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Research Article

COMPARISON BETWEEN ZERO SHEAR VISCOSITY AND STEADY SHEAR FLOW METHODS TO DETERMINE MIXING AND COMPACTION TEMPERATURES OF PMB

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ABSTRACT
In order to obtain a better performance, different modifiers types have been adopted to complement the rheological characteristics of the bitumen used in the asphalt road construction. To bring the asphalt mixture to the desired workability, bitumen and aggregate must be heated at an elevated temperature before mixing. Thus, estimating mixing and compaction temperatures is necessary to achieve the required performance. The equiviscous method (ASTM D 2493) has been developed through the bitumen viscosity measurement to calculate the required mixing and compaction temperatures. But a problem with excessive temperatures resulted through the implementation of this method when it is applied for the modified bitumen. Insufficiency of the equiviscous method led to a necessary need to investigate for an alternative method which should be more applicable for the modified bitumen. In this study, two methods named Zero Shear Viscosity (ZSV) and Steady Shear Flow (SSF) have been examined to measure the applicability for the modified bitumen. For this purpose, 50/70 bitumen grade was modified with 5% elastomeric type – Styrene Butadiene Styrene (SBS), and 1.5 % Reactive Elastomeric Terpolymer type – Elvaloy (RET). The results have shown that the application of the new alternative methods resulted in lower mixing and compaction temperatures for the modified bitumen.

Keywords: *Compaction, Mixing, Modified bitumen, Steady Shear Flow, Zero Shear Viscosity.*

1. INTRODUCTION

In the past two decades many modification types have been used in asphalt road construction to enhance the performance of the asphalt mixture and to extend the service life of the pavement. Generally, the construction of modified asphalt mixture can be done through either polymer or chemical modification. Although, the most common type modification is the polymer which is suggested to be used by several agencies. The polymers work on improving the characteristics of the bitumen and therefore the asphalt mixture performance. Based on the physical properties and the role that the modifiers playing in improving the bitumen properties, polymers are classified into two types elastomers and plastomers. In addition, nowadays reactive elastomeric terpolymer type has started to become more common in the asphalt road construction (Hunter *et al.*, 2015).

Some of the polymer types when added to the bitumen forms discrete particles and the bitumen becomes thicker. In other words, the chemical and physical changes in the bitumen composition after mixing with the polymer causes the bitumen to become stiffer, more viscous and the workability of the modified asphalt mixture will be affected. To obtain the same workability as the base bitumen, modified bitumen requires higher mixing and compaction temperatures than base bitumen during the construction. Although, the estimated mixing and compaction temperatures by the equiviscous method are extremely high and from the past experience on similar modified bitumen a lower mixing and compaction temperatures can be selected with no effect on the asphalt pavement performance (Hunter *et al.*, 2015; West *et al.*, 2010; Yildirim *et al.*, 2000).

The Newtonian behavior of the base bitumen is become a Non-Newtonian when the modification is added to the base bitumen. Generally speaking, the behavior of the modified bitumen become more shear dependent and the viscosity value decrease with the increase of the shear rate. While in the procedure recommended by the equiviscous method the viscosity is measured at specified shear rate value and this cannot be reliable in the case of modified bitumen. Thus, any alternative method must consider the shear dependency behavior of the modified bitumen (Micaelo *et al.*, 2012 and Yildirim *et al.*, 2000).

Several alternative methods have been suggested to select the mixing and compaction temperatures of the modified bitumen such as Zero Shear Viscosity and Steady Shear Flow methods. The two methods consider the shear dependency of the modified bitumen in term of shear rate and shear stress, respectively (Khatri et al., 2005 and Reinke, 2003).

In 2003, Reink has suggested a concept called steady shear flow to be implemented to find mixing and compaction temperatures of PMB using the dynamic shear rheometer (DSR) machine. This method is built on the shear dependency behavior of the PMB. The obtained mixing and compaction temperatures range for different polymer modified samples were 314 ºF to 345 ºF and 288 ºF to 320 ºF, respectively (Reinke, 2003).

In 2005, Zero shear viscosity (ZSV) approach has been developed by Khatri et al. to estimate mixing and compaction temperatures of PMB using Brookfield viscometer. This method is based on the shear thinning behavior of the PMB and the low shear dependency of the asphalt samples during gyratory compaction. To measure the applicability of this method different modification types, elastomer and plastomer, had been used to utilize the modified bitumen samples. According to the results, the range of the mixing temperatures was in between 194 ºF to 279 ºF and for compaction was between 178 ºF to 255 ºF for all modified bitumen samples (Khatri *et al.*, 2005).

The objective of this study is measure the applicability of each method and make a comparison based on the estimated mixing and compaction temperatures of different polymer modified bitumen samples.

2. MATERIAL AND METHODS

2.1. Materials

In this study 50/70 base bitumen grade supplied by DERE ASFALT was used. Some of the conventional tests have been conducted for the base bitumen such as penetration test, softening point test, etc., to measure the bitumen characteristics. Table 1 shows the test results according to the ASTM specification.

Table 1. Properties of the base bitumen

Test	Specification	Results	Specification limits
Penetration (25 ºC; 0.1 mm)	ASTM D5 EN 1426	65	50-70
Softening point (ºC)	ASTM D36 EN 1427	53	46-54
Penetration index (PI)	-	0.35	-
Specific gravity	ASTM D70	1.030	-
Flash point (ºC)	ASTM D92 EN 22592	334	230 (min.)
Rolling thin film oven test (RTFOT)	ASTM D2872-12		
Change of mass (%)		0.160	0.5 (max.)
Penetration (25 ºC; 0.1 mm) after RTFOT	ASTM D5 EN 1426	53	-
Retained penetration (%)	ASTM D5 EN 1426	82	50 (min.)
Softening point after RTFOT (ºC)	ASTM D36 EN 1427	58	48 (min.)

The SBS polymer used was Kraton® D-1101 supplied by the Shell Chemicals Company. The properties of the Kraton D-1101 polymer are presented in Table 2.

Table 2. The properties of Kraton D-1101 polymer

Composition	specification	Kraton D 1101
Molecular structure	-	Linear
Physical properties		
Specific gravity	ASTM D792	0.94
Tensile strength at break (MPa)	ASTM D 412	31.8
Shore hardness (A)	ASTM D 2240	71
Physical form	-	Powder, pellet
Melt flow rate	ASTM D-1238	<1
Processing temperature (ºC)	-	150–170
Elongation at break (%)	ASTM D 412	875

Reactive Elastomeric Terpolymer type was Elvaloy® 4170 supplied in pellet form by DuPont, USA. properties of the Elvaloy® 4170 are presented in Table 3

Table 3. The properties of Elvaloy 4170 Terpolymer

Physical	Nominal values	Test methods	
Density	0.94 g/cm³	ASTM D792	ISO 1183
Melt flow rate (190°C/2.16kg)	8 g/10 min	ASTM D1238	IS0 1133
Thermal	Nominal Values	Test methods	
Melting point (DSC)	72°C (162°F)	ASTM D3417	ISO 3146

2.1.1. Preparation of Modified Bitumens

The SBS Kraton D 1101 concentration in the base bitumen was chosen (5%) as an optimum content (Sengoz *et al.*, 2008). High shear laboratory mixer was used to prepare the SBS polymer modified bitumen. The base bitumen first heated to (180-185 ºC), and has been poured into 600 ml glass beakers. The SBS then added gradually to the base bitumen and the rotating speed of the high shear mixer was kept at 2000 rpm for 1 hour.

The Elvaloy 4170 content was 1.5 % of the bitumen weight as the optimum concentration. Laboratory mixer was used to prepare the modified bitumen and following the procedure recommended by DuPont company. The bitumen was heated at 185 °C to become fluid enough and then modifier was added gradually while the rotating speed was set at 200 rpm for 2 hours. The viscosity of the sample should be measured immediately after finishing the production and the sample must be cured in the oven for 24 hours at 190 °C to complete the reaction (Vachhani and Mishra., 2014; Kanabar, 2010).

2.1.2. Conventional bitumen test

The effect of SBS polymer and Elvaloy modifications on the base bitumen characteristics such as penetration and softening point as seen in table 4

Table 4. Conventional properties of the modified bitumen

Property	5 % SBS	1.5 % Elvaloy
Penetration (25 ºC; 0.1 mm)	52	49
Softening point (ºC)	77.9	65
Penetration index (PI)	4.14	1.92
	Rolling thin film oven test (RTFOT)	
Change of mass (%)	0.090	0.030
Penetration (25 ºC; 0.1 mm)	41	38
Softening point (ºC)	70	64

2.2. Determination of Mixing and Compaction Temperatures Methods

2.2.1. Equiviscous Method (ASTM D2493)

The rotational viscometer test is used to determine fluidity characteristics of bitumen at the high temperatures. For this purpose, "Brookfield Viscometer" is used in accordance with ASTM D2493 standard. In this method, spindle no 21 is used to measure the viscosity values at rotating speed of 20 rpm (6.8 1/s shear rate). To select the mixing and compaction temperatures of the bitumen, the viscosity measurement must be conducted at two temperatures (135 °C and 165 °C). The mixing and compaction temperatures of the mixture are those corresponding to the viscosities of 0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s, respectively as shown in figure 1.

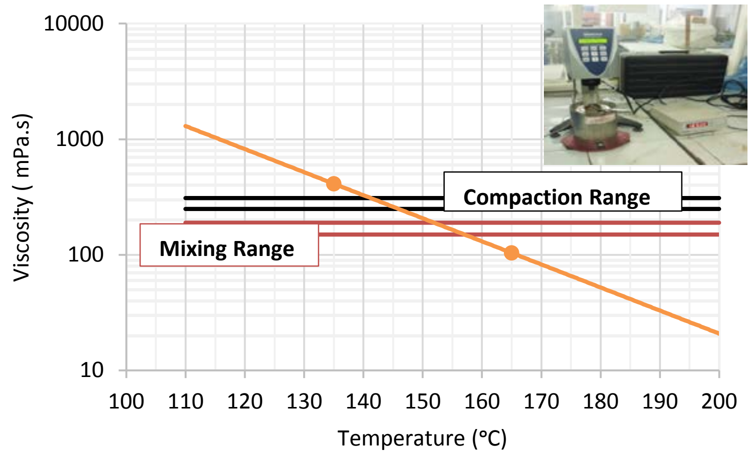

Figure 1. Calculation of mixing and compaction temperatures

2.2.2. Zero Shear Viscosity Determination

Khatri et. al., (2005) found that the gyratory compaction is more dependent on the low shear viscosity (zero shear viscosity) and recommended using this concept to calculate the mixing and compaction temperatures. The viscosity measurements are done using a Brookfield viscometer. Unlike the equiviscous method, different shear rate values are used to measure the viscosity. The test is conducted at 135 °C and 165 °C temperatures and Cross-Williamson model (CW) is used in a solver program to find the zero shear viscosity as shown in figure 2.

$$\boldsymbol{\eta} = \boldsymbol{\eta}_{\infty} + \frac{\boldsymbol{\eta}_0 - \boldsymbol{\eta}_{\infty}}{1+(k\gamma^{\cdot})^{n}} \text{ .... (1)}$$

where,
$\boldsymbol{\eta}_0$ = the zero shear viscosity
$\boldsymbol{\eta}_{\infty}$ = the terminal viscosity at infinite shear rate,
$\gamma^{\cdot}$ = dγ/dt = the shear rate, and
k, n = model constants

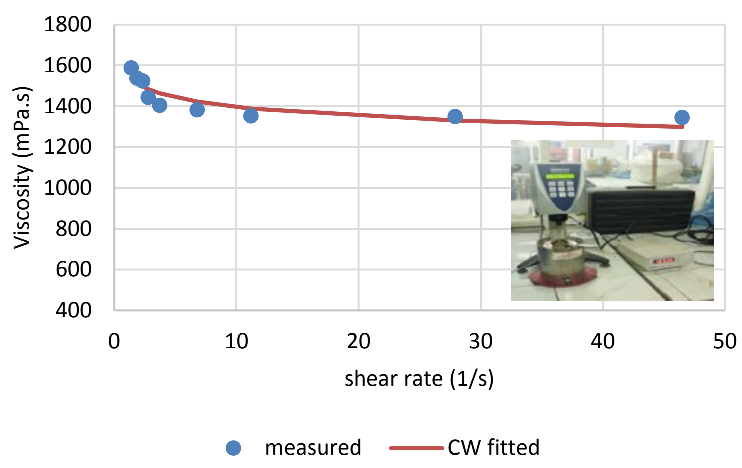

Figure 2. Zero shear viscosity determination

2.2.3. Steady Shear Flow Method

This method is based on the shear dependency behavior of the modified bitumen. Using Dynamic Shear Rheometer (DSR) and the procedure recommended by Reink (2003), mixing and compaction temperatures of the bitumen can be determined. It is proposed that the viscosity values are measured at different shear stresses and the suggested stress levels are from 0.3 to 500 Pa (or 1000 Pa) at different temperatures 76 ºC, 86 ºC and 88 ºC as shown in figure 3

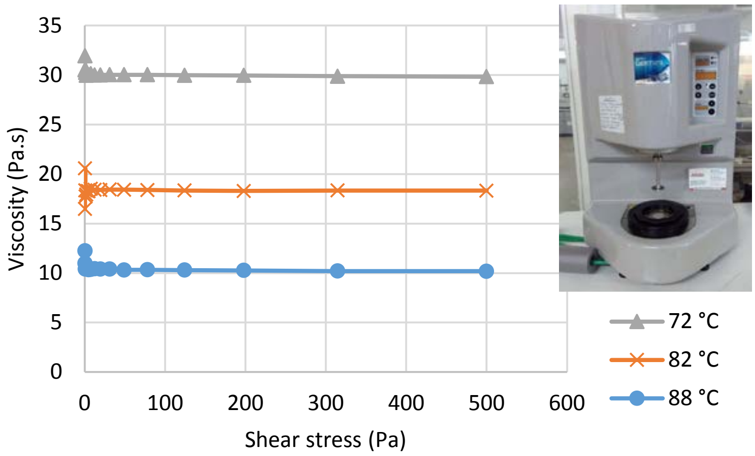

Figure 3. Steady shear flow method

The measured viscosity values at 500 Pa or 1000 Pa are then plotted using a log viscosity versus log temperature chart and extrapolated to obtain the mixing and compaction temperatures through using the suggested viscosity limits 0.17 ± 0.02 Pa s and 0.35 ± 0.03 Pa s, respectively.

3. RESULTS AND DISCUSSION

3.1. Equiviscous Method (ASTM D2493)

The mixing and compaction temperatures are determined according to ASTM D 2493. First, the mixing and compaction temperatures were calculated for the base bitumen and then for the modified bitumen (5% SBS and 1.5% Elvaloy) as shown in figure 4.

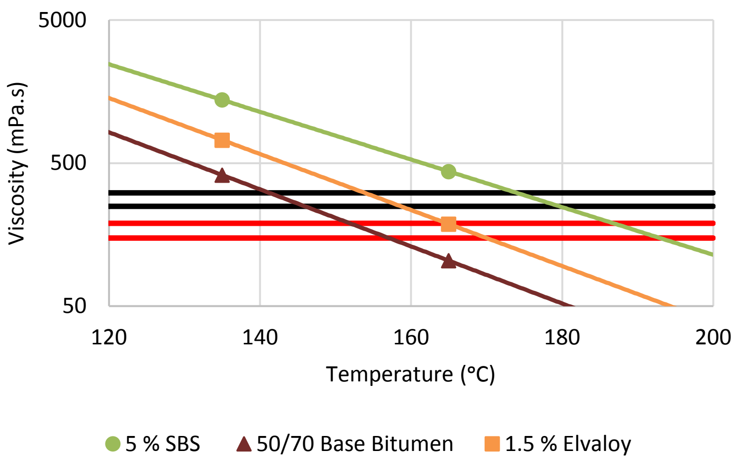

Figure 4. Determination of mixing and compaction temperatures

Table 5 illustrates mixing and compaction temperatures determined through the implementation of the equiviscous method.

Table 5. Mixing and compaction results for Equiviscous Method

Material	Mixing temperature ºC	Compaction temperature ºC
Base bitumen	155	143.5
PMB (5 % SBS)	189	177
PMB (1.5 % Elvaloy)	167.5	156

3.2 Zero Shear Viscosity Method (ZSV)

To find zero shear viscosity Cross-Williamson model has been used. The viscosity values obtained at different shear rates at two temperatures (135 ºC and 165 ºC) then using solver in excel the zero shear viscosity value is calculated as shown in figure 5 and figure 6.

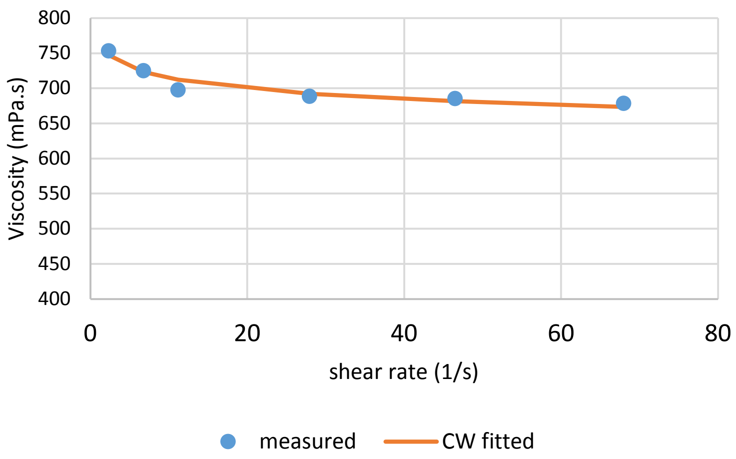

Figure 5. Example for ZSV determination for 50/70 PMB (1.5 % Elvaloy) at 135 ºC

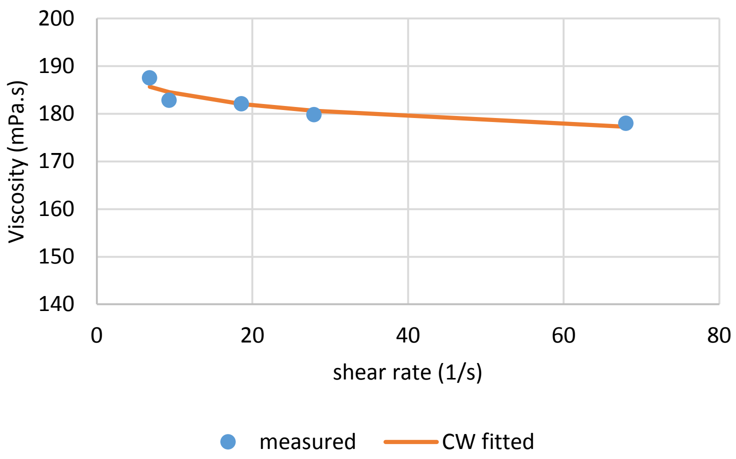

Figure 6. Example for ZSV determination for 50/70 PMB (1.5 % Elvaloy) at 165 ºC

The zero shear viscosity values are then plotted in log-log scale as a function of log temperature in Kelvin units. The mixing temperature is corresponding viscosity of 3 ±0.3 Pa. s and the compaction temperature is corresponding viscosity of 6 ±0.6 Pa. s. Table 6 illustrates the obtained mixing and compaction temperatures from ZSV.

Table 6. Mixing and compaction temperatures for ZSV method

Material	Mixing temperature ºC	Compaction temperature ºC
Base bitumen	144.8	141.5
PMB (5 % SBS)	151.5	145.5
PMB (1.5 % Elvaloy)	148.7	141.9

3.3 Steady Shear Flow (SSF)

This method tested the shear dependency of the bitumen by measuring the viscosity at different shear stress levels from 0.3 Pa to 500 Pa. The test is performed using DSR machine over range of temperatures 76 ºC, 82 ºC, and 88 ºC for each bitumen sample as shown in figure 7.

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Vol. 3, Issue 2, pp. 1-8, 12/2019

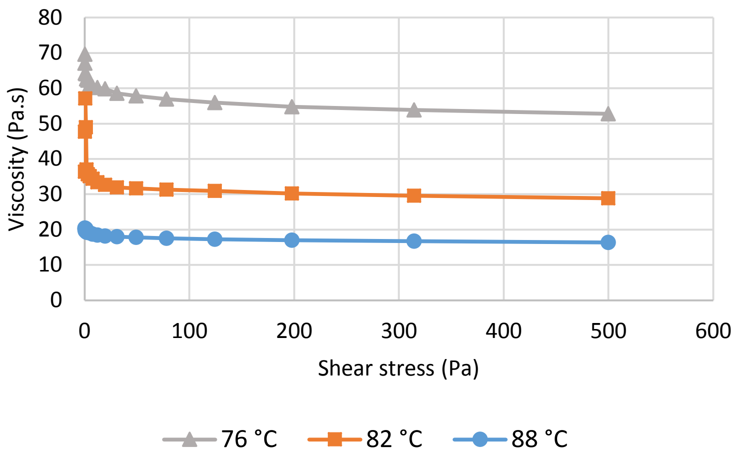

Figure 7. Viscosity vs Shear Stress for 50/70 PMB (1.5 % Elvaloy)

From the above figure, it can be noticed that the viscosity of modified bitumen has reached the state condition when the shear stress is approaching to 500 Pa. The log of viscosity values at the steady flow is then plotted against the log of temperatures as shown in figure 8.

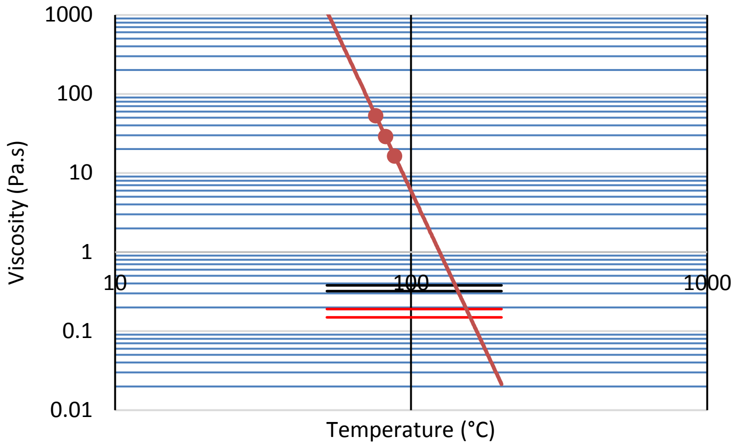

Figure 8. Shear Viscosity at 500 Pa vs Temperature for 50/70 PMB (1.5 % Elvaloy)

The obtained mixing and compaction temperatures are shown in table 7.

Table 7. Mixing and compaction temperatures for SSF

Material	Mixing temperature ºC	Compaction temperature ºC
Base bitumen	154	139
PMB (5 % SBS)	166	148
PMB (1.5 % Elvaloy)	157	142

4. CONCLUSION

The calculation of mixing and compaction temperatures of modified bitumen has no specific standards. Due to the limitation of the equiviscous method, most of the suppliers specifies the temperatures based on the experience. In this study, polymer modified bitumen has been produced using two modification types (SBS and Elvaloy). To estimate mixing and compaction temperatures two different methods proposed in the literature ZSV and SSF have been implemented and the results were compared to evaluate the applicability for the modified bitumen.

Based on the obtained results, the following conclusions ensued:

- The behavior of the modified bitumen is more shear dependent (shear stress or shear rate)
- The mixing and compaction temperatures obtained by the equiviscous for the non-modified bitumen are reasonable while for the modified bitumen the obtained temperatures were excessively high.

- The application of ZSV method and SSF method for the base bitumen showed close results with the equiviscous method and this can be attributed to the Newtonian behavior of the non-modified bitumen.
- For both modified bitumen samples, the implementation of the ZSV and SSF methods resulted in lower mixing and compaction temperatures compare to the equiviscous method.
- For both modified bitumen samples, ZSV method comparing to SSF gave lower mixing and compaction temperatures.

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