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Study of flow behavior for predicting mixing temperature of bitumen

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HIGHLIGHTS

- Modified binders behaves as a shear thinning fluid even at higher temperatures.
- Carreau–Yasuda model can be used to model the viscosity master curves of bitumen.
- Zero shear viscosity can be modeled using a simple exponential law.
- A new method has been presented to predict the viscosity of bitumen.
- The study suggests lower mixing temperatures for modified binders.

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ABSTRACT

Study of flow behavior is necessary for selection of proper grade and viscoelastic characterization of different asphalt binders. Shear thinning behavior of modified binders demands a critical study of viscosity at a wide range of temperatures and shear rates. Such analysis also leads to practical calculation of more appropriate mixing temperatures for asphalt concrete. This study focusses on evaluating the flow properties of different binders for a wide range of shear rates and temperatures using steady shear methods. Carreau–Yasuda (C–Y) and exponential model are combined with the concept of Rheogram to predict the viscosity of bitumen at any desired temperature and shear rate. It was found that C–Y model could be successfully applied to viscosity–shear rate master curves for all types of binders. Exponential model yielded good fit for zero shear viscosity and the model parameters were found to be binder specific. Lower mixing and compaction temperatures were obtained for modified binders, which decreased with increase in shear rate. A more practical method of obtaining mixing temperatures for bitumen is presented and discussed.

1. Introduction

Modification of bitumen is one of the several techniques to improve the structural performance of bituminous mix [1–4]. Polymer modified binders have been successfully used to ameliorate the viscoelastic response of bitumen, especially at higher temperatures [1,5,6]. When it comes to applicability, contractors and practitioners remain skeptical, mostly due to the high mixing and compaction temperature requirements for these binders. Increase in cost is another main concern. Traditionally, rotational viscometer is used for evaluating the mixing and compaction temperatures of bitumen. The viscometer applies $6.8\ s^{-1}$ (20 rpm) shear rate and the resulting torque is utilized to calculate the viscosity of the binder at different temperatures. The log–log plot of viscosity versus temperature is used to find the temperatures corresponding to 0.17 ± 0.02 Pa s and 0.28 ± 0.03 Pa s. These temperatures are used for mixing and compaction of bituminous mix.

NCHRP report 648 [7] presented new methods for evaluating the mixing and compaction temperatures for modified binders, which resulted in reduction of temperature requirement by 20–30 °C, as compared to the conventional method. In the first method named as "Phase Angle Method", the mixing and compaction temperatures are established by construction of phase angle master curve at 80 °C. Phase angle is more sensitive to chemical changes, as found in modified binders [1]. So it is rather difficult to construct a smooth master curve for phase angle, which results in a "wavy nature" (attributable to the transition and plateau regions) [1,3–5,8,9]. Moreover the use of frequency corresponding to 86° seems to have no practical significance. In the second method named as "Steady Shear Viscosity Method", Dynamic Shear Rheometer (DSR) is employed for finding the viscosity at 500 Pa shear stress at different temperatures. Extrapolation of the viscosity data is made for predicting the mixing and compaction temperature. The extrapolation

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by using straight line is questionable as the rheology of modified binder has high dependence on the molecular structure, which in turn is temperature sensitive [4,5,8,10,11].

The literature behind the new methods for finding out mixing and compaction temperatures for modified binder lies behind the concept that modified binders behave as a shear thinning fluid at higher shear rates which is practical in field conditions. But the concept of shear thinning and the reduction in viscosity could be applicable only when there is higher role of shear rate, typically found in mixing. But compaction (as in Marshall compactor or field roller), has very little dependence on shear rate. Rather it is the normal force and energy which has higher dominance. So reduction in compaction temperature with these literature background of shear thinning behavior is again not valid. The literature mentions that, for batch and continuous mixing plants, the shear rate applied at the time of mixing are typically of the order of 6×10^4–1×10^5 s^{-1} [7]. If the role of shear rate is considered, then the viscosity at such higher shear rate is expected to be even lower than predicted and hence even lower mixing temperatures can be suggested. But the same is not true for compaction temperature as there is no primary role of shear rate. A plethora of studies [7,12–14] have been done, where the change in density and strength of bituminous mixes have been evaluated by varying the compaction temperature, but no explicit study has been done by varying mixing temperatures. The main objective of the study is to evaluate the flow behavior of various binders at different shear rates and temperatures, and to establish a more practical way of finding the mixing temperatures for these binders.

2. Materials

Four binders were used in the study. VG 10 and VG 30 were the viscosity graded binder. VG 10 was being modified with Styrene Butadiene Styrene (SBS) and Ethylene Vinyl Acetate (EVA) at various percent of modification level. An earlier study [15] done by the authors found that the interlocked phase of polymer with the base binder could be obtained using 3% SBS and 5% EVA. Higher percentages yielded binder which was susceptible to phase separation. Also, using lower percentages did not fully optimize the properties of the base binder which could result in an uneconomical blend. So for comparison only 3% SBS and 5% EVA was considered in the study. The authors also studied the optimum blending requirements for both the polymers [15]. Following the study, SBS was modified at a temperature of 180 °C using a high shear mixture operated at 1500 rpm for 60 min. EVA on the other hand was modified at 190 °C, at a shear rate of 600 rpm for 30 min.

3. Experimental

Steady shear viscosity was evaluated for all the binders using Anton Paar Dynamic Shear Rheometer (DSR). Testing was done at a shear rate of 0–100 s^{-1} for a temperature range of 40–80 °C. 25 mm spindle geometry was used with 500 μm gap. The temperature of the assembly was set to 80 °C and was gradually reduced at an interval of 10 °C. 30 min conditioning time at each temperature was given before starting the test. High temperature viscosity was measured using Brookfield viscometer [16] using spindle No. 21 at 20 rpm standard rotational speed. Measurements were taken at 135 °C and 160 °C.

4. Results and analysis

The viscosity versus shear rate behavior for all the binders have been studied at different temperatures. The Carreau–Yasuda (C–Y) is further used to model the viscosity master curve plotted using the concept of Rheogram. Finally, the zero shear viscosity (ZSV) measured in the steady shear test is best fitted to a suitable model. A new technique has been proposed to evaluate the viscosity at any desired shear rate, which in turn can be used to predict the mixing temperature of bitumen.

4.1. Viscosity versus shear rate

The unmodified and modified binders were subjected to steady shear viscosity test at five different temperatures. Fig. 1 shows the variation of viscosity of different binders with shear rate at different temperatures. Due to delamination of the binder with the spindle at 80 °C, only readings up to 70 °C are shown for VG 10. It can be seen that normal binders (VG 10 and VG 30) behaves closely as Newtonian fluids at temperature above 50 °C. It was observed that even at higher temperatures there was some evidence of shear thinning behavior for very high shear rates. For VG 10 and VG 30 there was a sharp decrease in viscosity with increase in shear rate at 40 °C. However the critical shear rate at which the change in behavior started was different for both the binders. This sharp decrease is due to the sudden loosening of molecular networks. At this temperature, due to the higher stiffness, the binder behaves as a shear thinning fluid. After 50 °C, this shear thinning effect gradually reduces with smooth transitions with increase in shear rate, attributed to the dominance of Newtonian behavior. Modified binders, on the contrary, displayed shear thinning behavior at all temperatures. This characteristic was more dominant for plastomeric EVA polymer modified binder (PMB). For EVA PMB, after 50 °C, a sharp decrease in viscosity beyond the critical shear rate was observed. This can be attributed to the melt of EVA crystallites at higher temperature, making bitumen phase more dominant as compared to the polymer phase. This argument is based on the work done by Airey [1] on polymer modified binders. A study on the change of molecular level of different binders at different temperatures may provide more insight on approving such behaviors. This paper however deals only with the physical characteristics of the binder. The onset of shear thinning behavior for modified binders occurred at lower shear rates (critical shear rate) as compared to normal binders, especially at higher temperatures. Asphaltenes are mainly responsible for the non-Newtonian behavior of the bitumen, whereas maltene governs the Newtonian flow [17]. The increase in non-Newtonian behavior of PMB may be attributed to the decrease in effective maltene fraction which are used by polymers for dispersion. The aspect to be noted is that, for all the binders the critical shear rate were higher than 6.8 s^{-1} (shear rate used in Brookfield viscometer), and it increased at higher temperatures. This viscosity hence, is the zero shear viscosity (ZSV), also considered as low shear Newtonian viscosity. Two things has to be understood here. First, 6.8 s^{-1} is not the practical shear rate the binder experiences at the time of mixing an asphalt concrete. Secondly, it is due to this fact that higher mixing temperatures are obtained for modified binders, displaying high shear thinning behavior.

4.2. Construction and modeling of Rheogram

Shenoy [17] proposed a method of unifying the viscosity versus shear rate data at various temperatures for a number of asphalt grades. He presented the concept of Rheogram, through construction of master curve, which is independent of temperature and asphalt grade. The master curve is a plot of η/η_0 versus $\eta_0 \cdot \dot{\gamma}$, where η and η_0 are the corresponding viscosity and zero shear viscosity of the polymer. Melt flow index (MFI) has also been used in place of η_0 for such construction. Thus by knowing the ZSV at different temperatures η can be evaluated for any desired shear rate.

Shear rate dependency of non-Newtonian (shear thinning) fluid can be evaluated using various models [18–20]. Carreau Yasuda (C–Y) model [19], however has been found to be successfully applicable to polymers such as bitumen [21,22]. The model can be mathematically written as

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = [1 + (\lambda\dot{\gamma})^a]^{(n-1)/a} \quad (1)$$

where η is the viscosity of the fluid, η_0 and η_∞ are the zero and infinite shear viscosity, $\dot{\gamma}$ is the shear rate, λ, n and a are the shape