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EFFECT OF AGE HARDENING ON MODULUS OF WARM MIX ASPHALT MIXTURES

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Abstract: Within the past two decades, various warm mix asphalt technologies (WMA) have been introduced with the goal of mix production at lower temperature as compared to the traditional hot mix asphalt (HMA). Effect of the WMA additives on the rheology of binders and mechanical properties of the mixes have been well investigated by several researchers. However, studying the effect of age hardening on the mechanical properties of the compacted WMA has not been adequately researched. This paper presents the results of an experimental study on changes in shear and Young's dynamic modulus of three popular WMA technologies in the United States as well as a control HMA over a period of four years. To this end, small scale cylindrical specimens were prepared and studied in the laboratory. A chemical additive, a wax-based additive, and water foaming process were utilized in preparation of the specimens. The specimens were tested for properties at various time intervals. Modulus was measured right after preparation and laboratory short term conditioning, then at subsequent intervals after production: two years, and four years. The results indicate different trend of hardening with respect to the modulus across the technologies within the range of this study. Impact resonance (IR) tests at three temperatures of 10, 25, and 40°C were conducted on the replicates to non-destructively measure the shear and Young's modulus values of the specimens. IR results indicate that the trend of changes in modulus with time is different among the mixes.

Keywords: Dynamic Modulus, Impact Resonance Test, Warm Mix Asphalt, Age Hardening

1 INTRODUCTION

Warm-mix asphalt (WMA) technologies offer several advantages over the conventional hot-mix asphalt (HMA) due to their lower energy consumption, extended construction season, longer allowable hauling, and lower levels of construction related emissions (Hasan et al. 2017, Tavassoti Kheiry 2015). Resistance of WMA to thermal cracking, fatigue, rutting, and moisture susceptibility has been the focus of several studies in the past, which includes performance evaluation both in the laboratory and in the field (Hasan et al. 2017, Goh and You 2008, Hurley et al. 2009, Bower et al. 2016). It is expected that the use of WMA must not compromise the structural performance of the pavement. WMA technologies affect the mix properties directly through their effects on binder and reduced aging. Therefore, in addition to the aforementioned performance measures, aging related properties of the WMA should be further researched since these technologies are relatively new (Bower et al. 2016). Such studies can provide a better insight of the trend of changes in WMA properties with respect to time. A survey of the literature shows several indications of studies on the effect of WMA additives on binder rheology and aging properties (Bonaquist 2011, D'Angelo et al. 2008, Hurley and Prowell 2005a, 2005b, 2006). Aging of the compacted warm mix specimens has also been assessed in some studies, however, to a lesser extent as compared to the binder aging. In order to simulate the short and long-term aging in the laboratory, standard practices have been developed. A promising method seems to be conditioning the loose mix in forced-draft oven prior to mixture compaction for a given period of time and temperature rather than conditioning the compacted specimen in the oven (Elwardany et al. 2017).

When studying the changes in mechanical properties of asphaltic mixtures over time, it should be noted that part of the hardening may be contributed to mechanisms other than chemical aging. For example, due to the presence of binder phase in asphaltic mixtures, some mechanisms such as steric hardening may be reflected in the properties of specimens stored for a relatively long period of time. In such cases, studying the changes in material properties with respect to temperature can reveal valuable information (Brown et. al 1957).

The use of non-destructive tests (NDTs) to evaluate the asphaltic mixtures in the laboratory has gained more popularity recently. Techniques such as ultrasonic pulse velocity (UPV), impact resonance (IR), resonant column (RC), and acoustic emission (AE) testing are some examples that have been used with asphalt concrete characterization (Boz and Solaimanian 2015, Tavassoti Kheiry et al. 2017, 2018). The growing popularity of these techniques stems from their applicability to a wide range of materials in a relatively simple, economic, fast, and repeatable manner. The non-destructive nature of these tests makes it possible to monitor the trend of changes in the properties of a given specimen as a function of time; therefore, eliminating the concerns regarding the inherent variability among the replicate specimens in destructive tests.

In this paper, a different approach is employed with respect to studying the age hardening of compacted asphalt concrete specimens. The results of the study are presented for a laboratory scale study on three WMA and one control HMA mixes. The specimens were stored in the laboratory environment for a period of four years undergoing identical conditioning. The trend of changes in Young's and shear modulus was studied across the WMA and HMA technologies as a function of time to deliver an estimate of age hardening related properties of these mixes.

2 OBJECTIVES AND METHODOLOGY

While there is a considerable amount of information about performance testing of warm mix asphalt mixes in the laboratory, research data on monitoring the trend of changes in modulus of such mixes with time is limited, and the main reason for pursuing the research presented in this paper. The objective of this research is to assess the age hardening changes of the WMA that have been maintained in the laboratory environment for extended period of time, through monitoring damping ratio, shear, and Young's modulus of elasticity. For this purpose, the same replicate specimens are retested at different intervals using the Impact Resonance (IR) test. The non-destructive nature of IR test makes it possible to monitor the trend of changes in dynamic modulus of the same specimen at a range of temperatures.

3 MATERIALS AND SAMPLE PREPARATION

For the purpose of mix design and sample preparation, one source of aggregate and one source of binder were used for both the WMA and HMA mixtures in this study. The aggregate was 100% crushed dolomite limestone. The target particle size distribution of the aggregate is presented in Table 1. Superpave mix design was followed for a standard 9.5 mm dense graded hot mixed asphalt at 75 gyrations. The binder content was established at 5.4% and was used for all of the mixes investigated in this paper. The asphalt binder was graded as PG 58-22.

Superpave Gyratory Compactor (SGC) was used to prepare cylindrical specimens. The specimens were then trimmed and cored to retrieve small-scale specimens of 60 mm in diameter and 120 mm in height for impact resonance testing. Three replicates were prepared for each of the mixes of interest, resulting in a total of 12 specimens for Impact Resonance (IR) testing. An air void level of 7.5±0.5% was targeted and successfully achieved during the sample preparation.

The warm mix additives, i.e. an organic wax-based additive and a chemical additive, were first blended in the binder using a high shear blender at 135°C prior to preparing the mixtures. The organic and the chemical additives were blended at 1,000 and 500 revolutions per minute (rpm), respectively, as recommended by the manufacturers. Table 2 provides details of sample preparation. It can be seen that the mixing and compaction temperatures, i.e., 147 and 138°C for the conventional HMA mix in this study, are lowered by about 15 to 17°C depending on the WMA technology.

Table 1: Particle size distribution of aggregate used

Sieve and % Passing									
½" (12.5 mm)	3/8" (9.5 mm)	#4	#8	#16	#30	#50	#100	#200	Pan
100	95	74.8	44.5	28.35	19.5	12.25	8.2	5.65	0

Table 2: WMA sample preparation parameters

WMA Technology	Mixing Temperature (°C)	Compaction Temperature (°C)	Application Rate (%)
Organic (Wax) Additive	132	121	1.5
Chemical Additive	132	121	0.4
Water Foaming	138	128	2.0

The asphalt binder (either the neat for HMA, or the modified for WMA) was subsequently mixed with preheated aggregate. The loose mixture was then conditioned in an oven at 121°C for 2 hours. The mixture was then transferred to the SGC molds for compaction to achieve the desired air voids level. Table 3 provides a summary of the average volumetric properties for each of the mixes investigate in this study.

Table 3: Compacted asphalt concrete sample properties

Technology	Average G_{mb}	Average Air Void (%)
Organic (Wax) Additive	2.361	7.5
Chemical Additive	2.357	7.7
Water Foaming	2.353	7.9
HMA	2.360	7.8

4 IMPACT RESONANCE TEST

An approximately free-free boundary condition was maintained for the compacted specimens during the impact resonance testing. To this end, the experimental set-up outlined by ASTM C215 (2014) were adapted and the specimen was placed on a soft sponge rubber mat. Figure 1 shows schematics of the IR test in this study. The specimens were kept in a precise temperature control chamber with the ability to control the temperature by 0.1°C. IR tests were conducted at three temperatures of 10, 25, and 40°C. Each IR test was repeated five times on any of the specimens to mitigate the effect of test variability to the possible extent. Fast Fourier Transform (FFT) algorithm was used to process the time domain data into frequency domain data. Therefore, the resonant frequency and damping ratio of each vibration mode (longitudinal and transverse) were determined for each test at each temperature using the processed frequency domain data.

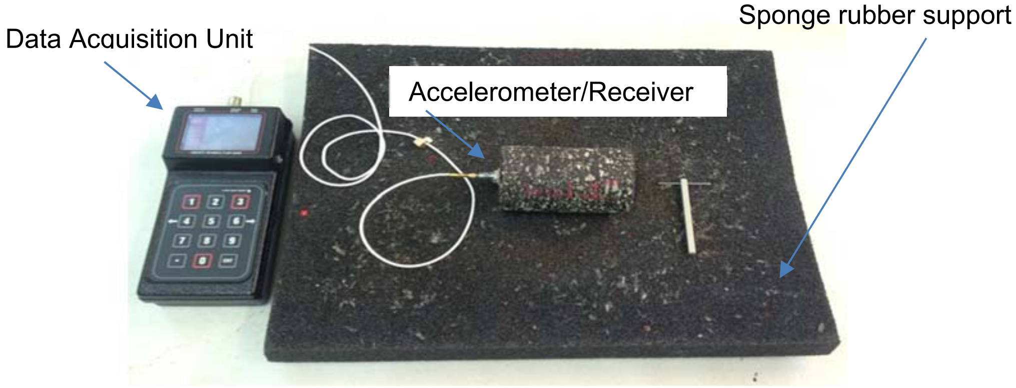

Figure 1: Schematics of impact resonance test of asphalt concrete

Given the fact that the IR test is a truly non-destructive test, same specimens were stored in the laboratory environment for the purpose of performing a second and third round of testing after two and four years. Thus, the specimens were retested using IR at the same temperatures at the time intervals of interest. The measured resonant frequencies at each temperature along with the specimen size, mass, and bulk specific gravity were used to calculate the shear modulus, dynamic modulus and damping ratio.

5 TEST RESULTS AND DISCUSSIONS

5.1 IR Resonance and Repeatability Validation

IR tests were performed in both transverse and longitudinal modes, which makes it possible to calculate shear and Young's modulus and Poisson's ratio for each of the specimens. Upon obtaining the IR responses, Hankel matrix was utilized to verify that the responses follow the second order of motion as expected for IR testing. The Hankel matrix was also employed as a filtering algorithm to eliminate unwanted noise with respect to the second order equation of motion. It was confirmed that the responses did not violate the equation of motion assumptions within the range of temperatures investigated in this study. Therefore, the filtered data was utilized to proceed with further analysis toward modulus calculation. Details of the Hankel matrix analysis is not within the scope of this paper, and can be found elsewhere (Boz et al. 2017a).

On the other hand, one of the crucial aspects in order to study the changes in properties of asphalt concrete specimens over a relatively long period of time would be repeatability of the test results. IR test is believed to be very repeatable, which makes it a reliable tool for the purpose of monitoring the changes in mechanical properties of the specimens over a given period of time. Table 4 provides a summary of the test results obtained for testing one of the HMA replicate specimens, which exhibited the highest level of variability among the HMA replicates at 10°C. Detailed results for every replicate specimen are not presented due to the space limitations, and instead the average results are provided in this paper. Inspecting the raw data obtained at the range of the test temperatures in this study revealed that even for the highest test temperature, i.e. 40°C, the coefficient of variation remained smaller than 10%. The variability was significantly lower at temperatures below 40°C.

Table 4: An example data set showing excellent repeatability of IR at 10°C

Mode of Test	1st test (Hz)	2nd test (Hz)	3rd test (Hz)	4th test (Hz)	5th test (Hz)	Average (Hz)	Std. (Hz)	COV (%)
Longitudinal	12,718	12,150	12,150	12,150	12,264	12,286	246.3	2.0
Transverse	7,608.1	7,721.7	7,608.1	7,721.7	7,267.4	7,585.4	186.6	2.5

5.2 High Frequency Modulus and Master Curve

Generally, the resonant frequency of specimens in IR testing ranges from 2 to 20 kHz, depending on the geometry and density of the asphalt concrete specimens, which is considerably beyond the conventional testing frequencies (Tavassoti-Kheiry et al. 2018). However, the results from IR tests conducted at different temperatures can be used to construct the modulus master curve through the use of established theories and assumptions. An important assumption that would be needed to construct the full spectrum master curve would be the binder shift factor assumption (Boz et al. 2017b). Several studies have shown that the mixture shift factors are not, generally, significantly different than the binder shift factor. Therefore, binder shift factor can be used in combination with IR test results to provide a meaningful modulus master curve over the full spectrum of the frequencies. The binder, therefore, was tested at a range of temperatures and at 16 frequencies (ranging from 0.1 to 100 rad/s). The generalized logistic model (Equation 1), which provides a better fit as compared to the conventional symmetric sigmoid function, was used in this study. Using the polynomial shift factor function (Equation 2) along with Equation 1 and replacing the E* with G* of the binder would result in the binder master curve.

[1] $$Log|E^*| = \delta + \frac{\alpha}{\left[1+\lambda e^{\beta+\gamma[log f_r]}\right]^{1/\lambda}}$$

where |E*| is the dynamic modulus, f_r is the reduced frequency in Hz, and δ, λ, α, β, and γ are treated as fitting parameters that specify the shape of the sigmoid function. The limiting minimum modulus (δ), so-called the low asymptote of the sigmoid function, can be estimated using the improved Hirsch model, which uses the VMA, VFA, G_{sb}, strain levels and G* values. Further details can be found in Boz et al. (2017b).

[2] $$Log[a(T)] = a_1(T)^2 + a_2(T) + a_3$$

where T is the reference temperature for the purpose of master curve construction, a(T) is the shift factor, and a_1, a_2, and a_3 are the fitting parameters.

Upon determination of the shift factor parameters and minimum limiting modulus, the fitting parameters of the sigmoid function in Equation 1 were determined through the numerical optimization at a reference temperature of 20°C. This process was repeated for each of the mixes investigated in this study to construct the associated modulus master curves based on the binder data and IR test results. Figure 2 shows the modulus master curve for the chemical additive-based WMA in this study at a reference temperature of 20°C.

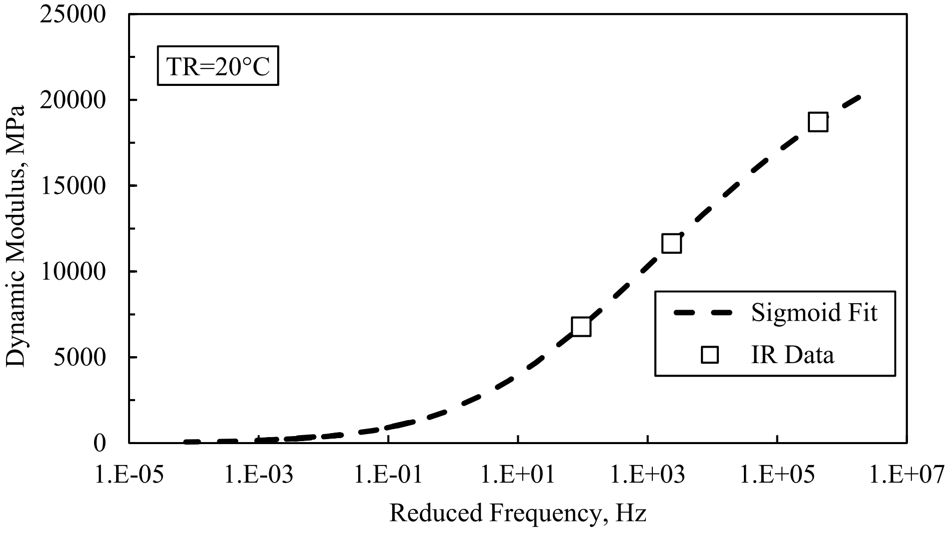

Figure 2: Modulus master curve using IR data for the chemical additive-based WMA

Similar analysis was conducted on the data from the organic additive-based, water foaming and conventional HMA mixes. As mentioned before, although the constructed master curves provide a reasonable estimation of the modulus of the mixes over the full spectrum of frequencies, there are several assumptions that introduce a level of uncertainty when comparing the modulus of different mixes. Regardless of the promising capabilities of the full spectrum master curve constructed from IR data, only the high frequency modulus values, which are the direct measurement through the IR tests, are used for studying the age hardening of different mixing technologies in this paper. Details are presented in the following sections.

5.3 Age Hardening and Modulus Changes

Measuring the modulus at different temperatures and different time intervals (i.e., after sample preparation, after 2-years, and after 4-years of storage in laboratory environment) can provide an estimate of the age-related hardening of the WMA in this study. Figure 3 provides a summary of the dynamic modulus results measured at 10, 25, and 45^{o}C over the period of four years from sample preparation for the specimens prepared through water foaming and organic wax-based additive. It can be seen that the hardening has a steeper rate for the first two years from the time of sample preparation compared to the rate of hardening for the last two years. The trend of changes, however, is different among the four mixes. The fact that the storage conditions were identical for all the mixes indicates that such difference can be contributed to the inherent differences in age-related hardening of the mixes. For example, the WMA specimens prepared using water foaming exhibit the highest age hardening as compared to the rest of the mixes. It should be noted that by comparing the initial modulus values among the four mixes in this study it can be recognized that water foaming provided a mix that was initially softer as compared to the other investigated technologies. This might be associated with a lower level of aging during the mix production and is found to be consistent with the findings of the previous NCHRP studies (NCHRP 843 2017). However, the focus of this paper is studying the trend of changes in the stiffness of these four mixes as a function of time, which is shown to be different than the initial stiffness of mixes. In spite of the magnitudes, similar trends were observed for both the shear modulus and Young's modulus of elasticity.

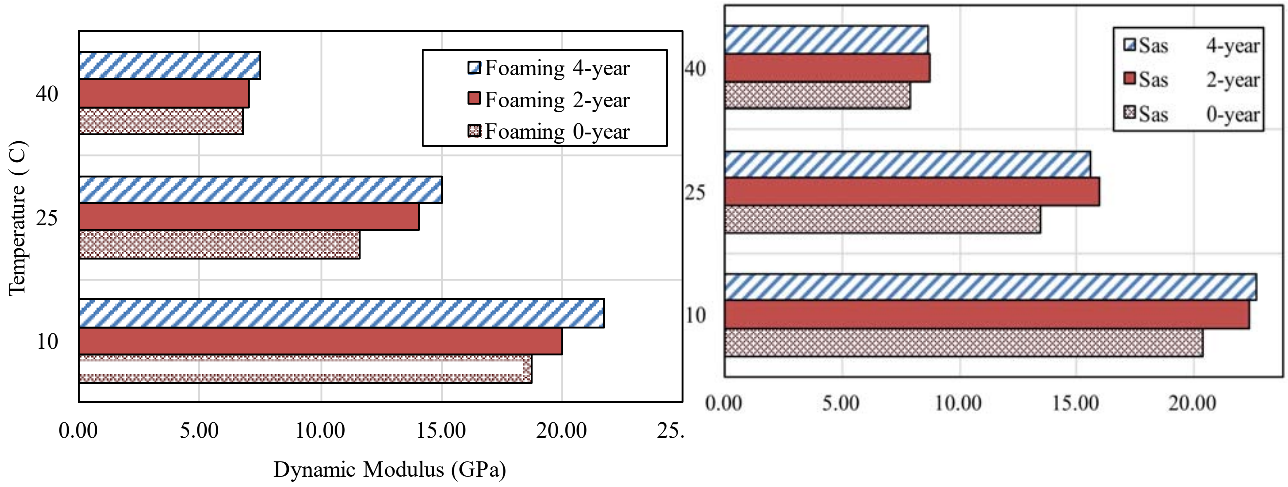

Figure 3: Changes in Young's modulus of water foaming (left) and organic wax-based (right) WMA specimens as a function of time at 10, 25, and 40^{o}C

Figure 4 illustrates the changes in shear modulus for the chemical additive WMA specimens and the control HMA mix. With respect to the percent changes in modulus as a function of time, it can be seen that water foaming WMA specimens exhibited the largest age hardening over four years (i.e., rate of 31%), followed by the organic wax-based specimens (i.e., rate of 26.9%). On the other hand, HMA and the chemical additive based WMA specimens showed maximum rates of 15.4 and 16.3%, respectively.

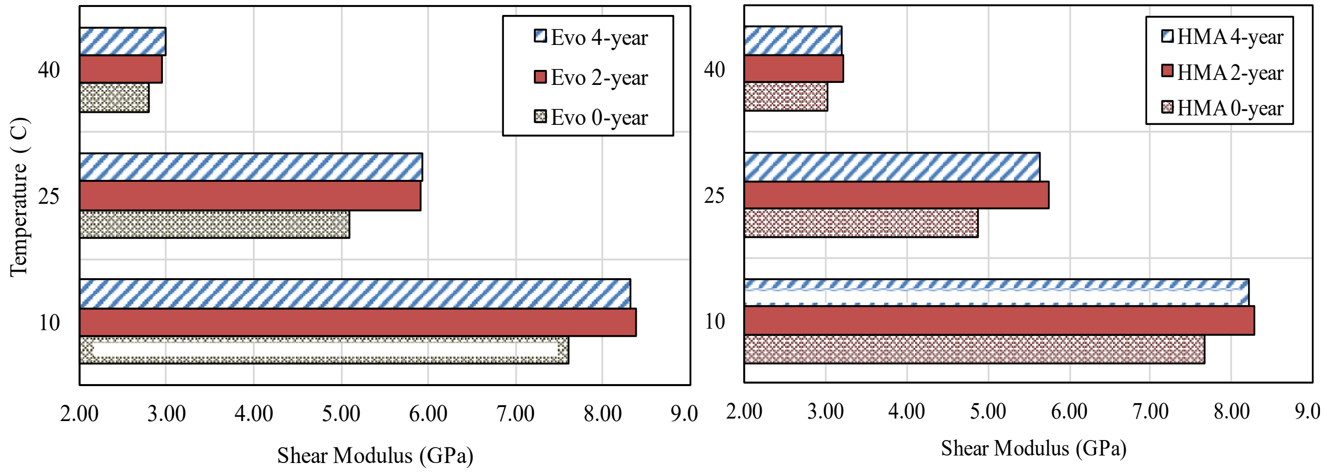

Figure 4: Changes in shear modulus of the chemical-additive based WMA (left) and HMA (right) specimens versus time at 10, 25, and 40°C

6 SUMMARY AND CONCLUSIONS

Four series of replicate specimens, consisting of three sets of warm-mix asphalt (WMA) and one set of control hot mix asphalt (HMA) mixtures, were prepared in the laboratory. The specimens were tested using the impact resonance (IR) tester at different time intervals over four years and the shear and Young's modulus of elasticity values were measured at 10, 25, and 40°C each time. The specimens were first tested within a week after sample preparation and were stored afterward for two years prior to retesting. The final set of testing was conducted when the specimens were four years old. The same specimens were used and tested at the same temperatures. The following conclusions can be drawn based on the results of this study:

It was shown that for a given gradation, binder, and mix design, the initial modulus of elasticity was consistently larger for the WMA prepared by the wax-based additive followed by the mix prepared with the chemical additive. The WMA prepared through water foaming technology as well as the HMA mix exhibited statistically similar stiffness, while foaming showed slightly softer response.

The trend of changes associated with age hardening of the mixes was different over the four-year study period. Foaming technology exhibited the highest rate of changes as compared to the other mixes in this research. HMA specimens, overall, exhibited the least changes due to the age-related hardening as compared to the rest of the mixes in this study.

Except for the WMA specimens prepared using water foaming, the rate of changes in modulus values can be considered very slow after 2 years. This conclusion is drawn based on the fact that no significant difference was found between the modulus of 2-year old specimens versus that of 4-year old specimens.

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