Cold Regions Science and Technology 85 (2013) 250–255

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Improvement of hot mix asphalt performance in cold regions by organic-based synthetic compounds

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ARTICLE INFO

Article history:
Received 23 May 2012
Accepted 26 September 2012

Keywords:
Asphalt
Organic-based magnesium compound
Organic-based manganese compound
Organic-based zinc compound
Stability
Stripping

ABSTRACT

In this study, newly synthesized additive materials, organic-based magnesium compound (OBMAGC), organic-based manganese compound (OBMANC) and organic-based zinc compound (OBZC), were used as asphalt modifier. 50/70 penetration grade asphalt was separately modified with these additives at different concentrations ranging from 1% (w/w) to 10% (w/w). The effects of modification on the asphalt and hot mix asphalt (HMA) mixtures properties were detected through conventional tests (softening point test, ductility test, Marshall stability test, Nicholson stripping test, and indirect tension test) and Superpave methods (rotational viscosity, bending beam rheometer (BBR), and dynamic shear rheometer (DSR)). The proper concentrations for OBMAGC, OBMANC and OBZC to use in the modification of asphalt were determined as 3% (w/w) based on the rotational viscosity test results. Low temperature performance of the asphalt, as well as, stability and stripping resistance of the HMA mixtures were found to be improved by each of the additive.

1. Introduction

Asphalt is waterproof, ductile, adhesive, cohesive material and widely used as binding agent in HMA mixtures for constructing roadway pavements. It exhibits varying characteristic properties depending on climatic conditions. Asphalt hardens when the temperature decreases and becomes softer by increasing temperature. Failures such as crackings and permanent deformations can be more severely occurred in roadways due to asphalt nature. Moisture is another problem and causes loss of adhesive bond at the asphalt–aggregate interface. These failures reduce roadway performance and should be prevented as much as possible in order to enhance roadway transportation quality. Therefore, asphalt and HMA mixture properties are being studied to improve by modification with several modifiers.

Modifiers are added to asphalt and HMA mixtures to alter their properties. Styrene–butadiene–styrene (SBS) is a well-known asphalt modifier. It increases softening point and viscosity of asphalt, as well as, rutting resistance, Marshall stability and aging resistance of HMA mixtures (Airey, 2003; Al-Hadidy and Tan, 2009; Özen, 2011; Sengoz and Isikyakar, 2008). Ethylene–vinyl–acetate (EVA) and rubber also make asphalt harder (stiffer) by increasing softening point and viscosity (Airey, 2002; Haddadi et al., 2008; Navarro et al., 2004; Yu et al., 2011). Harder asphalts are more resistant to rutting at high temperatures. Therefore, these kinds of modifiers are recommended to use in hot climates (Al-Hadidy and Tan, 2009; Çubuk et al., 2009). Moreover, several researches about modification of asphalt with fiber, polyethylene, polypropylene are noteworthy in literature. Newly synthesized additives, triethylene glycol based synthetic polyboron and organic-based zinc phosphate compound, were reported to be favorable for hot and cold climates, respectively (Arslan et al., 2011, 2012a). Diatomite was used as modifier in HMA mixtures and reported to improve low temperature performance (Tan et al., 2012). Besides improved properties, undesirable outcomes can be obtained from modification of asphalt. Asphalt gets harder especially with polymer modifiers which require increasing of asphalt plant temperature in order to ensure mixing-compaction temperature requirements of HMA mixtures. Related with this negation, studies about asphalt modification have been carried out with modifiers known as warm mix asphalt (WMA) additives in recent years. WMA additives are aimed to use in order to decrease energy consumption and emissions while preparing HMA mixtures by reducing asphalt plant temperature. They can be used either singly or together with another modifier (Akisetty et al., 2009; Edwards et al., 2010; Merusi and Giuliani, 2011; Shang and Wang, 2011). Researches about asphalt modifiers are still in progress and new additive materials are studied in order to improve asphalt properties.

The purpose of this study was to investigate the effects of novel additive materials, organic-based magnesium compound (OBMAGC), organic-based manganese compound (OBMANC) and organic-based zinc compound (OBZC), on the asphalt and HMA mixture properties through conventional tests (softening point test, ductility test, Marshall stability test, Nicholson stripping test, and indirect tension test) and Superpave methods (rotational viscosity, bending beam rheometer (BBR), and dynamic shear rheometer (DSR)).

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http://dx.doi.org/10.1016/j.coldregions.2012.09.014

2. Materials and methodology

2.1. Asphalt and aggregate

50/70 penetration grade asphalt (base asphalt) was supplied from Turkish Petroleum Refinery Corporation and used throughout the study. The physical properties of this base asphalt were given in Table 1.

HMA mixtures were prepared with 100% crushed basalt aggregate. The basalt aggregate was sourced from Gençosman quarry of Sakarya/Turkey. The physical and chemical properties of the aggregate were given in Table 2.

The aggregates were well-graded as shown in Fig. 1 to prepare Marshall samples. This gradation is the middle of the Type II gradation limits which is used for wearing courses in Turkey.

2.2. Preparation of additives and modified asphalts

Synthetic OBMAGC, OBMANC and OBZC were separately used as additive material in order to modify the base asphalt. Each additive material was synthesized at laboratory by using a spherical 3-necked flask reactor, a reflux condenser and a heating mantle with magnetic stirrer (Fig. 2). Different metal-oxides (MgO for OBMAGC, MnO_2 for OBMANC and ZnO for OBZC) were reacted with sylvic acid in a catalyzed oily media at 150 °C in order to produce the additives. Resin and H_2SO_4 were used as sylvic acid source and catalyst. The metal-oxide to resin to oil mass ratio for OBMAGC, OBMANC and OBZC was 1:7.5:17, 1:2.9:6.5, and 1:2.6:6, respectively. Ethanol was added in order to ensure the solubility of each mixture. The purities of all metal-oxides were ≥99% and bought from Merck.

Each additive was added to the base asphalt at %1, %2, %3, %5, %10 by mass. Firstly, the base asphalt was heated to 140 °C in an oven. Then, the additive (OBMAGC, OBMANC or OBZC) was incorporated to the base asphalt at the given concentrations and mixed for 10 min with a mechanical mixer rotating at 1300 rpm in an oil bath which was preset to 140 °C.

2.3. Methodology

The effects of each additive material on the asphalt and the HMA mixture properties were detected through conventional and Superpave test methods. Rotational viscosity tests were carried out between 90 °C and 160 °C with Brookfield DV III Rheometer according to ASTM D 4402 in order to determine the effects of the additives on the flow characteristics of the asphalt. A cylindrical spindle (no. 29) was immersed in asphalt sample and rotated at a constant speed at testing temperature. The torque required for the rotation of the spindle was measured and converted to viscosity in Pa·s by the rheometer. The softening point (R&B) and ductility of the base and modified asphalt samples were measured in accordance with ASTM D 36 and ASTM D 113, respectively. Softening point was measured with EL46-4502 model ring and ball apparatus. Two horizontal disks of asphalt with a steel ball centered were heated at a rate of 5 °C/min in a water bath. The softening point was reported as the mean of the temperatures at which the two disks soften enough to allow each sample to touch the base plate. Ductility tests were performed at 15 °C. Test samples were stretched at a rate of 5 cm/min. The distance that the sample elongated without breaking was defined as ductility. Creep stiffness (S) and creep ratio (m) properties of the asphalt samples were examined through BBR tests (AASHTO T313) at −12 °C and −18 °C using Thermoelectric BBR Instrument (Cannon). BBR test can be used to define low temperature performance of asphalt. 125 × 12.5 × 6.25 mm asphalt beam was immersed in a liquid bath and kept at test temperature for 60 min. A load of 100 g (980 mN) was applied to the center of the simply supported asphalt beam. The deflections were measured at 8 s, 15 s, 30 s, 60 s, 120 s, 240 s. S was calculated as follows:

$$S_{(t)} = PL^3 / \left(4bh^3\delta_{(t)}\right) \tag{1}$$

where; $S_{(t)}$ is the stiffness at a specific time, P is the applied load, L is the distance between beam supports, b is the beam width, h is the beam thickness and $\delta_{(t)}$ is the deflection at a specific time. The measurements at 60 s are used for S and m.

Table 1
Physical properties of the base asphalt.

Property	Value	Standard
Specific gravity, 25 °C	1.02	ASTM D-70
Viscosity, 130 °C, (Pa·s)	0.316	ASTM D-4402
140 °C, (Pa·s)	0.193	ASTM D-4402
Softening point, (°C)	48.4	ASTM D-36
Ductility, 15 °C (cm)	63.5	ASTM D-113

Table 2
Physical and chemical properties of the aggregate.

Property	Value
Specific gravity (coarse aggregate); bulk	2.814
Apparent	2.849
Specific gravity (fine aggregate); bulk	2.821
Apparent	2.855
Specific gravity (filler); bulk	–
Apparent	2.820
Chemical content (%); SiO_2	1.60
Al_2O_3	0.85
Fe_2O_3	0.57
MnO	0.03
MgO	21.50
CaO	29.67
Na_2O	0.10
K_2O	0.25
CO_2	45.45
Cl	0.006
SO_4	0.002

DSR tests were performed at 58 °C, 64 °C, 70 °C by means of Gemini Rheometer (Bohlin Instrument) to determine complex shear modulus (G^*) and phase angle (δ) of the asphalt samples with respect to AASHTO T315. Asphalt sample was sandwiched between two circular plates. The lower plate is fixed. A shearing force was applied by oscillating the upper plate at 10 rad/s (1.59 Hz) across the sample. The maximum applied stress, the resulting maximum strain and the time lag between them were measured by rheometer. G^* and δ were then calculated by DSR software. Marshall Tests were applied according to ASTM D 1559. Three samples were prepared for each asphalt type and the average results were reported. All Marshall Test samples (samples with and without modification) were identically fabricated using 1100 g aggregate and compacted by applying 75 blows/side with Marshall compactor device (EL45-6600) in a Marshall mold having 4 in. diameter. Samples were immersed in water bath at 60 °C for 30 min and then subjected to the Marshall test. The voids and density values of each sample were calculated prior to the test. Nicholson stripping tests were performed on the loose mixtures which were prepared with coarse basalt aggregate in conformity with ASTM D 1664. The coarse basalt aggregate was coated with base and modified asphalts separately at 110 °C. The loose mixtures were immersed in distilled water at 60 °C for 24 h. The stripping resistance of each mixture was visually determined as the non-stripped aggregate surface area to the total aggregate surface area which gives an indication about adhesion force at the asphalt–aggregate interface. Cylindrical samples of the diameter 150 mm were compacted with gyratory compactor and submitted for the Indirect Tension Tests at 0 °C in order to evaluate the asphalt mixtures in terms of low temperature performance. Indirect Tension Tests were