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INVESTIGATION OF RHEOLOGICAL BEHAVIOR OF ASPHALT BINDER MODIFIED BY THE ADVERA® ADDITIVE

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16. Abstract

Warm mix asphalt (WMA) technologies have attracted great interest in the field of pavement engineering due to its potential energy savings and environmental benefits. As one of the most popular WMA processes, Advera® utilizes zeolite to greatly reduce the production temperature of pavement without compromising the performance of the mixture. However, due to the lack of a comprehensive rheological characterization, the existing specifications cannot provide the optimum temperature and additive proportion for specific binder or aggregate types. Unanticipated by the existing engineering practice, the thermal history during material preparation has a significant effect on the end-results of the complex modulus of modified binders. The rheological investigation of asphalt binder modified by the Advera® additive:

The Advera® additive should be mixed with the binder for at least 20 minutes toallow water to be released in order to improve the workability. To effectively form foam within the binder, the lowest temperature for which this WMA technology is intended is 212°F. However, it achieves optimal performancebetween the temperatures of 230-250°F. Vapors produced from the Advera® additive significantly affect the rheologicalbehavior of the modified asphalt binder, particularly at lower frequencies. The effective phase angle does not depict any pattern with increasing temperature.The self-consistent model approach provides a satisfactory prediction of the experimental data at lower temperatures.

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INVESTIGATION OF RHEOLOGICAL BEHAVIOR OF ASPHALT BINDER MODIFIED BY THE ADVERA® ADDITIVE

ABSTRACT

Warm mix asphalt (WMA) technologies have attracted great interest in the field of pavement engineering due to its potential energy savings and environmental benefits. As one of the most popular WMA processes, Advera® utilizes zeolite to greatly reduce the production temperature of pavement without compromising the performance of the mixture. However, due to the lack of a comprehensive rheological characterization, the existing specifications cannot provide the optimum temperature and additive proportion for specific binder or aggregate types. An integrated multiphase viscoelastic characterization has been conducted to investigate how rheological behavior of asphalt binder changes with WMA additive proportions, time, and temperatures. Because gas, liquid, and solid material phases simultaneously exist in WMA, the phase transformation plays a crucial role in modifying the rheological properties and optimizing the materials design. Unanticipated by the existing engineering practice, the thermal history during material preparation has a significant effect on the end-results of the complex modulus of modified binders. Thermo-physical analysis and poromechanics-based studies are underway.

INTRODUCTION

With the development of human civilization, the earth has undergone considerable changes, especially in the recent centuries. The U.S. highway system is one of many noteworthy examples. Consider the fact that 94% of highway pavements are surfaced with hot mix asphalt (HMA) [1]. Every year, the U.S. uses billions of tons of asphalt materials in pavement construction. Consequently, large amounts of greenhouse gases and other hazardous emissions are produced, which potentially contribute to global warming and the undermining of healthy local environments [2]. Furthermore, billions of dollars are spent on fuel for material processing and manufacturing. Evidently, this trend can neither endure nor cease, but as most rudimentary practices, it must evolve to eliminate some dire issues. Due to the shortage of the world oil supply, asphalt material costs have rocketed in recent years, being a necessary ingredient in fuel and asphalt mixtures. Hence, state DOT's have been forced to reduce pavement construction.

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During the manufacturing of HMA, both asphalt binder and aggregate are heated to 300-350°F, so that they can be mixed smoothly and aggregates can be coated completely. In this process, asphalt binder is aged, which inevitably shortens the life of asphalt materials. To make asphalt pavement construction more sustainable and prolong the life of asphalt materials, the current engineering practice must be changed. Reducing the production and construction temperature can both save fuel cost and alleviate asphalt aging. The concept of warm mix asphalt (WMA) can be traced back to the 1980s when it was used in asphalt recycling [3]. In the 1990s, interest in employing WMA in pavement construction increased significantly in Europe due to the pressure of environmental movements [4], which called great attention to the Federal Highway Administration (FHWA). In 2007, a team of U.S. materials experts visited Belgium, France, Germany, and Norway to evaluate various WMA technologies, and verified that WMA performance can be the same as or better than the performance of HMA if used correctly [5]. Moreover, many construction projects that are impossible for HMA can be done with WMA, such as projects requiring long haul distances, projects taking place in lower temperatures or during the winter, or projects located in urban areas [6]. As a green construction technology, WMA will replace HMA with the validation of its long-term performance. Therefore, the fundamental understanding of these new materials is crucial for their future applications.

Advera® is a kind of hydrated zeolite powder [7], which contains approximately 18-22% moisture in its porous microstructure. In construction, Advera® can be either directly added into the asphalt mixture or pre-mixed with asphalt binder at about 250°F and placed on the road at about 240°F. When temperature increases, water releases from the microstructure and turns into steam and is trapped in asphalt binders as tiny bubbles. Therefore, the volume of asphalt binders will significantly increase, so that the workability of asphalt mixtures will be appreciably improved even at a lower temperature. In compaction, the bubbles are broken and moisture is expelled. When WMA is placed and the temperature cools, zeolite will reabsorb moisture in the mix so that the moisture susceptibility of WMA can be alleviated. In an ideal condition, water only serves as an agent during production and will ultimately be eliminated. Therefore, this additive does not change the chemical properties of asphalt aside from reducing the aging effects and significantly improving the workability [8].

In this study, we focus on the rheological behavior of asphalt binder modified by the Advera® additive. The phase transformation is first investigated by the weight loss rate of pure Advera® powder and volume increase rate of Advera® modified asphalt binder when keeping the specimens at fixed temperatures. Then, the viscoelastic properties of asphalt binders are tested with a highly sensitive rheometer. The complex modulus and phase angle of binders changing with the proportions of additives, temperatures, and testing frequencies are characterized and analyzed. The effective master curves of binders are obtained. At lower temperatures, the test results can be well interpreted by the viscoelastic self-consistent method for asphalt binder containing Advera® particles. However, at higher temperatures, water is released from the additive into the binder and vaporized into bubbles, and some air voids form. Therefore, four material phases exist in the binder, particularly, zeolite particles, water, air voids, and asphalt binder. Since this process significantly changes with the thermal history involving time and temperature, the test results are quite diverse. Furthermore, the test results indicate that rheological properties can be reasonably diverse if the testing conditions are altered.

EXPERIMENTAL RESULTS

First, the mass loss of Advera® at different temperatures is studied. At each of five temperatures (170-250°F in 20°F increments), a 10.0g Advera® sample is used. The mass is recorded in increments of two minutes until measurements are invariable. Figure 1(a) indicates that the overall mass loss for a fixed temperature increases with higher temperatures. An upper limit of total mass loss at high temperatures approaches approximately 18% of the original mass, which is consistent with the specifications of Advera® powder containing 18-22% of water. During the first 500 seconds, the mass loss rates are high, but progressively slow down until reaching a stable status. At 170°F and 190°F, the final mass losses are approximately 6% and 8%, respectively. When temperatures increase to 210°F, 230°F, and 250°F, the final mass losses reach 14%, 16%, and 18%, respectively. This behavior is explained by the fact that at lower temperatures, although water can be partially released from the crystal microstructure, the evaporation rate is quite small so the mass loss is not significant; however, at higher temperatures, such as those near or above 212°F, the released water will evaporate rapidly hence explaining the increased rate of mass loss. Therefore, it is recommended that the Advera® additive be used at temperatures above 212°F. Otherwise, the usage of this additive will not produce significant differences.

Figure 1(b) illustrates the results for the volume increase of Advera® modified asphalt binder containing different proportions of Advera® additive at 250°F. Intuitively, higher additive proportions exhibit an overall larger volume increase. Consequently, the workability of the asphalt binder mixture is improved considerably without compromising the chemical constituents of the asphalt binder since the Advera® powder only releases water at a certain threshold temperature. Within the first 20 minutes, the volume increase rate is fairly high, except at the low additive mass proportion of 1.5%. It is suggested that the Advera® additive be mixed with the binder for at least 20 minutes to achieve a desired workability.

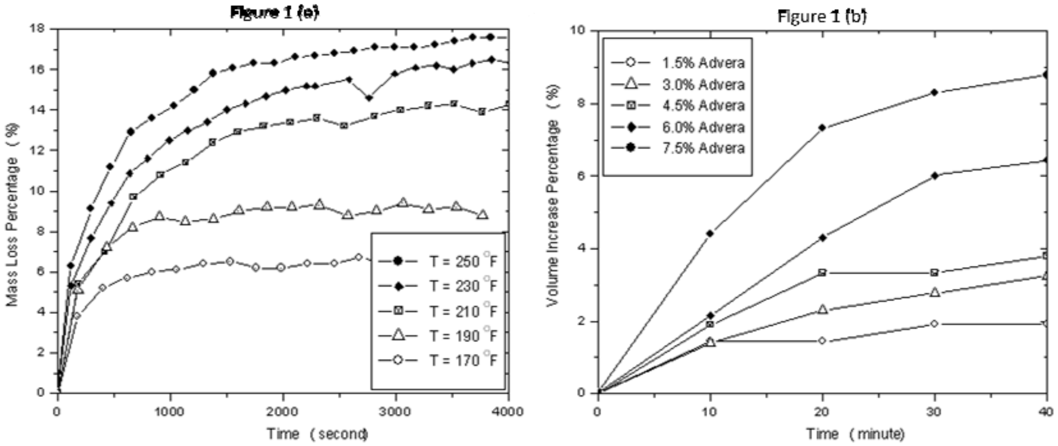

Figure 1. Water evaporation studies. (a) Mass loss of Advera® powder with an original mass of 10.0g for five temperatures; (b) volume increase of Advera® modified asphalt binder with an original volume of 20mL at 250°F.

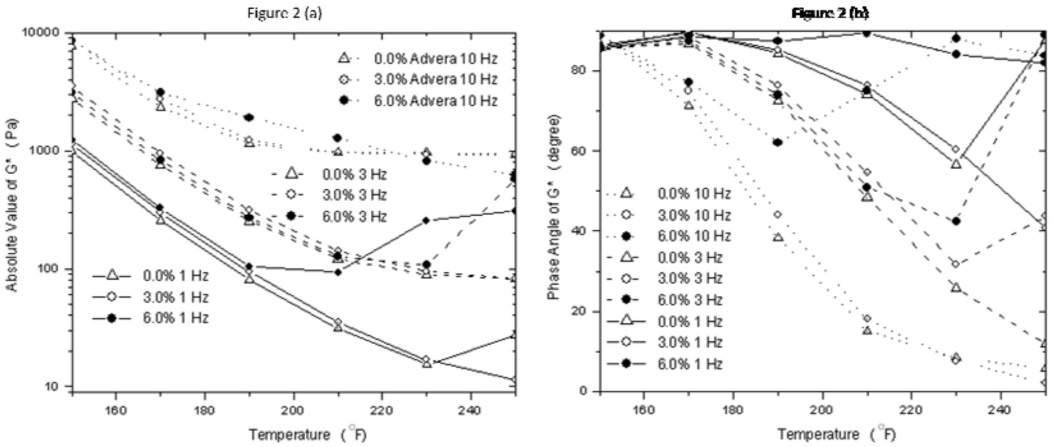

Figure 2. Complex modulus of asphalt binder modified by the Advera® additive. (a) The absolute value of complex modulus vs. temperature; (b) the phase angle of complex modulus vs. temperature.

Figure 2 shows the complex modulus, G^*, and the phase angle, δ, for the asphalt binder modified by 0.0%, 3.0%, and 6.0% of Advera® powder at different temperatures. In general, both the absolute value and the phase angle of G^* decrease with the increase of temperature. However, Figure 2(a) shows that the absolute value of G^*, for higher temperatures such as 230°F and 250°F, increases for the Advera® mass proportion of 6.0%. In Figure 1(b), it is evident that more than 8% of vapor in volume is generated at those temperatures, which greatly changes the rheological behavior, especially at lower frequencies. Since the Advera® powder and vapor are considerably different and modify the effective rheological behavior in opposite manners, the effective phase angle does not show any consistent trend with the increase of temperature.

MODELING RESULTS

Experimental evidence supports a theory known as time-temperature superposition. From this theory, master curves of different Advera® modified asphalt binders can be constructed. These master curves rely on the time-temperature superposition shift factor, computed as the quotient of the complex modulus at a given temperature, T, and the complex modulus at a reference temperature, T_o. However, the shift factors for a given weight fraction must satisfy

$$\log(a_T) = \frac{-C_1(T - T_o)}{C_2 + (T - T_o)} \tag{1}$$

Therefore, from the experimental results of the complex modulus for different temperatures, the shift factors can be computed based on the reference temperature. From these shift factors, the constants C_1 and C_2 can be determined. It should be noted, however, that the complex modulus is obtained by a strain control test with a dynamic shear rheometer, and at high temperatures, the asphalt may not exhibit a simple thermodynamic behavior. Therefore, time-temperature superposition is no longer applicable so the master curves are generated for only the four lower temperatures.

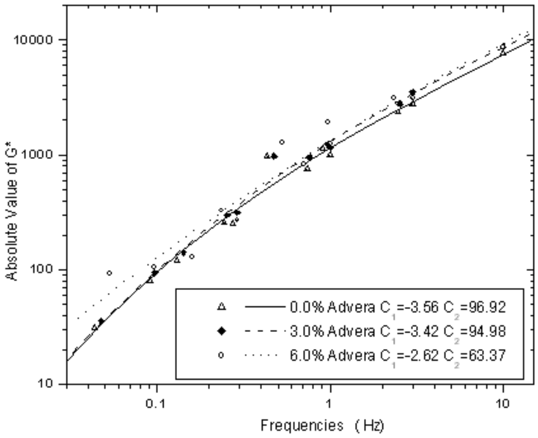

Figure 3. Master curves of the absolute value of the complex modulus for the asphalt binder modified by different proportions of Advera®.

Figure 3 illustrates the master curves for the asphalt binder modified by different proportions of Advera® at 150°F. Although some slight differences are noticeable, the difference in amount of additive used is too minor to notice significant change of the master curves at lower temperatures. Notice that this study is conducted in a certain temperature range and the results cannot be generalized to the full range of frequencies and low temperatures.

Once we obtain the material constants of the asphalt binder and Advera® additive, micromechanics-based models can be used to predict the effective material constants for modified asphalt binders. The self-consistent model is a micromechanical model from which the effective complex modulus can be predicted by the mechanical parameters of asphalt binder and Advera® particles [9]. By assuming the zeolite particles of Advera® are rigid and the viscoelastic binder is nearly incompressible, the formula of the complex modulus is simplified to an explicit equation as

$$\bar{G}^* = \frac{G^*}{1 - 2.5\phi} \tag{2}$$

where G^* denotes the complex modulus of the pure asphalt binder, $\bar{G}^*$ denotes the complex modulus of the modified asphalt binder, and ϕ denotes the volume fraction of the Advera® additive.

Notice that the proportions of additive are based on the mass of the material. The loose bulk density of zeolite is usually 0.8-0.9g/cc, whereas the binder density is about 1.02g/cc. Therefore, the volume fraction of Advera® is approximately 1.2 times the mass proportion. Using Equation (2) and the material parameters of the pure asphalt binder, the effective complex modulus of modified binders can be predicted. Figure 4 suggests that, at a lower temperature of 150°F, the self-consistent model provides a good prediction of the experimental data. However, at a higher temperature of 230°F, a larger deviation between the predicted values and the measured results is observed. Furthermore, it is proven that the self-consistent model overestimates the complex modulus rendering this model invalid at high frequencies [9].

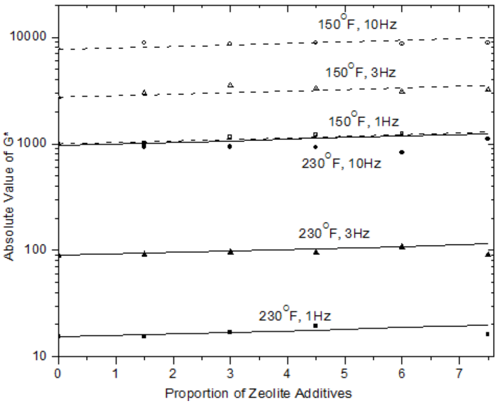

Figure 4. Self-consistent model for complex modulus at two temperatures, 150°F and 230°F.

CONCLUSION

The following conclusions can be obtained through the rheological investigation of asphalt binder modified by the Advera® additive:

– The Advera® additive should be mixed with the binder for at least 20 minutes to allow water to be released in order to improve the workability.

– To effectively form foam within the binder, the lowest temperature for which this WMA technology is intended is 212°F. However, it achieves optimal performance between the temperatures of 230-250°F.

– Vapors produced from the Advera® additive significantly affect the rheological behavior of the modified asphalt binder, particularly at lower frequencies. The effective phase angle does not depict any pattern with increasing temperature.

– The self-consistent model approach provides a satisfactory prediction of the experimental data at lower temperatures.

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