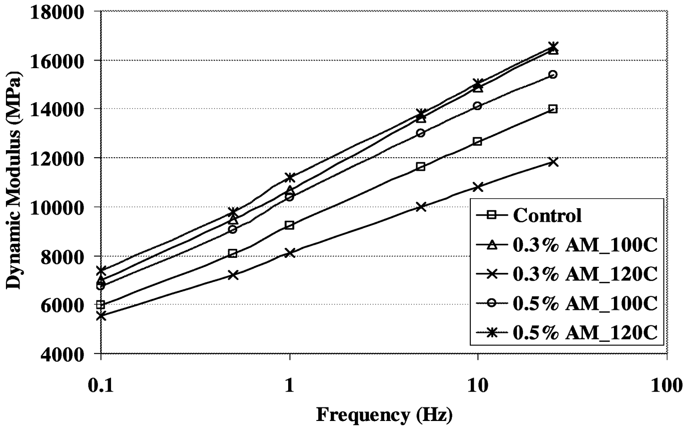

Fig. 6. Dynamic Modulus Test Result at 4°C.

These figures show the mixtures with additional 0.5% synthetic zeolite have a higher E* value in overall when compared to the control mixture. A statistical method, paired t-test, with 95% confidence level was performed to evaluate the effect of synthetic zeolite. Based on the statistical analysis, the E* for WMA made with 0.5% synthetic zeolite is significantly higher than the control mixture. In addition, WMA compacted at 120°C has higher E* based on the statistical analysis. This also indicated that WMA made with synthetic zeolite has a better performance in terms of rutting distress compared to tradition HMA.

Dynamic modulus values measured over a range of temperatures and frequencies of loading can be shifted into a master curve for analyzing the asphalt mixture's performance. The concept of sigmoidal master curve is to "shift" the relative E* from different temperatures to the time of loading using the sigmoidal fitting model so the various curves can be aligned to form a single master curve. In this study, a sigmoidal master curve was constructed for the measured E* for both control and synthetic zeolite mixtures as shown in Fig. 8. A reference temperature of -5°C was used for this curve. As expected, the overall E* of the WMA is higher than the control mixtures. This indicates that additional synthetic zeolite increased the value of the E* of the mixtures.

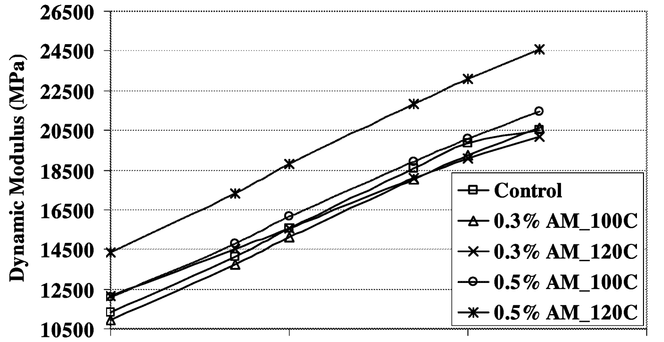

Fig. 5. Dynamic Modulus Test Result at -5°C.

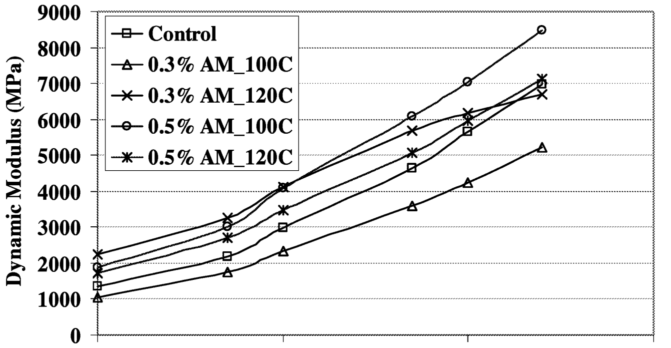

Fig. 7. Dynamic Modulus Test Result at 21.1°C.

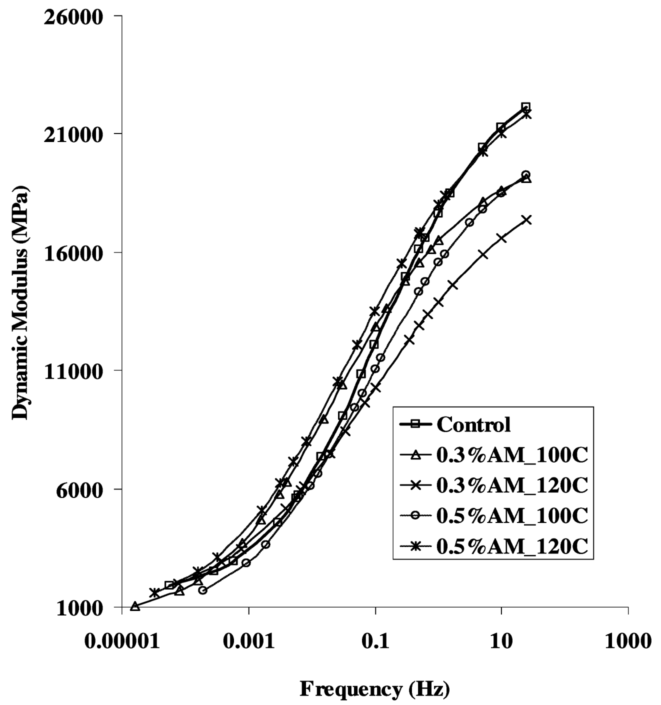

Fig. 8. Comparison of Dynamic Modulus Results using Master Curves.

Predicting Pavement Performance Using Mechanistic-Empirical Pavement Design Guide

MEPDG was developed in National Cooperative Highway Research Program (NCHRP) Project 1-37A and is to be used as the future pavement design guide for users in public and private sectors. MEPDG software is able to predict various kinds of distress including rutting and fatigue cracking by inputting the asphalt mixture characteristics from laboratory testing (or predicted dynamic moduli for some cases). There are three levels in MEPDG which are level 1, 2, and 3. The accuracy of prediction increases from Level 3 to 1. Level 3 is used for design where there are minimal consequences of early failure and the inputs would be typical average values for the region. Level 2 design is used when resources or testing equipment are not available for the tests required for level 1 and normal inputs could be user-selected from an agency database. It could also be derived from a limited testing program or through estimated correlations. Level 1 design is typically used for obtaining inputs for designing heavily used pavements or wherever there are dire safety or economic consequences of early failure. In addition, level 1 inputs require laboratory or field testing, such as dynamic modulus testing of HMA. In this study, level 1 of MEPDG was used to predict the distress of the pavement. Based on preliminary data, the MEPDG predicted rutting depths for WMA mixture has lower rutting depth. Through the prediction results, it was found that the greatest depth of rutting was for the control mixture which the percent different is at most 48% (after 20 years). Again, these results are based on many assumptions and should be considered as preliminary results. Further study is ongoing to verify the mixture properties, mixture design, and pavement field performance.

Conclusions and Recommendations

This paper presented the results of a laboratory evaluation of WMA made with synthetic zeolite. An asphalt mixture with the nominal maximum size of 12.5mm (1/2 inch) and Superpave Performance Grade binder was used in the laboratory evaluation. A control HMA mixture, WMA with 0.3% of synthetic zeolite, and WMA with 0.5% of synthetic zeolite were tested. For the asphalt test, it was found that addition of the synthetic zeolite in the binder slightly decreased the binder's viscosity. However, statistical analysis has shown this effect is not significant. The additional synthetic zeolite shows a higher potential in fatigue cracking through the DSR and BBR tests compared to the control binder. WMA showed a higher performance in overall for E* through the dynamic modulus test. E* is an important input parameter for the MEPDG. Based on the preliminary MEPDG prediction, WMA with additional synthetic zeolite reduced the rutting depth up to 48% over 20 years. These results are based on many assumptions and should be only considered as preliminary results.

Several recommendations are given based on the preliminary laboratory evaluation: 1) life cycle cost analysis should be performed to evaluate whether synthetic zeolite will produce a more economically efficient pavement; 2) the performance grade of asphalt binder with the additional synthetic zeolite should be examined for each project before construction; 3) the field performance should be monitored; 4) a guideline of the design, construction, and maintenance of WMA is needed for successful field applications.

References

1. U.S. Department of Transportation, Federal Highway Administration (2006). Warm Mix Asphalt Technologies and Research [cited; Available from http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm.]
2. Kristjansdottir, O., Muench, S.T., Michael, L., and Burke, G. (2007). Assessing the Potential Warm-Mix Asphalt Technology Adoption. *Transportation Research Board 86th Annual Meeting,* Transportation Research Board. Washington, D.C., USA, CD-ROM.
3. Goh, S.W. and You, Z. (2008). Mechanical Properties of Warm Mix Asphalt Using Aspha-Min®, *Proceedings of 2008 Annual Transportation Research Board Meeting*, Washington, D. C., USA, January 13-17, CD-ROM.
4. Goh, S., You, Z., Van Dam, T.J. (2007). Laboratory Evaluation and Pavement Design for Warm Mix Asphalt, *Proceedings of the 2007 Mid-Continent Transportation Research Symposium*, Center for Transportation Research and Education, Iowa State University, Ames, IA., USA, CD-ROM, also Available at http://www.ctre.iastate.edu/pubs/midcon2007/YouLaboratory.pdf
5. Devivere, M.V., Barthel, W., and Marchand, J.P. (2003). Asphalt Mixes by Adding a Synthetic Zeolite, *Proceedings of the XXIInd PIARC World Road Congress*, La Defense Cedex, France, CD-ROM.
6. Advisory note 17 – Warm Mix Asphalt – a-state-of-the-art review. *Australian Asphalt Pavement Association* (AAPA).

Available at http://www.aapa.asn.au/docs/no17.pdf

7. McKeon, B (2006). Aspha-Min® in warm asphalt mixes, Presented at *51st Annual Convention of the National Asphalt Pavement Association*, Lanham, Maryland, USA.
8. Daniel, J.S. (2006). Performance of Warm Mix Asphalt, *Cold Weather Paving 2006: Presented at Southeastern Asphalt User/Group 2006 Annual Meeting,* Wilmington, North Carolina.
9. Hurley, G.C., Prowell, B.D., Reinke, G., Joskowicz, P., Davis, R., Scherocman, J., Brown, S., Hongbin, X., and Bonte, D. (2006). Evaluation of potential processes for use in warm mix asphalt, *Journal of the Association of Asphalt Paving Technologists*, 75, pp. 41-90.
10. Prowell, B.D., Hurley, G.C., and Crews, E. (2007). Field Performance of Warm-Mix Asphalt at the NCAT Test Track, *Transportation Research Board 86th Annual Meeting*, Washington DC, USA, CD-ROM.
11. Wasiuddin, N.M., Selvamohan, S., Zaman, M.M., and Guegan, M.L.T.A. (2007). A Comparative Laboratory Study of Sasobit® and Aspha-Min® in Warm-Mix Asphalt, *Transportation Research Board 86th Annual Meeting*. Washington DC, USA, CD-ROM.
12. Kristjansdottir, O. (2006). Warm Mix Asphalt for Cold Weather Paving, *Civil and Environmental Engineering*, *Report No. WA-RD 650.1*, submitted to Washington State Department of Transportation, University of Washington, Seattle, Washington., USA.