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Experimental study on rheological characteristics and performance of high modulus asphalt binder with different modifiers

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HIGHLIGHTS

- Evaluate rheological, rutting, and fatigue properties of high modulus asphalt binders.
- Both rock asphalt and polyolefin significantly improve rutting resistance of asphalt binder.
- Asphalt binder modified by rock asphalt shows better fatigue resistance than that by polyolefin.

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ABSTRACT

The fundamental material for production of high-modulus asphalt (HMAC) is high modulus asphalt binder (HMAB), which is normally manufactured from hard-grade asphalt, rock asphalt modification, and polyolefin modification. This paper investigated rheological properties and performance of HMAB as compared to Styrene-Butadiene-Styrene (SBS) modified binder and neat binder using comprehensive laboratory performance tests. Specifically, the performance of HMAB modified with two different high modulus additives, rock asphalt (RA) and polyolefin (PR), were compared. The performance indicators include linear viscoelasticity characterized by temperature sweep and frequency sweep tests, rutting resistance by multiple-stress creep recovery (MSCR) test, and fatigue resistance by linear amplitude sweep (LAS) test. The effects of high-modulus modifier on master curve of dynamic shear modulus of HMAB were found identical. The temperature dependencies of asphalt binder were found to be significantly dependent on the material source of neat binder. However, the rutting resistance of HMAB modified by rock asphalt and polyolefin is better than that of SBS modified binder and neat binder. The polyolefin modified HMAB showed better rutting resistance than rock asphalt modified HMAB; while the comparison results was opposite for fatigue resistance. The simplified viscoelastic continuum damage (S-VECD) theory was employed to interpret the LAS test results for fatigue life prediction of asphalt binder. The SBS binder showed the best fatigue performance followed by HMAB and neat binder.

1. Introduction

In the early 1980s, high modulus asphalt concrete (HMAC) was originated in France as a solution to reduce the thickness of base course in the pavement structure. Later, HMAC was used for the surface layer to improve rutting resistance in heavy traffic conditions [1]. The observations of improved performance have resulted in the wide application of HMAC in different countries all over the world [1–4].

The permanent deformation resistance is the main advantage brought by the application of HMAC. The study presented by Capitão verified the improved rutting resistance of HMAC using laboratory wheel tracking tests on the extracted slabs from trial pavement sections [5]. Zou et al. found that the average rut depth and surface deflection observed in the test sections using HMAC were much smaller than those using the Styrene-Butadiene-Styrene (SBS) modified asphalt mixture after one year of service [6]. Although it is demonstrated that HMAC can improve rutting resistance, the concern is the impact of HMAC on cracking potential of asphalt pavements. For thermal cracking resistance, the negative effect of HMAC material has been observed due to the higher stiffness of HMAC [7–9]. This negative effect became worse with

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the further addition of reclaimed asphalt pavement (RAP) materials into HMAC [3,10,11]. On the other hand, it was found that the stiffer HMACs normally presented the better fatigue resistance at intermediate temperatures than asphalt mixtures made with neat binders [1,3,4,8]. However, adding the aged and stiffer RAP materials into HMAC reduced fatigue life [3,10,11]. Researchers have attempted to increase fatigue cracking resistance of HMAC by adding variable additives such as crumb rubber, acrylic fibers, and WMA additives [12,13].

The key material for production of HMAC is high modulus asphalt binder (HMAB). Normally HMAB can be obtained by three different approaches: hard-grade asphalt, rock asphalt modification, and polyolefin modification. The modification mechanisms of three approaches are different. Hard-grade asphalt binder and rock asphalt modified binder reduce temperature sensitivity and self-healing ability as compared to the conventional asphalt binder [6]. On the other hand, polyolefin droplets tend to form a network within asphalt binder that is similar to the polymer modification process [8]. Literature shows that the hard-grade paving asphalt is mainly used in European countries for construction of base course layers; while HMAB modified with rock asphalt or polyolefin are mainly used in China to produce HMAC for wearing course in pavement sections with high traffic volume [1,3,6,8]. However, few studies have focused on the study of HMAB considering different failure mechanisms of asphalt binder.

The main objective of this paper is to evaluate rheological properties and performance of HMAB obtained from different modification approaches using comprehensive laboratory performance tests. The performance indicators include linear viscoelasticity characterized by temperature sweep and frequency sweep tests, rutting resistance by multiple stress creep recovery (MSCR) test, and fatigue resistance by linear amplitude sweep (LAS) test. The testing results provide material properties and performance of HMAB that can be used for selection of asphalt binder for HMAC based on the specific failure mechanism.

2. Materials and testing methods

2.1. Materials

In this study, three neat asphalt binders were tested with and without modification. The neat binders were labeled based on their penetration grades and material sources. Three HMABs were obtained from either rock asphalt (RA) or polyolefin (PR) modification approach. The commonly used polymer modified asphalt (styrene-butadiene styrene [SBS]) that is produced from the neat binder of 70# (BJ) was included for comparison analysis. Totally seven different types of asphalt binder, which were directly obtained from local asphalt suppliers, were tested and the test results were compared. A summary of binder types is presented in Table 1, in which the acronyms of IR and BJ represent Iran and Beijing, respectively, and the terms of 70# and 50# indicate penetration grades of neat binders.

2.2. Testing methods

All asphalt binder tests were conducted using Anton Paar MCR 302 dynamic shear rheometer (DSR). The 25-mm parallel plate geometry was employed for testing of asphalt binders at high temperatures (46–82 °C), whereas at intermediate temperatures (5–35 °C) testing was completed with the 8-mm parallel plate geometry. The binder performance tests included the temperature sweep and frequency sweep tests for linear viscoelasticity, and the damage-based rutting and fatigue tests. All binder materials were subjected to short-term aging using the Rolling Thin-Film Oven (RTFO) procedure before performance tests [14]. The testing procedures and data analysis methods are summarized below.

2.2.1. Temperature sweep test

The temperature sweep tests were conducted on the original (unaged) binder materials to determine the high-temperature performance grades (PG) of asphalt binder [15]. The test temperature started at 58 °C and increased to 82 °C in 6 °C intervals. The applied strain level was 12% and testing frequency was 10 rad/s, following the recommendations in AASHTO T 315-06. The rutting parameter $G^*/\sin\delta$ was recorded at each temperature during the tests, which was the ratio of dynamic shear modulus, $|G^*|$, to the sine of phase angle, δ.

2.2.2. Multiple stress creep recovery (MSCR) test

The MSCR test was developed to provide a more accurate approach for evaluating permanent deformation resistance of asphalt binder [15,16]. Using the creep-recovery loading mode of DSR, a one-second creep load was applied to the RTFO-aged asphalt binder sample. After the load was removed, the sample was allowed to recover for 9 s. The test began at a relatively low stress of 0.1 kPa for 10 creep-recovery cycles. Then the stress level was increased to 3.2 kPa and the creep-recovery was repeated for another 10 cycles. The performance indicators consist of the recovery percent (R) and the non-recoverable compliance (J_{nr}), which can be calculated using Eqs. (1) and (2), respectively.

$$R = \frac{\gamma_p - \gamma_n}{\gamma_p - \gamma_0} \tag{1}$$

$$J_{nr} = \frac{\gamma_n - \gamma_0}{\tau} \tag{2}$$

where γ_0 is the shear strain at the beginning of cycle; γ_p is the peak strain after one-second creep duration; γ_n is the non-recoverable strain after nine-second recovery; and τ is the creep stress.

2.2.3. Frequency sweep test

The linear viscoelastic properties of asphalt binders at the intermediate temperature were obtained from frequency sweep tests. The loading frequencies spanned from 0.1 rad/s to 100 rad/s. The fixed strain amplitude of 1% following SHRP specification was used for testing temperatures of 5 °C, 20 °C, and 35 °C.

The Christenson–Anderson–Marasteanu (CAM) model was employed to fit dynamic shear modulus ($|G^*|$) master curves to provide the undamaged material responses [17]. The fitting function of CAM model is given in Eqs. (3) and (4).

$$|G^*| = \frac{|G^*|_g}{\left[1 + (f_c/f')^k\right]^{m/k}} \tag{3}$$

$$f' = \phi_T \times f \tag{4}$$

where, $|G^*|_g$ is the glassy dynamic shear modulus of asphalt binder and 10^9 Pa was selected in this study; f_c, k, and m are the fitting parameters of the $|G^*|$ master curve; Φ_T is the time-temperature shift factor; and f is the actual testing frequency.

The time–temperature shift factor was fitted with the Williams–Landel–Ferry (WLF) nonlinear function as shown in Eq. (5) [18]. In order to construct a smooth master curve, an optimization solution was obtained using the Solver function in Microsoft Excel to minimize the error between predicted and measured shear modulus.

$$\mathrm{Log}\,\phi_T = -\frac{D_1 \cdot (T - T_0)}{D_2 + (T - T_0)} \tag{5}$$

where, T_0 and T represent the reference temperature and actual testing temperature, respectively; and D_1, D_2 are the fitting parameters.

Table 1
Summary of tested asphalt binder types.

Binder Types	Binder ID	Neat Binder Source	Additives	PG Grade
Neat Binder	70#(IR)	Iran	/	PG 58-22
	50#(IR)	Iran	/	PG 70-16
	70#(BJ)	China	/	PG 70-16
High Modulus Asphalt Binder	70#(IR)+RA	Iran	0.3% RA	/
	50#(IR)+RA	Iran	0.3% RA	/
	50#(IR)+PR	Iran	0.3% PR	/
SBS Modified Binder	SBS (70#(BJ))	China	4.5% SBS	/