Construction and Building Materials 149 (2017) 724–732

Contents lists available at ScienceDirect

Construction and Building Materials

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

Investigation on rheological performance of sulphur modified bitumen (SMB) binders

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HIGHLIGHTS

- Rheological and aging behavior of sulphur modified bitumen were investigated.
- Dosage of sulphur, mixing time and temperature influenced performance of bitumen.
- Rutting, fatigue and aging resistance of bitumen is greatly influenced by sulphur.
- Sulphur by 2% wt. was found to be suitable for homogeneous modified bitumen matrix.

ARTICLE INFO

Article history:
Received 24 March 2017
Received in revised form 20 May 2017
Accepted 23 May 2017

Keywords:
Sulphur
Viscosity
Rutting
Fatigue
Aging
Master curve
MSCR

ABSTRACT

In order to enhance the properties of base bitumen so as to improve the performance of bituminous mixture, it has been a common practice to modify the bitumen by adding some modifiers. Sulphur has been reported to be an effective extender for conventional bitumen. This study was attempted to develop a modified binder in the laboratory using VG-30 bitumen with sulphur (S) and study the effects of 'S' on the viscosity, rheological, penetration index and storage stability with effects of short and long term aging. The rheological study includes rutting, fatigue, master curve and Multiple Stress Creep Recovery (MSCR) test using Dynamic Shear Rheometer (DSR). It is observed that the modification of VG-30 with 2% of 'S' by weight at 140 °C temperature for about 60 min, resulted in homogeneous modified bitumen binder. The Superpave rutting parameter ($G^*/\sin\delta$) and MSCR test results showed that, SMB-2S (VG-30 + 2% S) and SMB-3S (VG-30 + 3% S) binder exhibited better rut resistance performance, especially at high temperature. However, SMB-2S showed relatively lower value of Superpave fatigue factor and aging index value than SMB-3S, implying superior performance in fatigue and aging resistance behavior, respectively. Storage stability test results showed that modification with 2% S possessed better compatibility in bitumen matrix. Thus, it can be stated that the SMB-2S showed superior rheological and storage stability properties that can satisfy the requirements for resisting the rutting and fatigue cracking.

1. Introduction

Bitumen is generally used as a binder in construction of highway flexible pavements due to its viscoelastic and thermoplastic properties. Though aggregate skeleton structure contributes overall rutting performance of bitumen mixture, bitumen also plays an important role in strength and resistance to rutting of the mixture. Bitumen normally becomes brittle at low temperature, and even at an average temperature causes load associated fatigue cracking of the bituminous surface. Similarly, at relatively high temperature in summer, it becomes soft, causing rutting failure of the bituminous layer. Generally these two types of failures are very common in India particularly in pavements subjected to high traffic volume with adverse environmental conditions. With the quality and grading of aggregates remaining the same, these two failures can be attributed to the physico-chemical characteristics of the bitumen used, that may change with temperature.

Oxidative aging and heavy dynamic loading under adverse environmental conditions are being considered as some of the major issues influencing the performance of bitumen binder and indirectly to overall performance of the mixture. Aging of bituminous binder is a phenomenon which is nowadays addressed before selecting a particular binder for a bituminous mix as this effect may cause serious pavement related failures before the expected

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.198
0950-0618/

design life. Progressive aging of bitumen in the field degrades the intermolecular structure of the bitumen matrix, thus overall performance of binder gets affected [1,2]. Therefore, in order to enhance the performance of base bitumen so as to improve the performance of bituminous mixture, it has been a common practice to modify the base bitumen by effectively using some modifiers such as various polymers, elastomers, crumb rubber, warm mix additives, sulphur, etc. Among the different types of additives used with base bitumen sulphur (in combination with other polymer additives) has been reported to be an effective cross linking agent to improve the basic physical and some performance properties [3–7].

The storage-stable SBS/sulphur-modified asphalts showed improvement in viscous behavior compared to SBS-modified asphalts and this led to an improved low-temperature creep performance after aging [5]. The dynamic mechanical analysis illustrates that the oxidative aging has a great impact on the rheological behavior of the styrene-butadiene rubber (SBR) and SBR/ sulphur modified asphalts [6]. The rheological behavior of styrene-butadienestyrene (SBS), with or without sulphur, is fairly well reproduced by blends of SBS-modified asphalts with relatively small amounts of sulphur, suggesting that sulphur facilitates the formation of three-dimensional structures which effectively reinforces bitumen [7]. Bitumen modification with sulphur results in improved the physical properties and the aging criteria of the sulphur modified bitumen are within its permissible limits [8]. The incorporation of the modified sulphur pellets, up to 40 per cent by mass of the total binder volume showed less thermal and loading-time susceptibility than the base asphalt mixture [9]. Sulphur modified asphalt mixtures can be tailored to provide pavement structural enhancement through improved material properties as well as energy savings, i.e. bitumen saving, energy savings during production, and possibly pavement thickness reduction or longer pavement life [10]. Though various polymer modifiers have been enormously familiar, issues related to high cost involved, phase separation and thermal instability motivated the authors to explore new materials or other performance enhancer to improve the performance of bituminous binder. From the above brief review of literature it was observed that the rheological characteristics of sulphur modified bitumen needs to be studied under both aging and unaging conditions so that the viscoelastic parameters related to the binder are understood, which is the motivation for the present research work.

For better development of a modified bitumen binder, it is most essential to carry out advanced characterization using reliable test protocols. Bituminous binder can be characterized in a more effective way using rheological approach as per strategic highway research program (SHRP) [11]. Thus, in this study the rheological characteristics were investigated using Superpave rutting and fatigue factor, master curve and Multiple Stress Creep Recovery (MSCR). The MSCR test helps in estimating stress sensitivity behavior of binder subjected to different stress levels, which is not possible under the test condition (i.e. under linear viscoelastic range) stipulated for calculating Superpave rutting factor parameter [12]. Furthermore, master curve helps to understand the behavior of a bitumen binder over a wide range of loading frequencies at different temperature conditions [13]. Thus, the rheological investigation of bitumen binders was carried out in this study using Dynamic Shear Rheometer (DSR). It is expected that the present study would help in developing better understanding on characterization and effects of sulphur on base bitumen binder.

1.1. Objectives of the study

This work involves several trials for preparation of sulphur modified binder. Finally, the optimum dosage of sulphur with appropriate mixing temperature and mixing time were figured out by considering the rheological responses of bitumen binders. The main objectives are:

- To evaluate well-defined mixing time and temperature conditions for preparation of sulphur modified bitumen binder with ideal sulphur content.
- To study the influence of sulphur on rheological behavior of bitumen based on rutting, fatigue, MSCR and phase separation.
- To study the influence of aging on rheological responses of sulphur modified bitumen.

2. Experimental program

2.1. Materials

In this research study a control grade of bitumen (VG-30) was selected which is commonly used for most of Indian roads. The basic physical characteristics of VG-30 are given in Table 1. It has been decided to use sulphur (locally available in powder form) for modification of VG -30. The physical properties of sulphur used are given in Table 2.

2.2. Preparation of modified binder

1 kg of VG-30 binder was heated separately at 150 ± 5 °C for 1 hr so as to attain a particular fluid state, taken for the preparation of each binder sample. Prior to heating of bitumen, sulphur (S) was oven dried to ensure moisture free surface. After that, hot VG-30 binder and S were stirred slowly using a glass rod to avoid preliminary non-uniform dispersion of S. Vigorous stirring of VG-30 and S was carried using a mechanical mixer at a speed of about 3000 R.P.M for 15 min. The entire experimental plan consisted of four steps to meet the objectives as stated in Section 1.1. Fig. 1 represents the flow chart for experimental program for this study.

2.3. Aging of binder

Short term aging (STA) and long term aging (LTA) of both modified and unmodified VG-30 binders were conducted using Rolling thin film oven test (RTFOT) [14] and Pressure aging vessel (PAV) [15] respectively at standard conditions. The STA is being used to simulate field mixing and compaction stage of flexible pavement surface course materials. The LTA simulates the field condition for 5–7 years of service life in a road. In this study, STA was done in RTFO conditioned at 163 °C for 85 min, while LTA was done using PAV at 100 °C for 20 h with air blow of 2.1 MPa.

2.4. Viscosity test

The viscosity of bitumen binders can be significantly affected by variables such as molecular structure, molecular weight, temperature, shear rate and time of shearing [16,17]. The mixing and compaction temperatures of a bituminous mix depend on high temperature viscosity of bituminous binders. The viscosity of VG-30 and SMB was measured using a rotational Brookfield viscometer at various temperatures as per ASTM D-4402 [18]. The viscosity of a Newtonian fluid remains constant across different shear rate, but Non-Newtonian fluid is dependent on the change in applied shear rate. Thus, to have proper understanding on the Newtonian/Non-Newtonian behavior VG-30 and SMB binder, viscosity measurements were made at different shear rates. The effect of shear rate on the viscosity of modified binders were studied at different shear rate in a range of 0.03–68 s^{-1} at temperatures of 100, 120, 135, 140, 150, 160 and 180 °C. While operating the Brookfield viscometer efforts were made to achieve a torque of about at least 50% to minimize the error in viscosity measurement.

2.5. Rheological characterization

Rheological characterization of bitumen binder is used to understand the performance behavior subjected to dynamic loading condition at different temperatures. Rheological testing methods and instruments developed during the SHRP research contribute a better understanding of the time and temperature dependent viscoelastic behavior of the bitumen binder [19]. The rheological performance of bitumen binder helps to evaluate resistance potential against rutting and fatigue failure, using viscoelastic approach. Rheological testing, using a Dynamic Shear Rheometer (DSR), represents the viscoelastic behavior of asphalt binder subjected to different loading and temperatures [11,19]. A stress controlled DSR was used to conduct rheological characterization of bitumen binder [20]. Parallel plates of 8 mm dia with gap of 2.0 mm for fatigue characterization and 25 mm diameter with 1.0 mm gap for rutting characterization were used.