COMPREHENSIVE LABORATORY PERFORMANCE EVALUATION OF WMA WITH LEADCAP ADDITIVES

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Submitted to the 2nd International Conference on Warm Mix Asphalt
National Asphalt Pavement Association

May 2011

ABSTRACT

This paper presents the laboratory test and analysis results from a reference hot-mix asphalt (HMA) mixture and warm mix asphalt (WMA) mixtures modified by two different LEADCAP additives (KW3 and KW6) of a wax type. The performance characteristics investigated in this study include rutting, fatigue cracking, and moisture susceptibility. Rutting performance is evaluated by the triaxial repeated load permanent deformation (TRLPD) test and the asphalt pavement analyzer (APA) test. Fatigue performance of the mixtures with and without moisture conditioning is evaluated using the direct tension cyclic test following the simplified viscoelastic continuum damage (S-VECD) protocol. The resulting damage characteristics and dynamic modulus are used in the layered viscoelastic analysis program to assess the fatigue performance and the moisture susceptibility of these mixtures in pavement structures with different asphalt layer thicknesses.

Both the TRLPD and APA test results show that the KW3 and KW6 mixtures exhibit more resistance to rutting than the HMA mixture. In particular, the rutting resistance of the KW3 mixture is superior to that of the HMA and KW6 mixtures. In addition, the HMA and KW6 mixtures exhibit approximately the same favorable characteristics of fatigue resistance, whereas the KW3 mixture's fatigue performance is worse than that of the HMA and KW6 mixtures. However, the moisture susceptibility results indicate that the KW6 mixture is more susceptible to moisture damage than the HMA mixture in terms of fatigue resistance. This increased moisture susceptibility in the KW6 mixture is currently being addressed by modifying the KW6 additive. This study demonstrates the importance of the comprehensive performance testing of mixtures for the development and optimal design of a WMA additive.

INTRODUCTION

Various national efforts to develop warm mix asphalt (WMA) have increased dramatically over recent years. These efforts have strived to reduce the mixing and compaction temperatures by increasing the workability of the asphalt mixture, thus resulting in energy and cost savings and low environmental costs. However, to realize these benefits of WMA, the performance of WMA should at least be comparable to that of HMA, because the frequency of reconstruction causes an increase in energy consumption and toxic fumes. One of the recently developed WMA technologies is LEADCAP. LEADCAP is a polyethylene wax-based additive that is designed not only to improve the workability of the mixture but also to enhance the permanent deformation resistance at high temperatures and the cracking resistance at low temperatures.

In order to assess the effects of LEADCAP additives (KW3 and KW6) in WMA, rutting, fatigue and moisture susceptibility laboratory tests were conducted as part of this study. After determining the optimal asphalt contents of the HMA, KW3, and KW6 WMA mixtures, triaxial repeated load permanent deformation (TRLPD) tests were conducted to determine the permanent deformation characteristics based on the permanent to resilient strain ratio model used in the Mechanistic-Empirical Pavement Design Guide (MEPDG). Then, the asphalt pavement analyzer (APA) was employed to verify the TRLPD results. To evaluate the fatigue cracking performance and moisture susceptibility of the mixtures, direct tension cyclic tests were performed with and without moisture conditioning. A modified AASHTO T-283 protocol was used to moisture-condition the test specimens. Dynamic modulus and damage characteristic relationships were used in the viscoelastic continuum damage (VECD) analysis and three-dimensional (3-D) layered viscoelastic analysis to predict the fatigue life of asphalt pavements with different asphalt layer thicknesses.

The purpose of this paper is two-fold: 1) to present the test and analysis results for the LEADCAP additives and 2) to demonstrate the importance of comprehensive performance testing in developing new WMA technologies.

MATERIALS

Three asphalt mixtures are evaluated in this paper, including one reference HMA mixture and two KW3 and KW6 WMA mixtures that consist of powder (KW3) and chip (KW6) types of wax additive, as shown in Figure 1.

Figure 1 Powder (KW3) and chip (KW6) type additives

The aggregate structure for each of the mixtures is coarse 19 mm nominal maximum aggregate size (NMAS) comprised of 25% 12.5 mm, 20% 9.5 mm, 17% #4, 12% #8, 6% #16, 7% #30, 4% #50, 4% #100, 3% #200, and 2% hydrated lime. The blended gradations are shown in Figure 2.

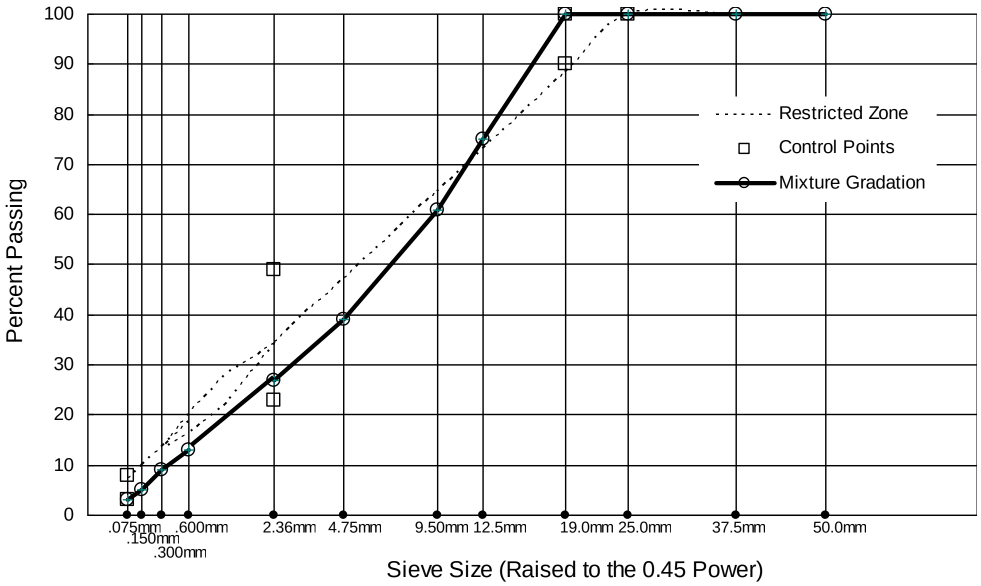

Figure 2 Mixture gradation chart

The HMA, KW3, and KW6 WMA mix designs were performed to meet the 4% air void requirement using a gyratory compactor with 100 gyrations. The KW3 and KW6 dosage rates are 3% and 1.5% of the total asphalt binder weight, respectively, based on viscosity and economic considerations. The HMA mixture was mixed at 160°C and compacted at 140°C in accordance with the requirements for PG 64-16 binder. The HMA mixture was aged at a compaction temperature for 1 hour (referred to as short-term oven aging). The WMA mixtures were mixed at 130°C (aggregate at 130°C, binder at 160°C) and compacted at 115°C. The aging temperature and length of time for compaction were also 115°C and 1 hour, respectively.

The mix design specimens were compacted in a Superpave gyratory compactor that has a 150 mm diameter mold and a target mixture weight of 4,500 g. Results from the mix design process for all the mixtures are shown in Table 1.

Table 1 Mix Design Results for HMA and WMA Mixtures at 4% Air Void

Mixture	% AC	% Additive	% VMA	% VFA	G_{mm}	G_{mb}	G_{se}
HMA	4.9	0	15.6	75	2.542	2.445	2.420
KW3	4.27 (97% of 4.4%)	0.13 (3% of 4.4%)	15.4	73.1	2.544	2.439	2.435
KW6	4.43 (98.5% of 4.5%)	0.07 (1.5% of 4.5%)	16.9	75	2.539	2.397	2.428

Using the same aggregate type and structure, the optimal asphalt contents of the HMA, KW3, and KW6 mixtures were determined to be 4.9%, 4.4% (4.27% binder and 0.13% WMA additive), and 4.5% (4.43% binder and 0.07% WMA additive), respectively. It should be noted that replacing a 0.30% asphalt binder with the powder type of KW3 additive decreases the optimal asphalt binder content of the Superpave volumetric mix design content up to 0.63 percent. In addition, replacing 0.15% asphalt binder with the chip type of KW6 additive decreases the optimal asphalt content up to 0.47 percent.

All specimens were compacted to a height of 178 mm and a diameter of 150 mm. To obtain specimens of uniform air void distribution, these samples were cored and cut to a height of 150 mm with a diameter of either 75 mm for dynamic modulus and fatigue testing, or a diameter of 100 mm for compression (rutting) testing. It is noted that the air voids for all cored test specimens are between 5 and 6 percent.

TEST PROTOCOLS

Rutting Performance Testing

TRLPD tests were conducted to assess the rutting potential of the asphalt mixtures following the protocol presented in NCHRP Report 465 (3), and then APA tests were used to verify the TRLPD test results.

The TRLPD tests were carried out to 10,000 cycles without observing tertiary flow at 54°C. Such results indicate that each of the mixtures should exhibit adequate rutting performance. Even though none of the mixtures exhibited tertiary flow, differences in the material performance may be assessed by examining the permanent strain growth over the 10,000 cycles.

The APA is designed to simulate field rutting performance in the lab. Test parameters of 8,000 cycles with a 534 N (120 lbs) wheel load and 827 kPa (120 psi) hose pressure were used.

Typically, test temperatures for the APA range from 40.6° to 64°C (105°F to 147°F). The rut depth was measured after the application of 8,000 loading cycles. Six samples were placed under repetitive loads of the APA to assess the rutting susceptibility of the mixtures. The failure criterion used by the NCDOT for the APA testing is a rut depth of 12 mm.

Fatigue Performance Testing

Dynamic modulus and cyclic tension testing were conducted for VECD characterization, and then 3-D layered viscoelastic analysis was carried out to determine the fatigue performance of various asphalt pavements.

The dynamic modulus testing was performed in load-controlled mode in axial compression, generally following the protocol given in AASHTO TP62-03 (4). Tests were completed for all mixtures in this study at –10°, 5°, 20°, 40°, and 54.4°C and at frequencies of 25, 10, 5, 1, 0.5, and 0.1Hz. Load levels were determined by a trial and error process so that the resulting strain amplitudes were between 50 and 70 microstrains.

The viscoelastic damage characteristics were determined by conducting CX cyclic tension tests at 19°C. All tests were performed at two different strain amplitudes (relatively high strain and low strain). The high strain amplitude targets initial cracking failure at around 1,000 cycles, and the low stain amplitude targets the failure at about 10,000 cycles. The resulting two sets of cyclic test data were used to develop the VECD model. The strength of the VECD model is that the fatigue performance for conditions different from the testing conditions (i.e., strain amplitude and temperature) can be predicted from the results from these two sets of data by determining the unique damage characteristic relationship of a mixture expressed by the pseudo stiffness (C) and the damage parameter (S). A complete review of the VECD model can be found in the literature (5~11).

In order to simulate various asphalt pavement structural responses, four pavements with different asphalt layer thicknesses (4, 8, 12, and 20 inches) were simulated. Those pavements were subjected to a single wheel moving at a constant speed and with a constant load and contact pressure. The input parameters are represented in Table 2. In this analysis, outputs from this program are simulated for transverse strain or stress at the bottom of the asphalt layer.

Table 2 3-D Layered Viscoelastic Analysis Input Conditions

Structural Input Condition	
AC Material Types/ Poisson's Ratio	HMA and WMA/0.3
Thickness of Pavement	4, 8, 12, 20 in
Pavement Length/Width	2.9718 m/1.778 m
Subgrade Stiffness/Poisson's Ratio	70 MPa/0.45
Temperature	19°C
Single Wheel Moving Condition	
Contact Pressure	758.45 kPa
Load Area	0.29718 m x 0.1778 m
Velocity	26.82 m/sec

By combining the VECD characterization with the linear viscoelastic structural responses, the fatigue life predictions for the different asphalt pavement thicknesses can be simulated. The number of cycles to failure, or the fatigue life, was determined using the criterion of 20% surface cracking in the lane (5).

In terms of the failure point in the direct tension cyclic testing, the traditional fatigue analysis method determines failure as the point at which the material's modulus drops to 50% of its initial value. However, this method is purely empirical, and the approach suggested by Reese (12) is used here whereby the cycle at which the phase angle shows a sharp decrease is defined as the number of cycles to failure.

Moisture Damage Susceptibility Testing

Fatigue cracking tests that examine moisture susceptibility for the HMA and WMA mixtures generally consist of two primary tasks. First, a procedure for conditioning the moisture damage of the testing specimens must be determined, and then a procedure for evaluating the moisture-conditioned specimens must be determined. In this paper, a modified AASHTO T-283 protocol test was conducted for the moisture damage conditioning procedure, and then, dynamic modulus and direct tension cyclic tests were carried out to evaluate the moisture susceptibility of the HMA and KW6 mixtures. (The modified AASHTO T-283 specification does not include the freeze-thaw cycle procedure.) The moisture damage conditioning procedure is to put specimens in a water bath at 60°C for 24 hours after applying water pressure of 23 in. Hg to reach a 65~80% saturation level using Gilson vibro-deairator equipment. In order to evaluate the moisture susceptibility of a mixture, moisture damage-conditioned specimens and unconditioned specimens are compared via dynamic modulus and direct tension cyclic testing. Both tests were performed using specimens that were completely dry.

RUTTING PERFORMANCE TEST RESULTS

The permanent strain growths for all three mixtures measured by the TRLPD tests are presented in the plot shown in Figure 3 (a). Figure 3 (b) shows the resilient strain, and the ratio of permanent to resilient strain is plotted against the applied loading cycles in Figure 3 (c) and (d) in arithmetic and log-log scales respectively. When comparing the HMA with the WMA mixtures, the rutting resistance of both the KW3 and KW6 mixtures is better than that of the HMA mixture. In particular, the KW3 mixture exhibits superior performance when compared to the other mixtures in the permanent strain and ratio of permanent to resilient strain plots. However, it is important that the superiority of a given mixture should be considered by examining both fatigue and rutting resistance at the same time.

APA testing was conducted to compare the TRLPD test results. The failure criterion used by the North Carolina Department of Transportation (NCDOT) for the APA testing is a rut depth of 12 mm. The NCDOT performs this testing to determine a pass or fail for mixture performance prior to constructing asphalt pavements in the field. The test results are shown in Figure 4. Based on these test results, all HMA and KW3 and KW6 WMA mixtures are acceptable by the NCDOT in terms of rutting resistance. The performance rankings in order are: KW6 (average 3.79 mm), KW3 (average 4.12 mm), and HMA (average 4.76 mm). However, the error range bars with 98% reliability show that the difference among the three mixtures is statistically insignificant.

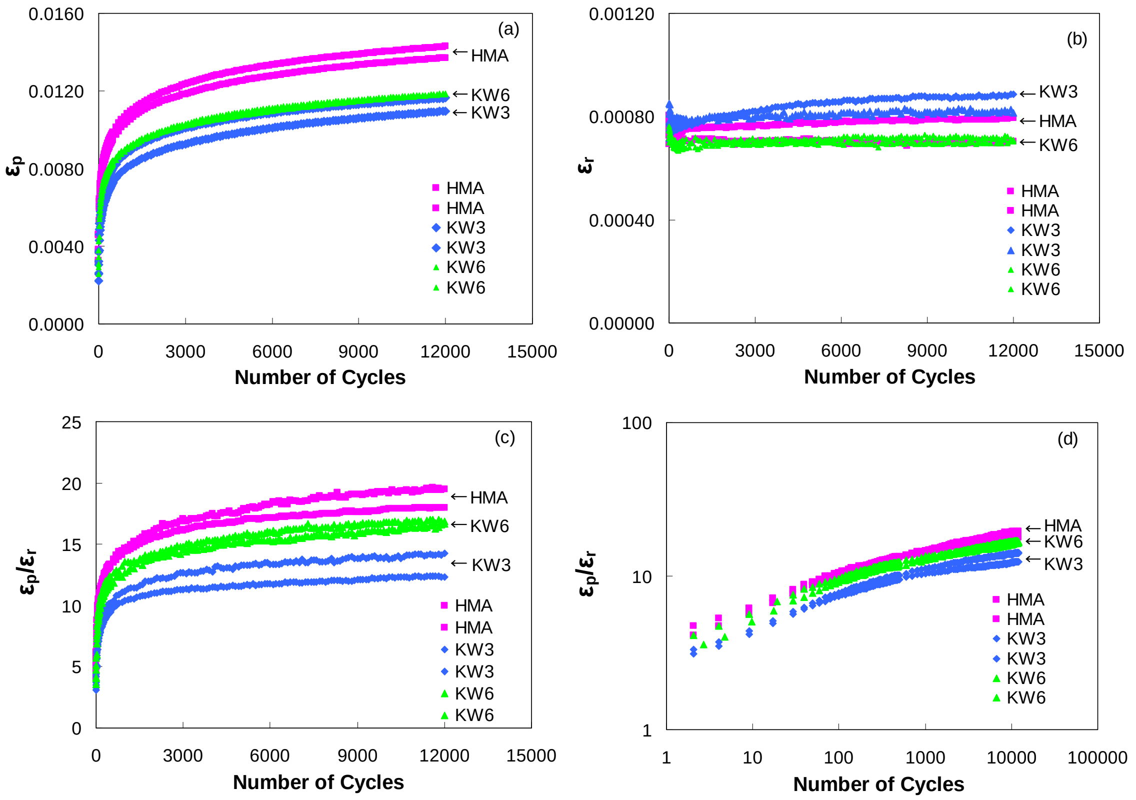

Figure 3 TRLPD testing results: (a) permanent strain, (b) resilient strain, (c) ratio of plastic to resilient strain, and (d) ratio of plastic to resilient strain in log-log scale

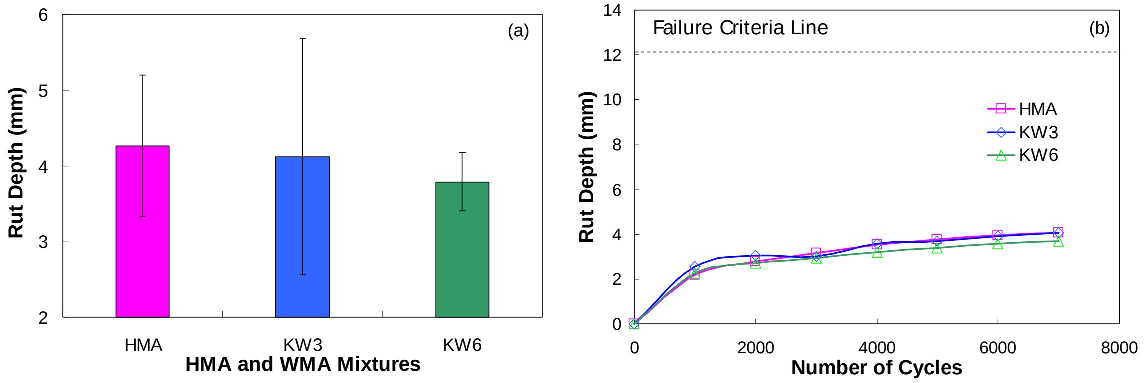

Figure 4 APA testing results: (a) rut depth with number of cycles, and (b) average rut depth and error range bar

FATIGUE PERFORMANCE TEST RESULTS

The dynamic modulus test results of the HMA, KW3 and KW6 mixtures are presented in a graphical format plotted against reduced frequencies after shifting the data, as shown in Figure 5. The reference temperature used as the basis for shifting the data is 5°C. Data are presented in both log-log (Figure 5 (a)) and semi-log (Figure 5 (b)) scales. Both scales are presented to show both the high temperature (log-log) and low temperature (semi-log) behavior. In general, the dynamic modulus and phase angle of the three mixtures are similar. The KW3 mixture shows slightly higher stiffness at a higher reduced frequency and slightly lower stiffness at a lower reduced frequency when compared to the HMA mixture.

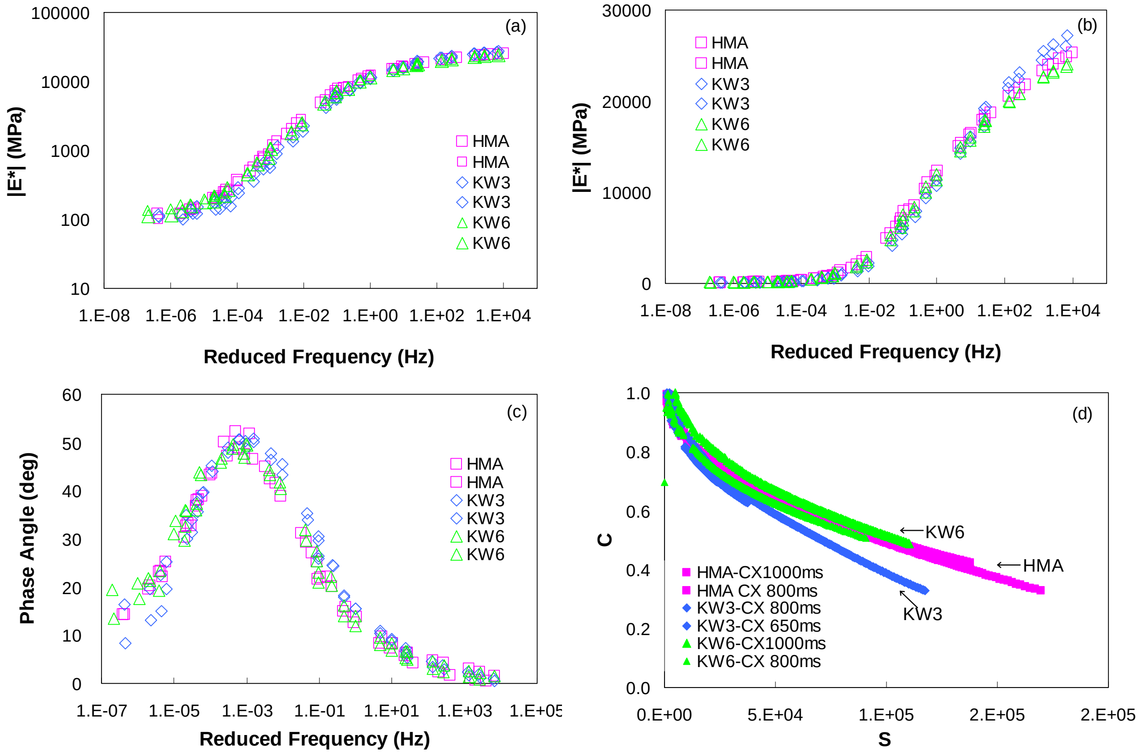

Figure 5 VECD characterization for HMA, KW3 and KW6 WMA mixtures: (a) |E*| in log-log scale, (b) |E*| in semi-log scale, (c) phase angle in semi-log scale, and (d) damage characteristic curves.

All cyclic tension tests were performed at a constant frequency of 10 Hz at 19°C, and failure is defined as the point at which the phase angle starts to drop. Figure 5 (d) represents the damage characteristic curves for the HMA, KW3 and KW6 mixes. The damage characteristic curves depict each mixture’s resistance to damage. However, comparison of the damage characteristic curves cannot yield reliable information about the different mixtures’ fatigue resistance, because the energy input by the mechanical forces is consumed not only in creating and propagating cracks in the material, but also in deforming the material. Therefore, it is important to include both stiffness and damage characteristics of the material when the fatigue cracking resistance is determined, which is done in this study by evaluating the fatigue cracking performance of different pavement structures.

The pavement fatigue simulation was performed by running the 3-D layered viscoelastic analysis on a specific pavement structure to determine the strain kernel at the bottom of the asphalt layer. This strain kernel was then input to the VECD model to predict the fatigue life of that pavement. Figure 6 represents the final prediction of fatigue life for all mixtures for the pavements with different asphalt layer thicknesses. For all the pavements, the KW6 mixture exhibits a similar performance to HMA, and the KW3 mixture performs the worst.

The results from the rutting and fatigue tests reveal that the KW3 mixture performs extremely well in terms of rutting resistance, but performs poorly in terms of fatigue cracking.

The KW6 mixture presents a more balanced performance than the KW3 mixture. The KW6 mixture shows better rutting resistance than the HMA mixture and about the same fatigue performance as the HMA mixture. Based on these observations, moisture susceptibility testing was performed on the HMA and KW6 mixtures only.

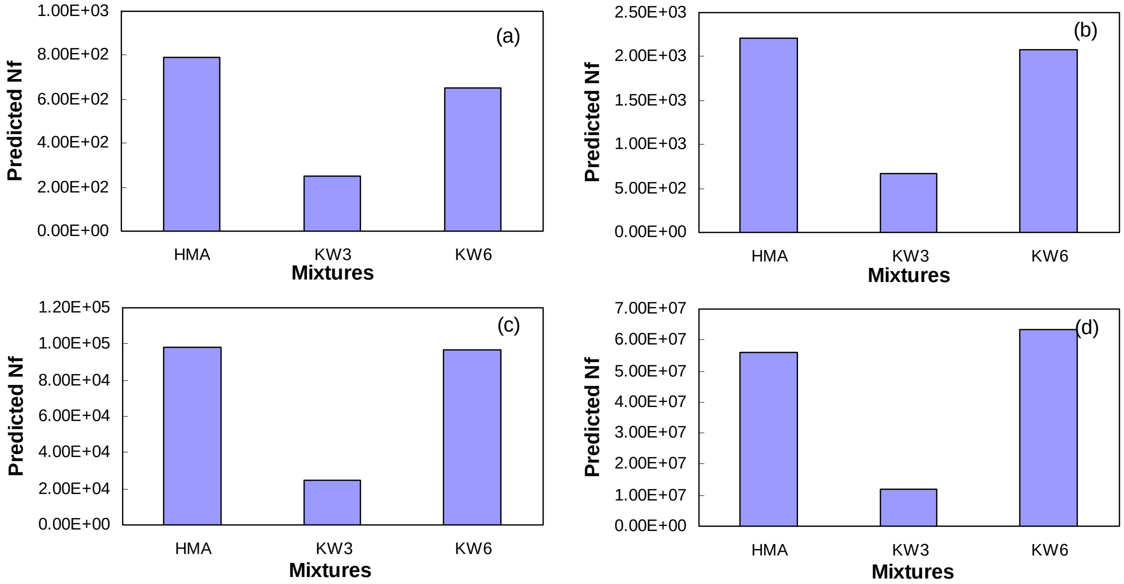

Figure 6 Final prediction of fatigue life for HMA, KW3, and KW6 mixtures: (a) 4 in., (b) 8 in., (c) 12 in., and (d) 20 in. pavement depths

MOISTURE SUSCEPTIBILITY TEST RESULTS

Figure 7 (a) through (c) represent the dynamic modulus test results of the HMA and KW6 mixtures before and after moisture conditioning. In general, the dynamic modulus decreases and the phase angle increases slightly due to moisture conditioning, regardless of mixture type.

In addition, cyclic tension testing and 3-D linear viscoelastic simulations were performed for the two mixtures with and without moisture conditioning. Figure 7 (d) presents the damage characteristic curves for the two mixtures before and after moisture conditioning. It is evident that moisture conditioning changes the damage characteristics of the KW6 mixture much more so than it changes those of the HMA mixture.

Figure 8 shows the fatigue performance simulations of the pavement structures. It is clear that moisture conditioning reduces the fatigue life of all the pavements, regardless of mixture type. This reduction in fatigue life is more dramatic in the KW6 mixture than the HMA mixture.

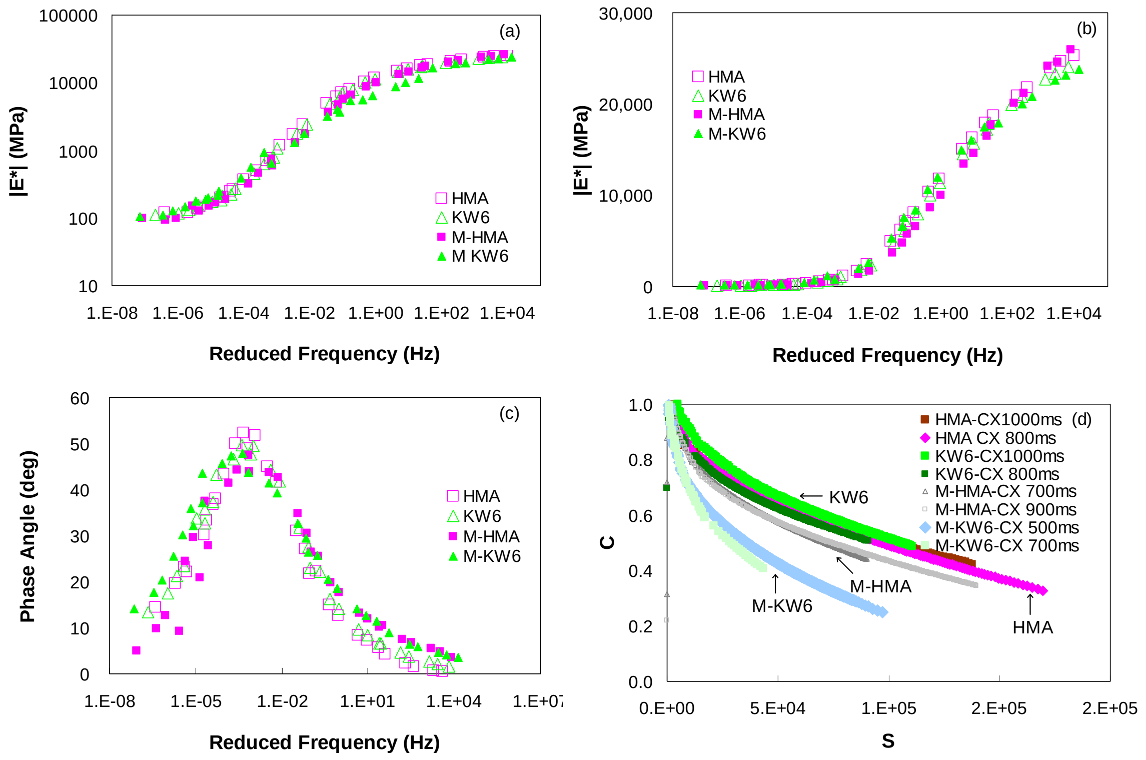

Figure 7 VECD characterization for HMA, KW6, moisture damage conditioned HMA, and moisture damage conditioned KW6 WMA mixtures: (a) |E*| in log-log scale, (b) |E*| in semi-log scale, (c) phase angle in semi-log scale, and (d) damage characteristic curves

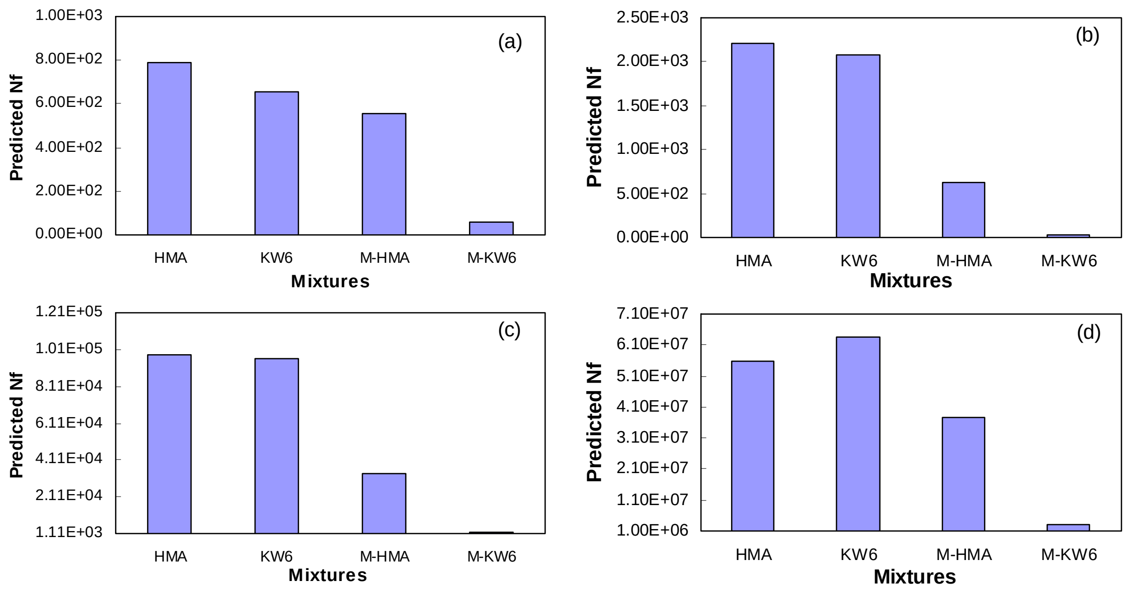

Figure 8 Final prediction of fatigue life for HMA, KW6, and moisture damage conditioned HMA, and moisture damage conditioned KW6 WMA mixtures: (a) 4 in., (b) 8 in., (c) 12 in., and (d) 20 in. pavement depths

SUMMARY AND CONCLUSIONS

The following conclusions can be drawn from the results of the Superpave mix design, the TRLPD testing, and the direct tension cyclic testing with and without moisture conditioning:

- Replacing asphalt binder with the KW3 and KW6 additives decreases the optimal asphalt binder content.
- The dynamic modulus and phase angle of the KW3 and KW6 mixtures are similar to those of the HMA mixture.
- TRLPD test results show that both the KW3 and KW6 mixtures exhibit more favorable characteristics than the HMA mixture. In particular, the rutting resistance of the KW3 mixture is superior to that of the HMA and KW6 mixtures.
- The APA test results indicate that rut depth differences among the three mixtures are statistically insignificant. Based on the failure criterion of 12 mm, it is concluded that the three mixtures exhibit satisfactory rutting resistance.
- Based on the results of dynamic modulus and cyclic tension testing and 3-D layered viscoelastic simulation, the HMA and KW6 mixtures exhibit approximately the same favorable characteristic of fatigue resistance, whereas the KW3 mixture’s fatigue performance is worse than that of the HMA and KW6 mixtures.
- According to the moisture susceptibility analysis of the fatigue resistance performance test results, the KW6 mixture is more susceptible to moisture damage than the HMA mixture in terms of fatigue resistance.
- Based on these test results, the KICT is developing the next version of the LEADCAP WMA additive that maintains the fatigue and rutting performance of the KW6 additive, but has even more moisture-resistant characteristics than the KW6 additive currently exhibits.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the financial support from the Korea Institute of Construction Technology.

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