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International Journal of Pavement Research and Technology 9 (2016) 63–72

www.elsevier.com/locate/IJPRT

Use of flow properties for rheological modeling of bitumen

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Received 14 July 2015; received in revised form 24 January 2016; accepted 25 January 2016
Available online 4 February 2016

Abstract

The flow properties in steady-shear and dynamic domain are investigated to model the rheological properties of bitumen. The concept of rheogram is used to produce a temperature independent master curve, which is modeled using a simple Carreau–Yasuda (C–Y) equation. It is found that the variation of zero shear viscosity (ZSV) with temperature can be modeled using a simple power law equation. The results showed that the traditional equiviscous method, using a Brookfield viscometer is inappropriate for predicting the mixing and compaction temperatures for bitumen. The applicability of the Cox–Merz rule is found to be valid in the ZSV region. The C–Y equation gave an excellent fit for modeling the variation of complex viscosity/modulus with frequency. Higher dependence of modified bitumen to shear rate indicated that, modified binders can be mixed even at lower temperatures as compared to conventional binders. Accurate determination of ZSV is found to be crucial for successive application of the proposed mathematical model. The modeling technique is also extended for phase angle master curves, using the rheological relationship between loss and complex modulus. Phase angle master curves are found to be more sensitive to the type and chemistry of bitumen.

Keywords: Rheology; Time temperature superposition; Modified binder; Master curve

1. Introduction

Rheology is the study of flow of matter, in a liquid or soft-solid, which are both time and temperature dependent. Over the last five decades much research has been done in studying the various rheological aspects of bitumen and asphalt [1–7]. Bitumen is a complex hydrocarbon which is traditionally regarded as a colloidal system consisting of high molecular weight asphaltenes dispersed in a lower molecular weight maltenes. The C–H bond are mainly arranged in branched, cyclic or aromatic fashion and the variation of these molecules and structural arrangement imparts intrinsic mechanical properties to the respective binder. The viscoelastic characteristic of bitumen can be determined either by transient or oscillatory type of testing. Oscillatory testing, using dynamic shear rheometer (DSR) is currently recommended, as it is less time consuming and can be successfully used to determine the elastic, viscous and viscoelastic properties of bitumen [2].

Predictive models and equations are excellent tools for quantifying the mechanical/rheological properties of any material. It is time saving, less laborious and does not require any skilled operators. Since 1950s researchers have tried to predict the linear viscoelastic characteristics of bitumen using nonlinear multivariable models, also known as nomographs. These nomographs were later replaced by empirical equations and the use of mechanical elements (spring and dashpot), for modeling the linear rheological properties. These techniques were mainly used for predicting the variation of complex modulus and phase angle master curves, at any desired reference temperature. Yusoff

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Peer review under responsibility of Chinese Society of Pavement Engineering.

http://dx.doi.org/10.1016/j.ijprt.2016.01.005
1996-6814/

et al. [8] presented a brief overview of all the models developed over the past years. Most of the algebraic models consist of large number of model parameters which are empirical and does not have any physical significance. A more simple model is hence desired which can be directly related to the flow properties of the binder.

1.1. Time temperature superposition principle (TTSP)

Time temperature superposition principle (TTSP) is a competent tool for describing the viscoelastic behavior of linear polymers over a broad range of time and frequency, by shifting data obtained at several temperatures to a common reference temperature [9,10]. By obtaining data at several temperatures for a measurable range of frequency, a master curve could be plotted at a single reference temperature which could cover many decades of frequency/time. A material to which this technique is applicable is said to be thermorheologically simple [3]. The TTSP can be applied to all materials that undergo a transition, such as the glass transition, as well as to heterogeneous materials, provided the disperse phase undergoes no structural change in the transition zone [11].

Temperature dependent shift factors are used for the magnitude of stresses (vertical shift) and time/frequency (horizontal shift) on log-log plots of material functions, like complex modulus, phase angle and creep compliance. The temperature dependent, vertical shift factor, b_T, multiplies a stress, determined at temperature T to yield a “reduced stress”. This value of reduced stress corresponds to the value at the reference temperature chosen. Similarly, the horizontal shift factor, a_T, divides a time or multiplies a frequency (ω) to yield a “reduced frequency/time scale” (ωa_T or t/a_T). This principle can be mathematically written as

$$b_T E(\omega a_T, T) = E(\omega, T_0) \quad (1)$$

1.2. Concept of rheogram

Shenoy [12] proposed a method of unifying the viscosity versus shear rate data at various temperature for a number of asphalt grades. The concept of rheogram was presented, which included the construction of temperature independent master curve. The master curve is a plot of η/η_0 versus $\eta_0 \cdot \dot{\gamma}$. η and η_0 represents viscosity and zero shear viscosity (ZSV) of the polymer, while $\dot{\gamma}$ is the rate of shear. Melt flow index (MFI) has also been used in lieu of η_0 for such construction. Using this concept, the viscosity of any binder can be evaluated corresponding to any desired shear rate, provided the ZSV at different temperature is known. This can be a more fundamental approach instead of using the normal shifting procedure, as it uses the intrinsic binder property, i.e. the ZSV for the creation of single curve which is independent of temperature. This single curve can further be fitted using a mathematical equation for modeling the rheological property of bitumen. Such procedure can also help in discarding too many model parameters, making the equation practically sound.

Table 2
Result of Brookfield viscometer test.

Temperature (°C)	Brookfield viscosity (Pa s)			
	VG 10	VG 30	PMB (S)	PMB (E)
135	6.5E−01	7.7E−01	9.9E−01	1.7E+00
165	1.1E−01	1.5E−01	2.9E−01	5.7E−01

Table 3
Mixing and compaction temperatures for different bitumen.

Binder	Mixing temperature (°C)	Compaction temperature (°C)
VG 10	154	145
VG 30	160	150
PMB (S)	170	160
PMB (E)	190	178

1.3. Modeling viscosity

Shear rate dependency of non-Newtonian (shear thinning) fluid can be evaluated using various models [4,13]. Carreau–Yasuda (C–Y) model, however has been found to be successfully applicable to polymers such as bitumen. The model can be mathematically written as

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = [1 + (\lambda\dot{\gamma})^a]^{(n-1)/a} \quad (2)$$

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

Table 1
Conventional properties of binders used in the study.

Binders	Penetration (dmm)	Softening point (°C)	Penetration index	Viscosity @ 60 °C (Pa s)	Storage stability, ΔSoft. Point (°C)	High temperature PG[a] grade	True grade, intermediate temperature (°C)
VG 10	75	47	−1.01	258	–	PG 58- XX	25.3
VG 30	62	49	−0.95	375	–	PG 64-XX	20.1
PMB (S)	56	60	1.31	2120	1.5	PG 70-XX	15.7
PMB (E)	49	65	1.92	6120	1.3	PG 76-XX	12.2

[a] Performance Grade.