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Viscosity-Temperature Effects of Polymer Modification as Depicted by Heukelom's Bitumen Test Data Chart

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Polymer modified bitumens (PMBs) have the ability to enhance a number of the performance properties of conventional bituminous binders. One aspect affected by the addition of a polymer to bitumen is the viscosity-temperature characteristics of the modified bitumen. This paper describes the assessment of the suitability of the Bitumen Test Data Chart (BTDC) and conventional binder properties at quantifying the viscosity-temperature characteristics of PMBs. The testing methodology that has been used in this investigation is to combine empirically-based test parameters (Penetration, Softening Point and viscosity) with fundamental rheological data measured with a dynamic shear rheometer (DSR). Two construction techniques, developed during the Strategic Highway Research Program (SHRP) and in the 1960s by Puzinauskas, have been used to convert the DSR parameters of complex viscosity, phase angle and strain rate to zero shear viscosity for incorporation in the BTDC. Results from the investigation indicate that although the BTDC can depict the advantages of polymer modification in terms of increased high temperature viscosity, the charts do not provide any additional information from that found in conventional viscosity-temperature plots. Although both the SHRP and Puzinauskas construction methods are able to calculate zero shear viscosities from DSR test data for penetration grade bitumens, only the Puzinauskas method is suitable for PMBs. The results also indicate that empirically-based binder tests, such as Softening Point, are not suitable at quantifying the performance of highly modified PMBs.

Keywords: Bitumen Test Data Chart, Dynamic Shear Rheometer, Polymer Modified Bitumen, Viscosity

INTRODUCTION

Historically, empirical binder properties have been used to provide an indication of the performance of asphalt mixtures. For example, Softening Point has been used to predict the permanent deformation resistance of the pavement at high service temperatures and Fraass breaking point has been used as a performance indicator of low temperature brittle fracture. With the advent of larger axle loads, increased traffic volumes and higher tyre pressures, there has been an increase in the use of polymer modified bitumens (PMBs) and other specialised binders. Such modification can significantly alter the rheological properties of the binder, which are not necessarily characterised by conventional, empirically-based binder tests and properties.

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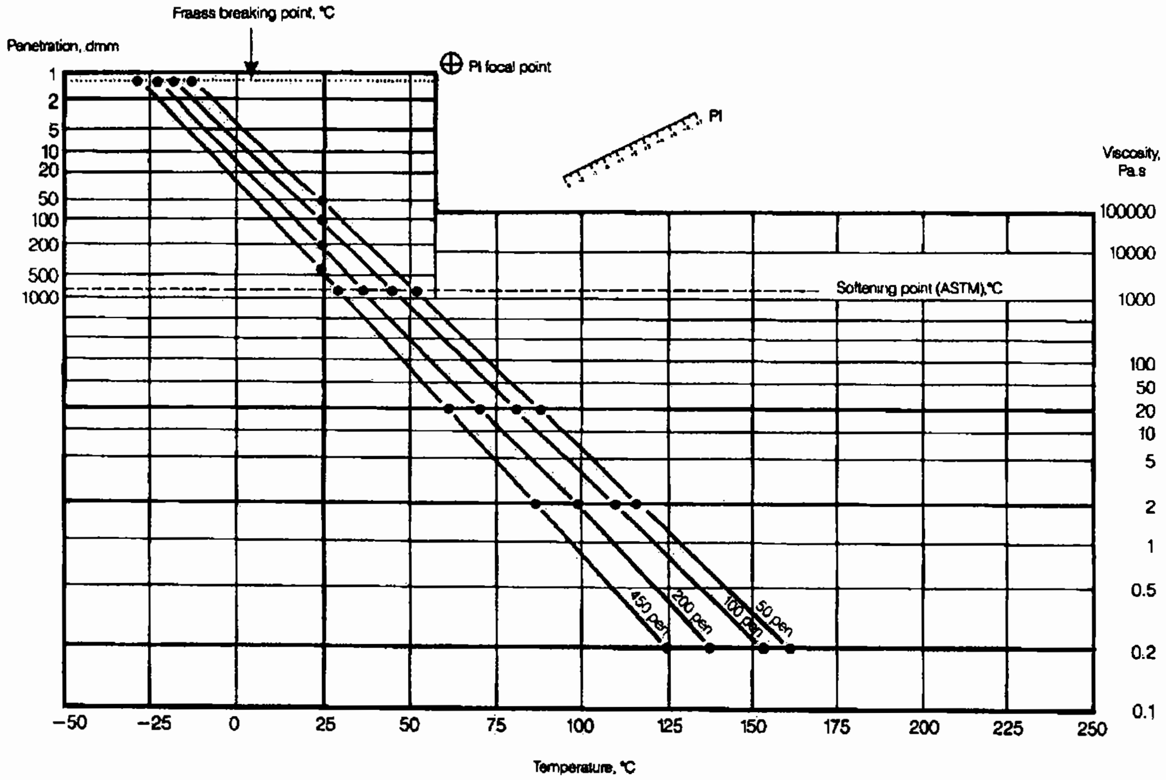

FIGURE 1 Bitumen test data chart comparing different penetration grade bitumens *[after Heukelom, 1969]*

One aspect that can be significantly affected by the addition of a polymer into a binder system is the viscosity-temperature characteristics of the modified bitumen. One method that uses empirical binder properties to characterise the viscosity-temperature properties of bituminous binders is the Bitumen Test Data Chart (BTDC) (Heukelom, 1969). Developed in the late sixties, this chart has been used over the last thirty years to predict the viscosity-temperature characteristics of penetration grade bitumen using routine binder properties such as Penetration and Softening Point.

The objective of this paper is to investigate the suitability of using the BTDC, and consequently conventional binder tests and properties, to describe the viscosity-temperature characteristics of PMBs. To achieve this objective, fundamental rheological data, measured by means of a parallel-plate dynamic shear rheometer (DSR), together with conventional binder test data (Penetration, Softening Point and high temperature viscosity) have been obtained for a number of unmodified and polymer modified bitumens. The DSR data was than converted by means of two construction techniques (one developed during the Strategic Highways Research Program (SHRP) (Anderson *et al*, 1994) and another by Puzinauskas (1967, 1979) and combined with the conventional data in the form of standard log viscosity versus temperature plots and BTDCs. The applicability of the BTDC to characterise the polymer modification of bitumen was then assessed in terms of the uniqueness of the rheological data obtained from the BTDC compared to other viscosity-temperature figures and the ease of construction of the chart.

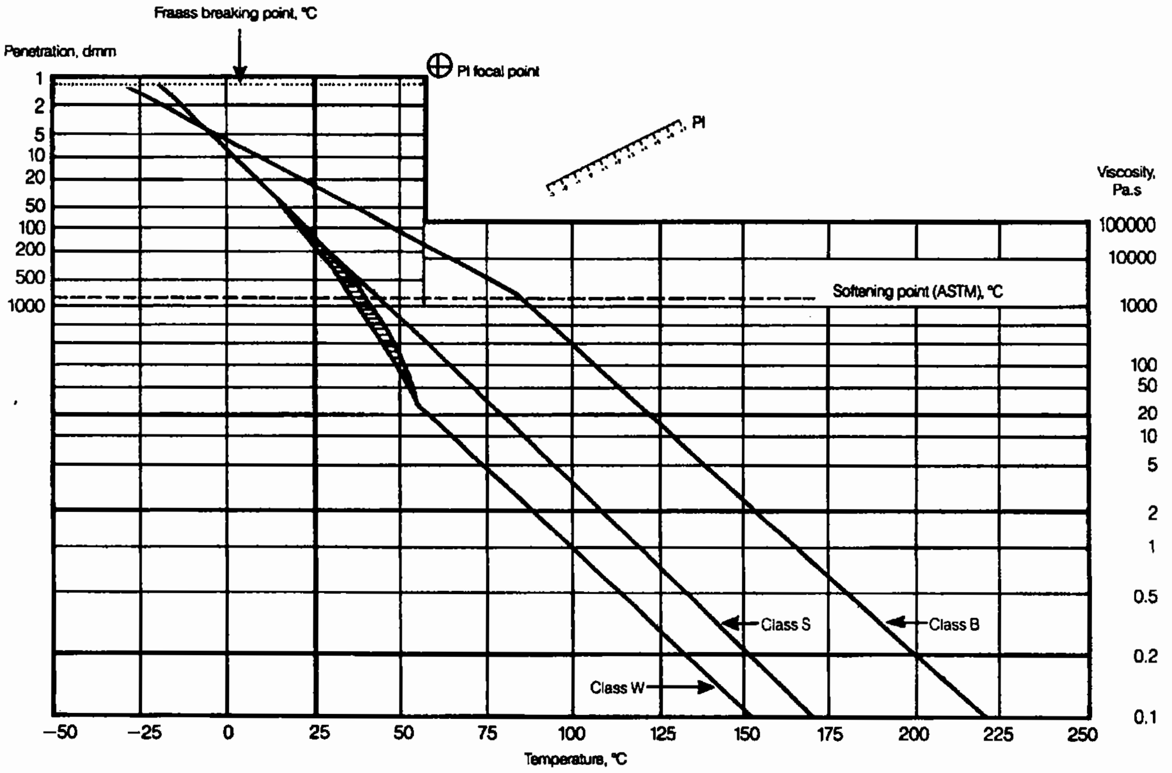

FIGURE 2 Bitumen test data chart comparing class S, B and W type bitumens *[after Heukelom, 1969]*

POLYMER MODIFICATION

Polymer modification is a method used to enhance the performance of conventional penetration grade bitumens in certain highly stressed highway pavement and airfield runway applications. The process of polymer modification involves the addition of a polymer to a base bitumen system in order to improve one or more of the unmodified bitumen's performance properties. The polymers that are generally used in polymer modification can be grouped into two broad categories, namely plastomers and elastomers. Within these two groups, further sub-groups exist of which thermoplastic polymers in the plastomer group and thermoplastic rubbers in the elastomer group are the most common.

Thermoplastic Polymers

One of the principal thermoplastic polymers is the semi-crystalline, ethylene copolymer – ethylene vinyl acetate (EVA), which consists of a random structure produced by the co-polymerisation of ethylene and vinyl acetate. EVA polymers have been widely used in the road construction industry for more that 20 years, where they have been found to improve both the workability of the asphalt during compaction and its deformation resistance in service (Goos and Carre, 1996).

Thermoplastic Rubbers

The most widely used group of thermoplastic rubbers is the styrenic block copolymers of which the copoly-

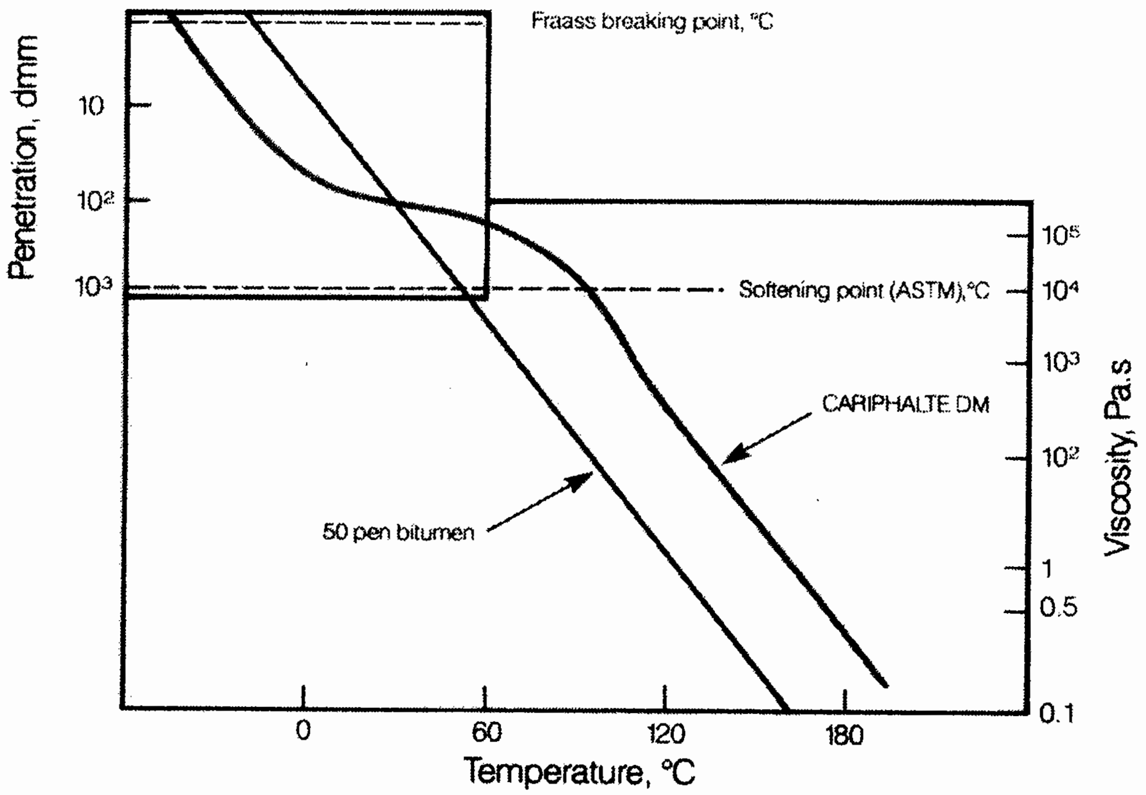

FIGURE 3 Idealised viscosity-temperature relationship for a polymer modified bitumen *[after Whiteoak, 1990]*

mer styrene-butadiene-styrene (SBS) is the best known. SBS copolymers derive their strength and elasticity from the physical cross-linking of their molecules into a three-dimensional network (Whiteoak, 1990; Isacsson and Lu, 1995). This network provides the modified asphalt mixture with improved high temperature, permanent deformation resistance while the increased flexibility of the SBS PMB provides the asphalt mixture with enhanced fatigue resistance.

BITUMEN TEST DATA CHART

In the late sixties, Heukelom (1969, 1973) developed a system that enabled Penetration, Softening Point, Fraass breaking point and viscosity data to be described as a function of temperature on one chart, known as the bitumen test data chart (BTDC). The horizontal and vertical scales of the chart were chosen in such a manner as to enable penetration grade bitumens with so-called "normal" temperature susceptibilities to be plotted as straight lines as shown in Figure 1.

In addition to comparing bitumens, the chart enables the temperature/viscosity characteristics of a penetration grade bitumen to be determined over a wide range of temperatures from only the Penetration and Softening Point of the bitumen and is therefore a refinement of the Penetration Index (PI) method developed by Pfeiffer and van Doormaal (1936). Using the BTDC, bitumen can be grouped into three categories, "S" or normal bitumens, "B" or blown bitumens and "W" or waxy bitumens, as shown in Figure 2. The viscosity-temperature characteristics of

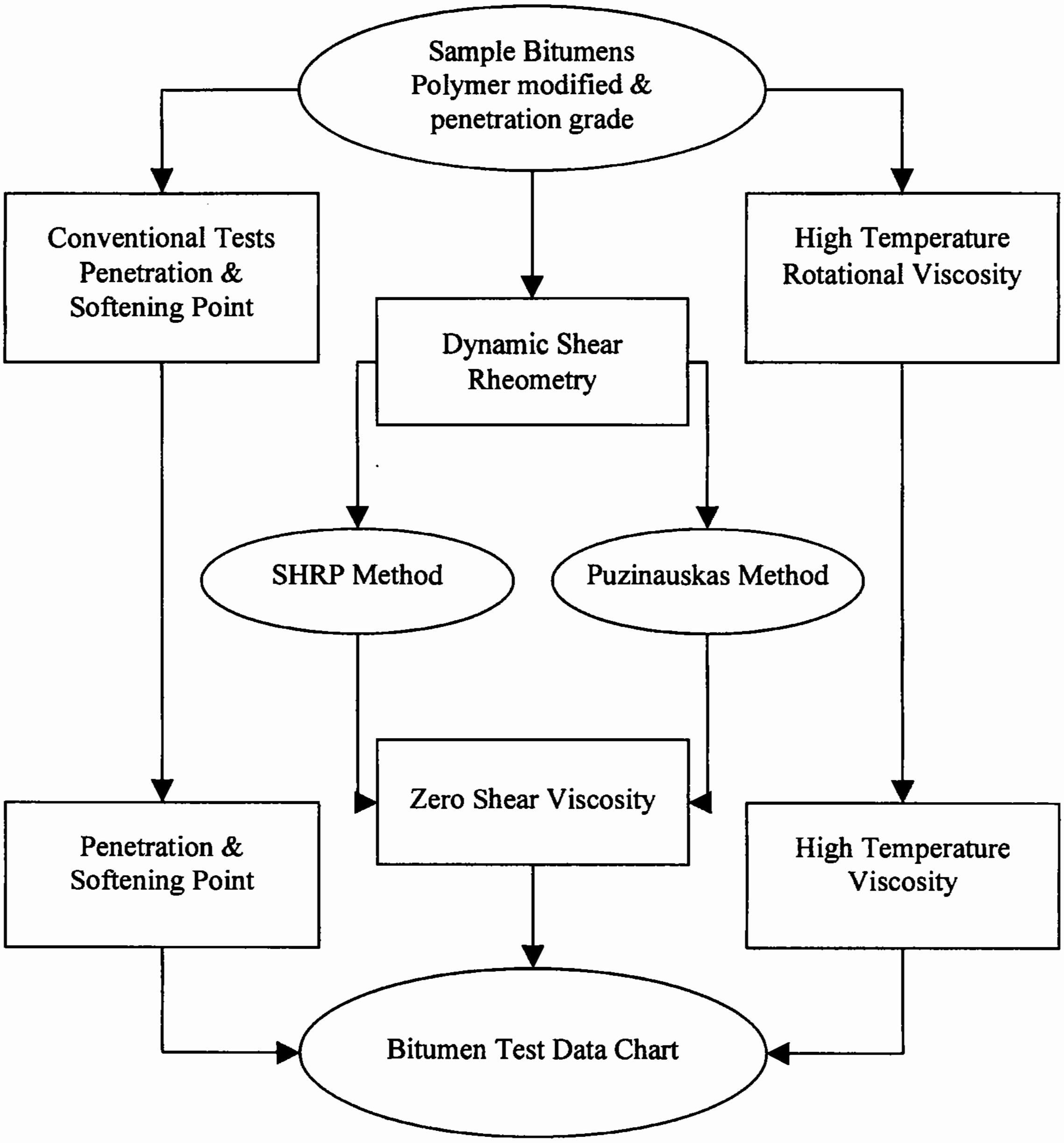

FIGURE 4 Testing methodology flow chart

the "S" type bitumens are reflected by the slope of a straight line. The "B" type bitumens are represented by two intersecting straight lines with different viscosity-temperature characteristics above and below the softening point of the bitumen, while the "W" type bitumens produce straight lines with very similar slopes that are not aligned.

Although the BTDC was not designed to represent the viscosity-temperature characteristics of polymer modified bitumens, the chart has been used as a

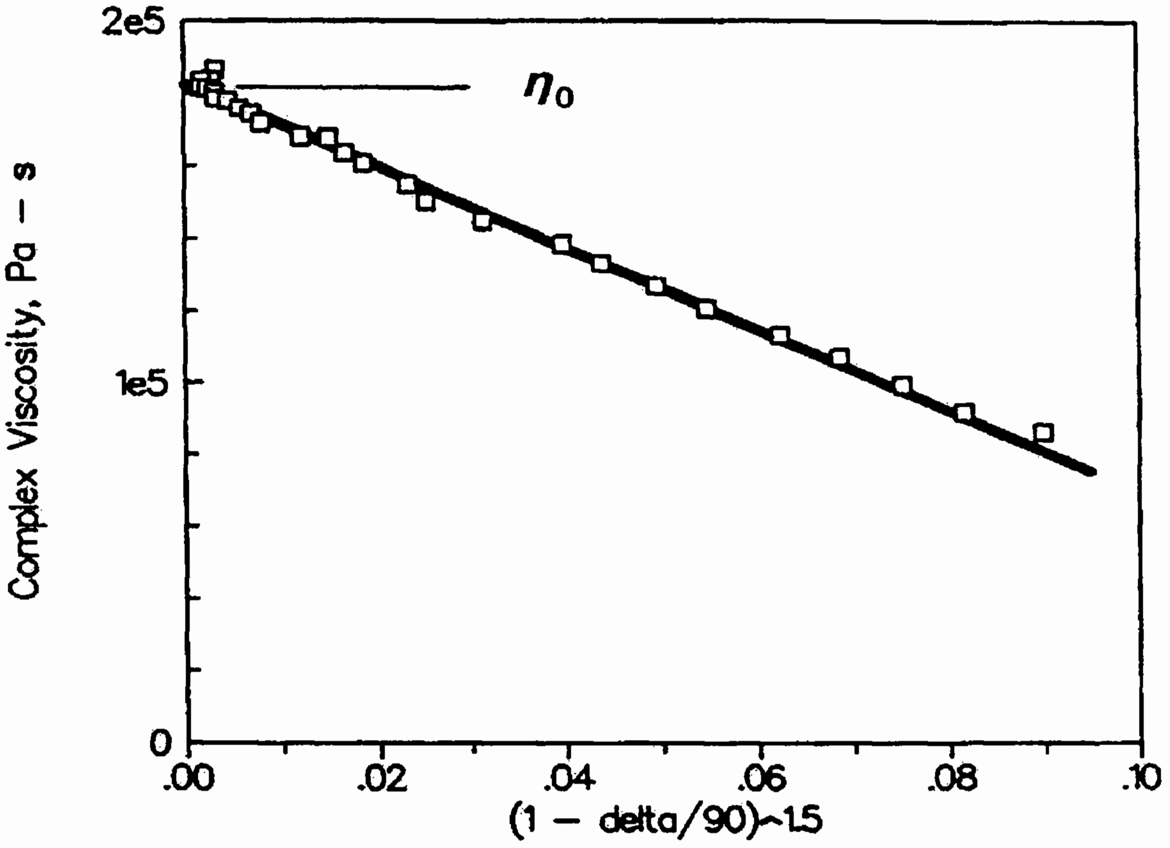

FIGURE 5 Example of the SHRP method [after Anderson et al, 1994]

means of indicating the benefits of polymer modification. An example of a SBS PMB versus a "normal" penetration grade bitumen is presented in Figure 3.

The curve for the SBS PMB clearly shows the advantages of modification as demonstrated by increased stiffness at high temperatures with the implication of improved high temperature, permanent deformation resistance. In addition, there is a reduction in stiffness at low temperatures and consequently improved flexibility at low temperatures and therefore greater resistance to thermal and fatigue cracking. It should be noted that the viscosity-temperature relationship above 25°C for the modified binder (Figure 3) is similar to that seen for the blown bitumen (Figure 2), in that both show an increase in viscosity compared to a normal "S" type bitumen.

TESTING METHODOLOGY

The testing methodology that is used in this paper is presented in Figure 4. The flow chart shows the incorporation of both conventional, empirically-based test data and fundamental rheological data into Heukelom's BTDC. The fundamental rheological data, generated by means of DSR testing, is converted by means of two construction techniques into a rheological parameter suitable for the BTDC.

Once completed, the BTDCs provide a means whereby the effect of varying degrees and types of polymer modification on standard, penetration grade bitumen can be quantified. In addition, the BTDCs allow the suitability of using conventional test data to

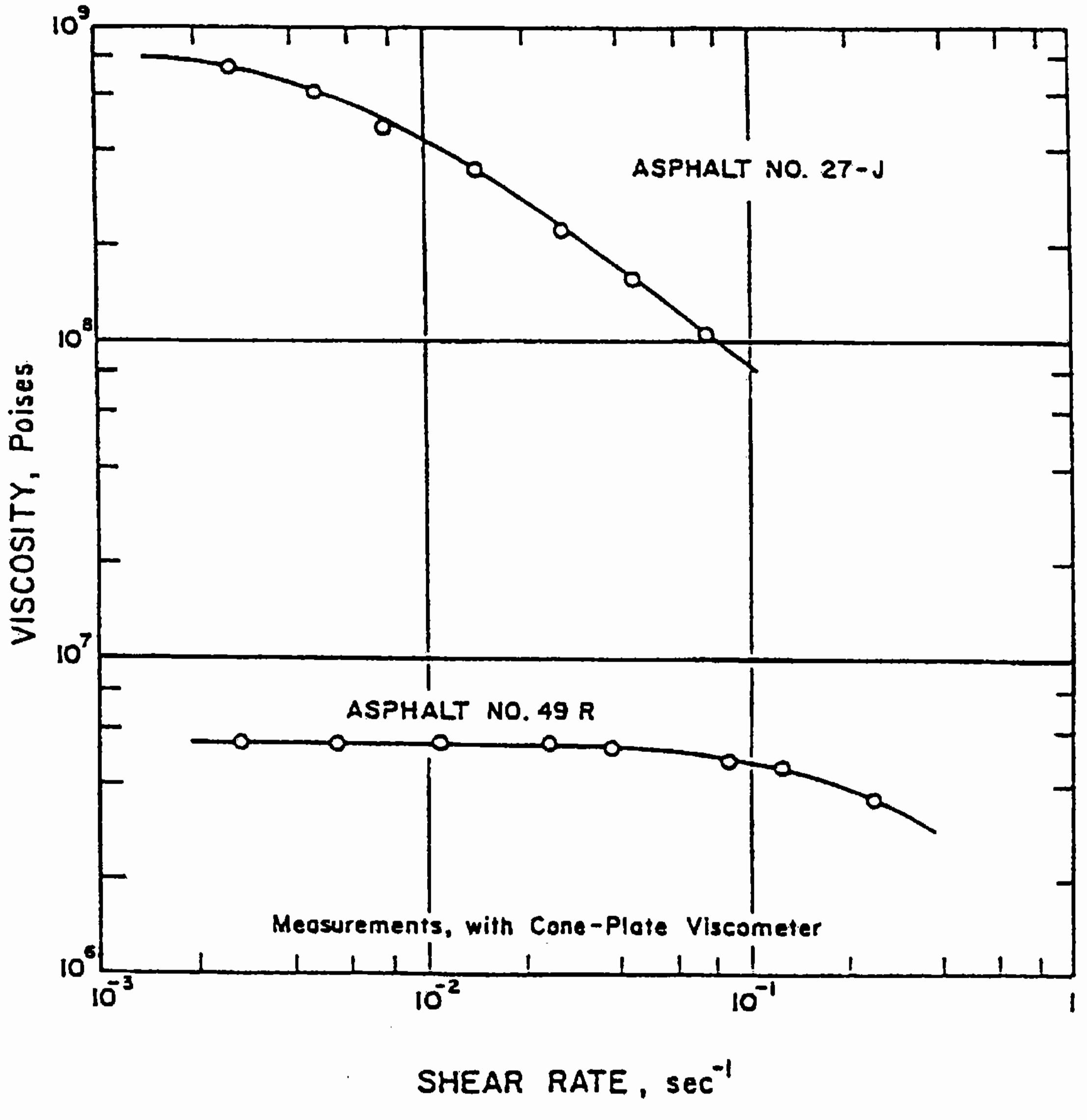

FIGURE 6 Example of the Puzinauskas method [after Puzinauskas, 1979]

describe the rheological characteristics of PMBs, particularly highly modified PMBs, to be evaluated.

Materials

Three base bitumens, from different crude oil sources, were used to produce a variety of EVA and SBS PMBs. All three base bitumens have similar consistencies (Penetration and Softening Point) and differ only slightly in their chemical composition.

The three base bitumens (Base Bitumens A. B and C) have been blended with the following two polymers:

- EVA 20/20, and
- SBS – linear.

at polymer contents of 3, 5 and 7% by mass.

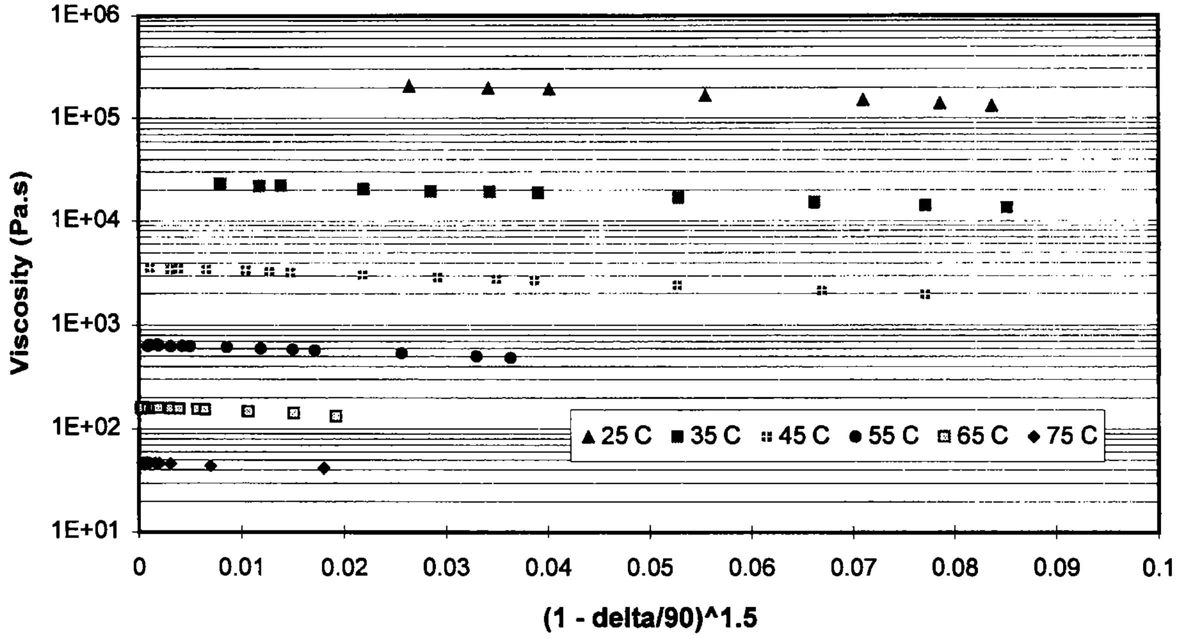

FIGURE 7 Zero shear viscosity – SHRP method for Base Bitumen A

Conventional Binder Tests

The three base bitumens together with the laboratory blended PMBs have been subjected to conventional Needle Penetration testing at 25°C (BS 2000: Part 49, 1983) and Ring-and-Ball Softening Point testing (BS 2000: Part 58, 1983). The results from these conventional tests are presented in Table I.

High Temperature Viscosity

Viscosity testing of the sample bitumens was conducted using a rotational viscometer over a temperature range of 60°C to 160°C for the penetration grade bitumens and 100°C to 200°C for the PMBs.

Dynamic Shear Rheometry

The fundamental rheological properties of the base bitumens and PMBs were measured by means of oscillatory-type, dynamic shear rheometry (DSR) testing (Anderson *et al*, 1994; Goodrich, 1988; Petersen *et al*, 1994) over a range of temperatures (10°C to 75°C) and frequencies (0.01 Hz to 15 Hz) (Airey and Brown, 1998). The rheological parameters that were used in the subsequent sections of this paper were the complex viscosity, η^*, the phase angle, δ, and the shear strain, γ.

Strain sweeps were performed at each temperature and selected frequencies to determine the linearity limits of the viscoelastic response of each bitumen. The tests were then performed under controlled strain conditions, using 8 mm (low temperatures) and 25 mm (high temperatures) parallel plate geometries with strain levels within the linear viscoelastic (LVE) range of the binder (Airey and Brown, 1998).

NEWTONIAN VISCOSITY FROM DSR TEST DATA

Although the traditional input parameters of the BTDC consist of combinations of two or more of the Fraass breaking point temperature, Penetration at

25°C, Softening Point temperature and high temperature rotational viscosities (temperatures greater than 60°C), zero shear viscosities at temperatures less than 60°C can also be included.

Two construction methods have been used to estimate the steady-state (zero shear or Newtonian) viscosities at temperatures between 25°C and 75°C from the dynamic oscillatory data obtained with the DSR.

SHRP construction method (Anderson et al, 1994)

This first method consists of plotting complex viscosity, η^*, versus $(1 - \delta/90°)^{1.5}$ and extrapolating to the intercept where $(1 - \delta/90°)^{1.5}$ equals 0. When constructing the plot, the data should only include phase angles greater than approximately 70°. An example of the SHRP method is shown in Figure 5.

Puzinauskas zero shear rate construction method (Puzinauskas, 1967; 1979)

The second method consists of estimating the zero shear viscosity, η_o, by plotting the complex viscosity, η^*, against shear rate for each loading frequency and extrapolating the calculated complex viscosity to a zero shear rate. The shear rates used with this method were calculated from the controlled strain DSR tests using the following equation:

$$Strain\ rate\ (s^{-1}) = (\gamma) \times (2\pi f) \qquad (1)$$

γ = shear strain in the DSR test
f = frequency (Hz)

An example of the Puzinauskas zero shear rate method is shown in Figure 6.

The SHRP (Anderson *et al*, 1994) and Puzinauskas (1967, 1979) constructions for Base Bitumen A are shown in Figures 7 and 8. The constructions for the other two base bitumens showed similar behaviour and are not shown for brevity. The zero shear viscosities, extrapolating from these two construction methods, are presented in Table II. The consistency of the viscosities as calculated by the two methods indicates the suitability of both methods at calculating η_o for unmodified, penetration grade bitumens.

TABLE I Penetration and Softening Point for Sample Bitumens

Bitumen	*Modification*	*Penetration (dmm)*	*Softening Point (°C)*
Rase Bitumen A	0% EVA	60	48.8
	3% EVA	53	54.8
	5% EVA	43	61.0
	7% EVA	37	69.4
Rase Bitumen B	0% EVA	73	47.0
	3% EVA	61	59.5
	5% EVA	51	66.6
	7% EVA	47	69.2
Base Bitumen C	0% EVA	81	46.8
	3% EVA	65	53.7
	5% EVA	58	63.8
	7% EVA	53	69.2
Rase Bitumen B	0% SBS	73	47.0
	3% SBS	63	52.4
	5% SBS	57	78.0
	7% SBS	50	95.0
Base Bitumen C	0% SBS	81	46.8
	3% SBS	63	52.2
	5% SBS	54	74.0
	7% SBS	49	88.0

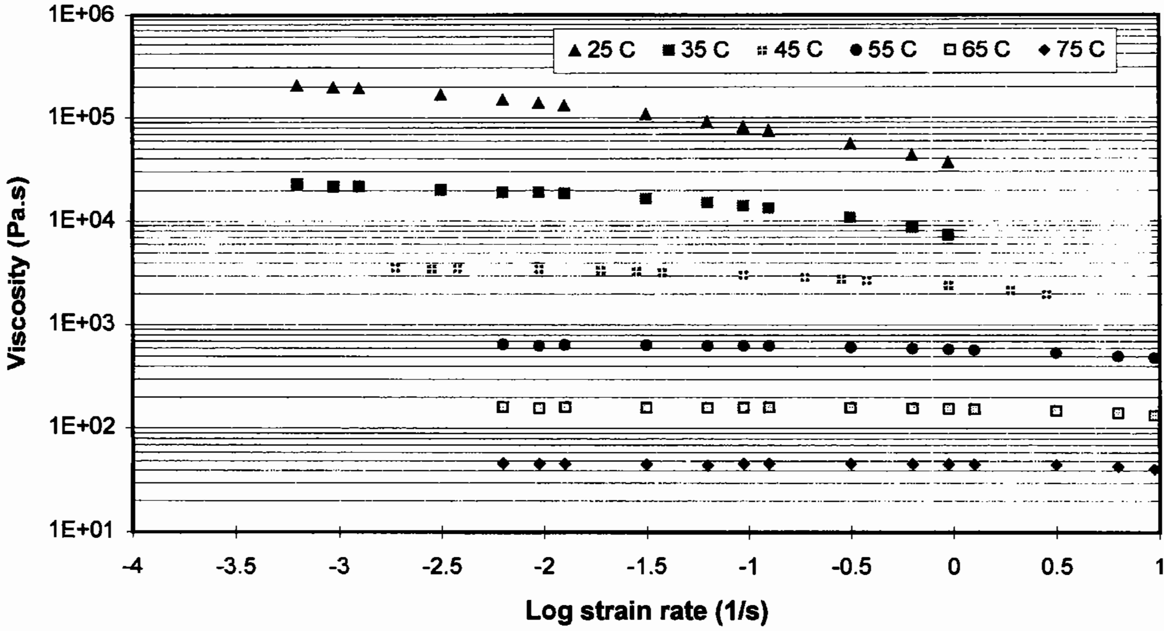

FIGURE 8 Zero shear viscosity – Puzinauskas method for Base Bitumen A

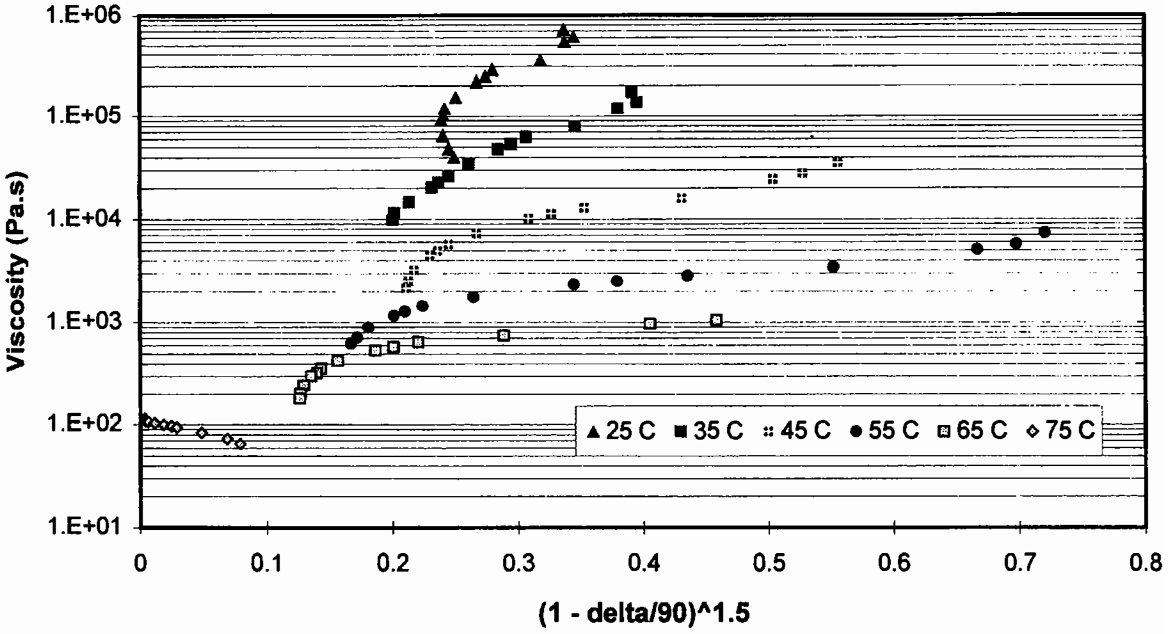

FIGURE 9 Zero shear viscosity – SHRP method for 7% EVA – Base Bitumen B

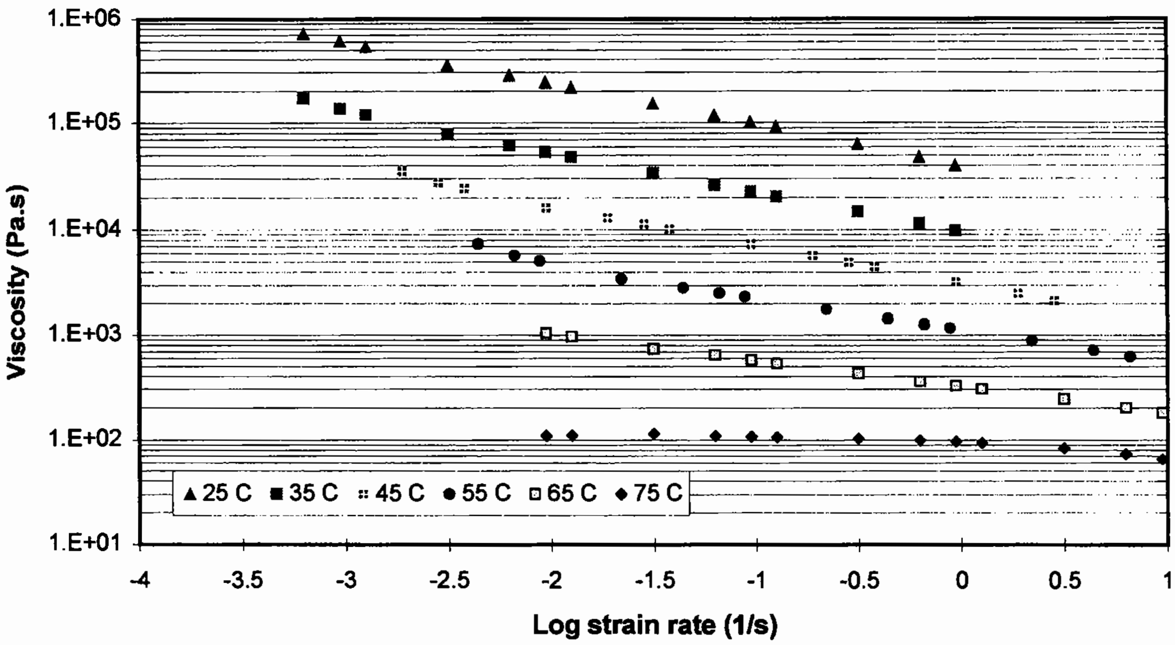

FIGURE 10 Zero shear viscosity – Puzinauskas method for 7% EVA – Base Bitumen B

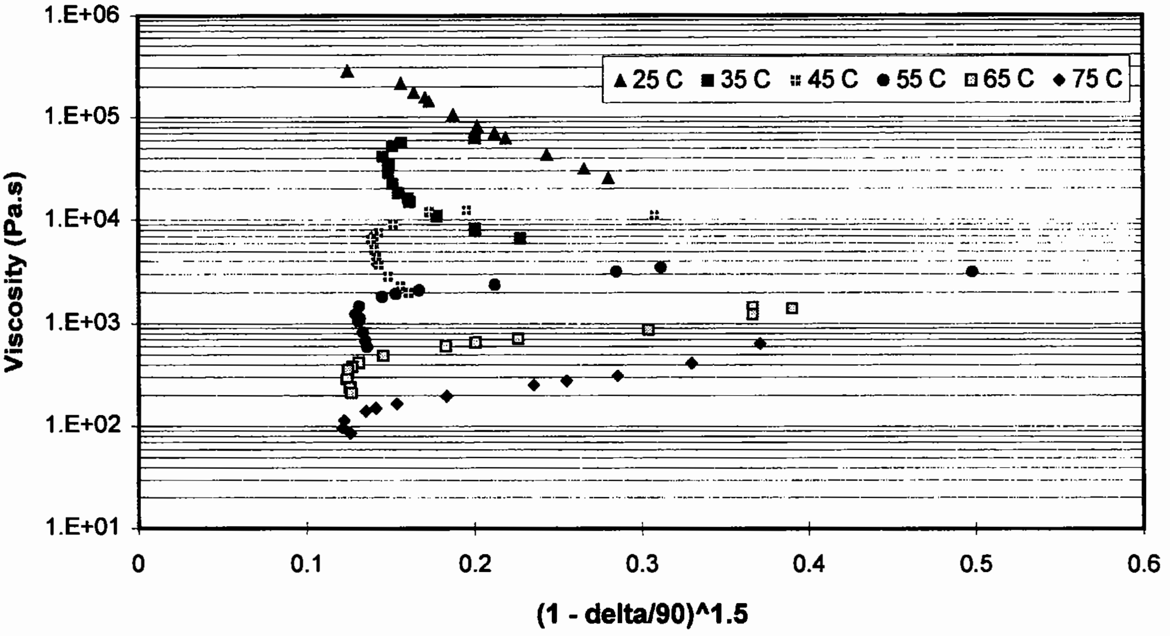

FIGURE 11 Zero shear viscosity – SHRP method for 7% SBS – Base Bitumen B

TABLE II Zero shear viscosities, η_o, for Base Bitumen A

Temperature (°C)	*SHRP – viscosity (Pa.s)*	*Puzinauskas – viscosity (Pa.s)*
25	244,064	219,167
35	23,380	23,725
45	3,596	3,578
55	653	647
65	161	159
75	47	47

The SHRP and Puzinauskas plots for the 7% EVA – Base Bitumen B and 7% SBS – Base Bitumen B PMBs are shown in Figures 9 to 12. As for the base bitumens, the constructions for the other PMBs showed similar behaviours and are not shown for brevity.

The plots for the two PMBs show vast differences between the SHRP and Puzinauskas methods. Whereas the Puzinauskas plots (Figures 10 and 12) show similarities with the plots produced for the penetration grade bitumen, the SHRP plots (Figures 9 and 11) differ considerably from each other and from the plot for the penetration grade bitumen (Figure 7).

The SHRP method relies on the bitumen having tradition viscoelastic behaviour, with the phase angle, δ, approaching 90° at high temperatures and/or low loading frequencies. The method therefore relies on the bitumen fulfilling the time-temperature superposition principle (TTSP) (Ferry, 1971) and consequently is not applicable for highly modified PMBs. The SHRP plots for the 7% EVA – Base Bitumen B (Figure 9) and 7% SBS – Base Bitumen B (Figure 11) PMBs depict the inability of this method to provide an estimate of the zero shear viscosities for highly modified PMBs as the parameter $(1 - \delta/90°)^{1.5}$ cannot be extrapolated to 0.

To illustrate this point, isothermal plots of phase angle and complex viscosity versus frequency for a penetration grade bitumen, an EVA PMB and a SBS PMB are presented in Figures 13 to 15.

The isothermal plots for the penetration grade bitumen clearly show the phase angle approaching 90° at low frequencies. In addition the viscosities are seen to be approaching constant Newtonian behaviour at the lower end of the frequency domain, particularly at the higher temperatures. This indicates, as it has been shown above, that both construction methods are able to calculate η_o for unmodified, penetration grade bitumens

Compared to the isothermal plots of phase angle for the penetration grade bitumen, the plots for the EVA and SBS PMBs do not approach 90° (pure viscous behaviour) at low frequencies and/or high temperatures. This is due to the increased polymeric behaviour of the PMBs at low frequencies and high temperatures which negates the use of the SHRP method as a means of calculating the zero shear viscosity for these highly modified binders. However, the isothermal plots of complex viscosity for the two PMBs are similar to those found for the penetration grade bitumen, allowing the data to be manipulated by the Puzinauskas plots to determine the zero shear viscosities for these binders.

The limitation of the SHRP method can therefore be attributed to its inability to account for the different semi-crystalline structures found at different temperatures in EVA PMBs and the increased elasticity, especially at low frequencies, of SBS PMBs. Both these factors result in the viscoelastic response of highly modified PMBs becoming more elastic rather than more viscous at low frequencies at particular temperatures. However, at lower levels of modification or at temperatures above the fusion temperature of the EVA copolymer (approximately 65°C for these EVA PMBs (Airey and Brown, 1998)), the SHRP method can still successfully be used to estimate zero shear viscosity.

Zero shear viscosities obtained for the penetration grade bitumens and certain EVA and SBS PMBs by means of both the Puzinauskas and SHRP method are plotted in Figure 16.

The figure shows that for the penetration grade bitumens the viscosity data, as determined by the SHRP and Puzinauskas methods, lies almost exclusively along the viscosity equivalency line. However, the viscosity data for the EVA and SBS PMBs does not show the same high degree of equivalency between the two methods, particularly within the viscosity range from 1,000 Pa.s to 100,000 Pa.s (corre-

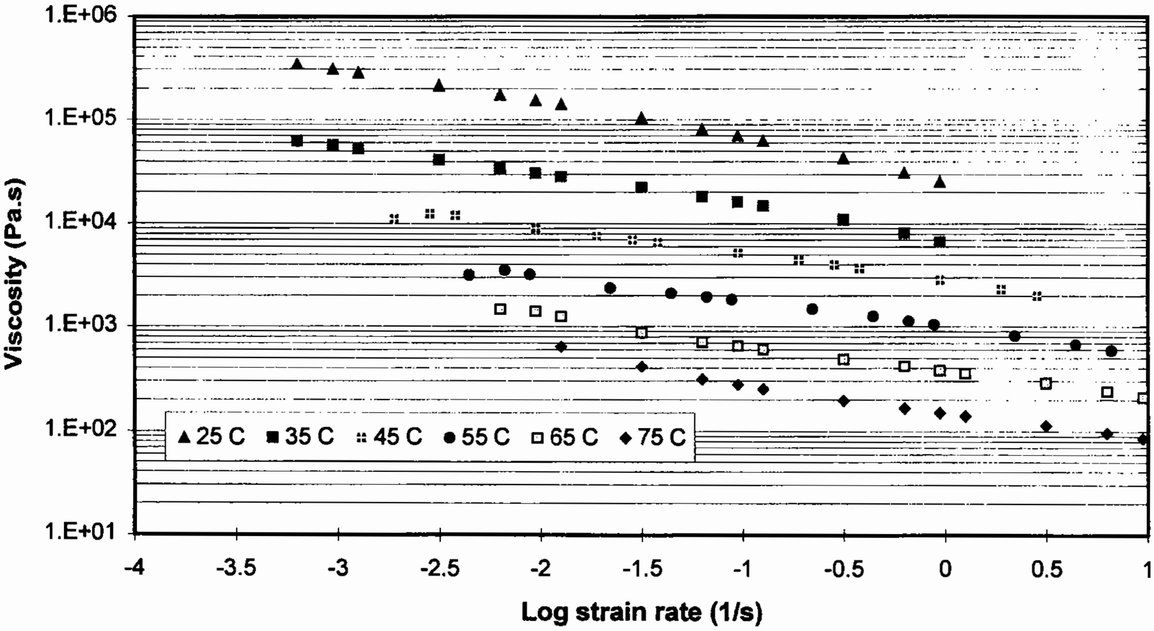

FIGURE 12 Zero shear viscosity – Puzinauskas method for 7% SBS – Base Bitumen B

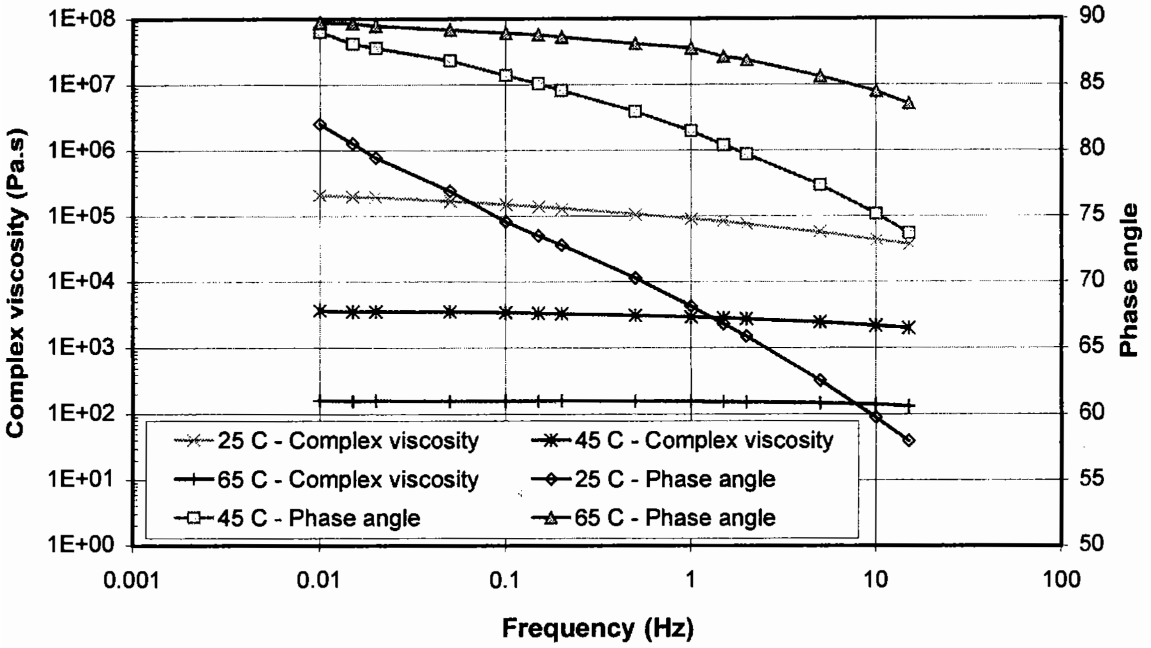

FIGURE 13 Isothermal plots of phase angle and complex viscosity for Base Bitumen A

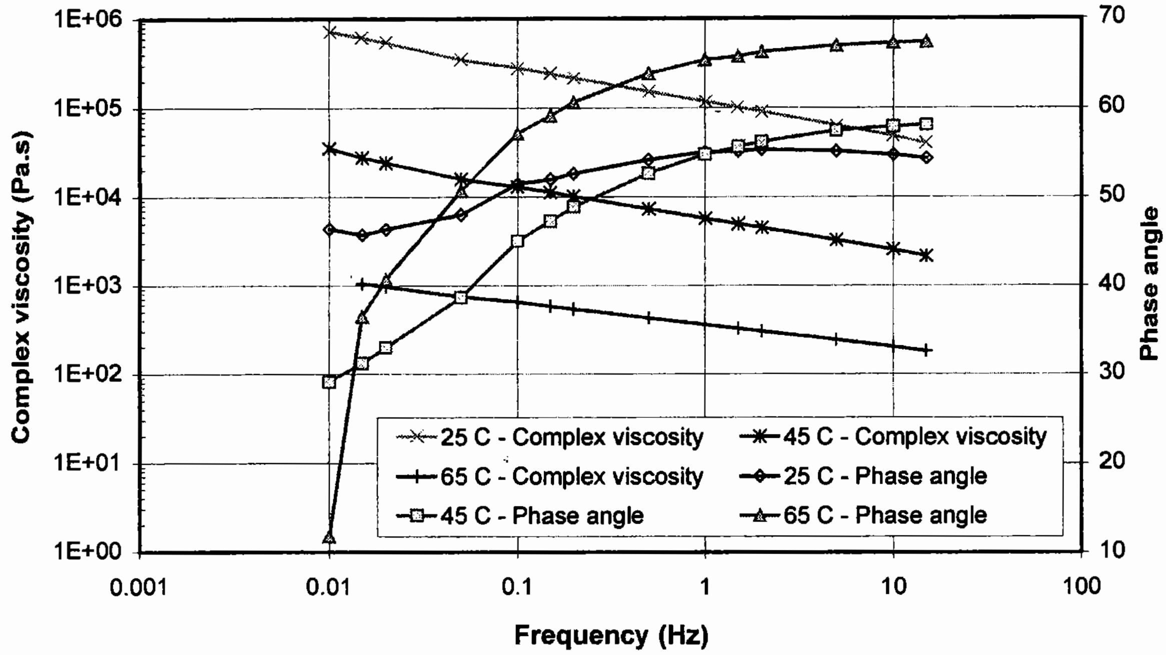

FIGURE 14 Isothermal plots of phase angle and complex viscosity for 7% EVA – Base *Bitumen B*

sponding to temperatures between 30°C and 60°C). The lack of agreement between the two methods increases with increasing polymer modification. To overcome the problems associated with the SHRP method all the zero shear viscosities used in the subsequent sections of this paper have been determined by means of the Puzinauskas construction method.

ZERO SHEAR VISCOSITY ANALYSIS

In addition to plotting the viscosities, calculated from the dynamic oscillatory test data and measured with the rotational viscometer, onto Heukelom's BTDC, the data was also plotted in the form of a log viscosity versus temperature plot. The viscosity-temperature relationship for Base Bitumen A, 7% EVA – Base Bitumen B and 7% SBS – Base Bitumen B are shown in Figure 17.

The three plots show distinctly different viscosity-temperature relationships for the penetration grade bitumen, EVA and SBS PMBs. The penetration grade bitumen shows a smooth continuous decrease in viscosity with increasing temperature and a good correlation between the DSR and rotational viscometry data. The viscosity-temperature relationship for the penetration grade bitumen can be accurately modelled using an equation in the following form (Garrick, 1992):

$$\log(100\eta_T) = r + sT^{-m}$$

where: η_T = initial viscosity at temperature T, in cp T = temperature in degrees Kelvin (K) r, s and m = constants or in a more conveniently, rearranged form:

$$\frac{\log(100\eta_T)}{\log(100\eta_{333})} = 1 + G^m(T^{-m} - 333^{-m})$$

where: η_{333} = viscosity at 60°C (333 K), in cp G and m = constants ($G = \sqrt[m]{B}$)

These simple, empirical models have been successfully used to model the viscosity-temperature rela-

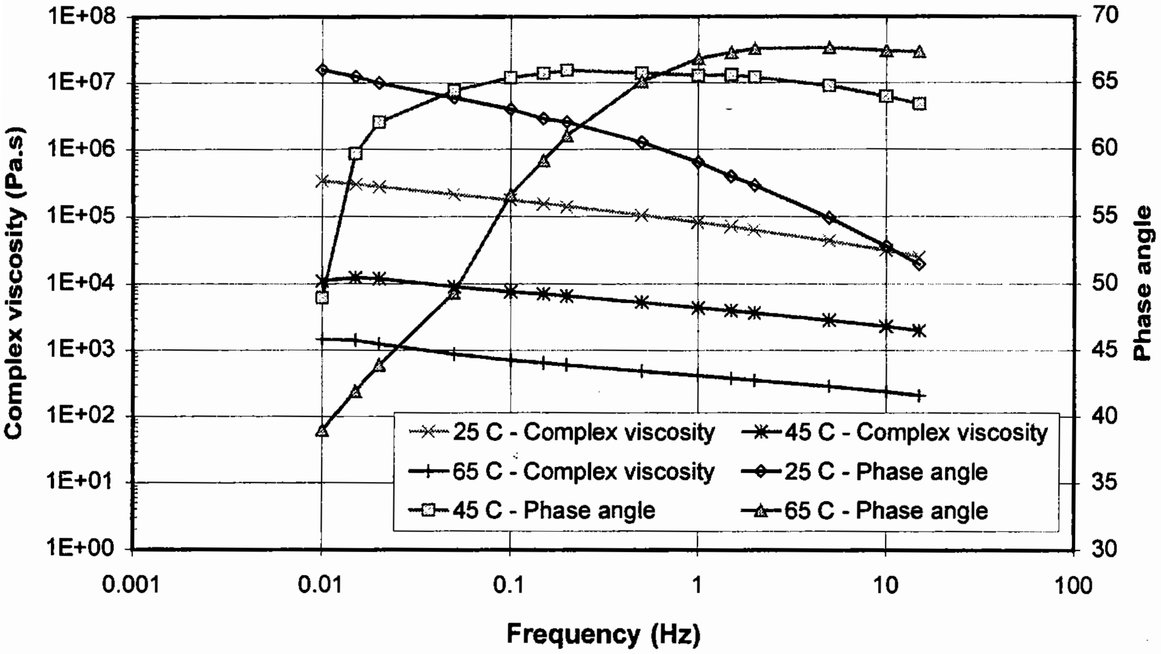

FIGURE 15 Isothermal plots of phase angle and complex viscosity for 7% SBS – Base Bitumen B

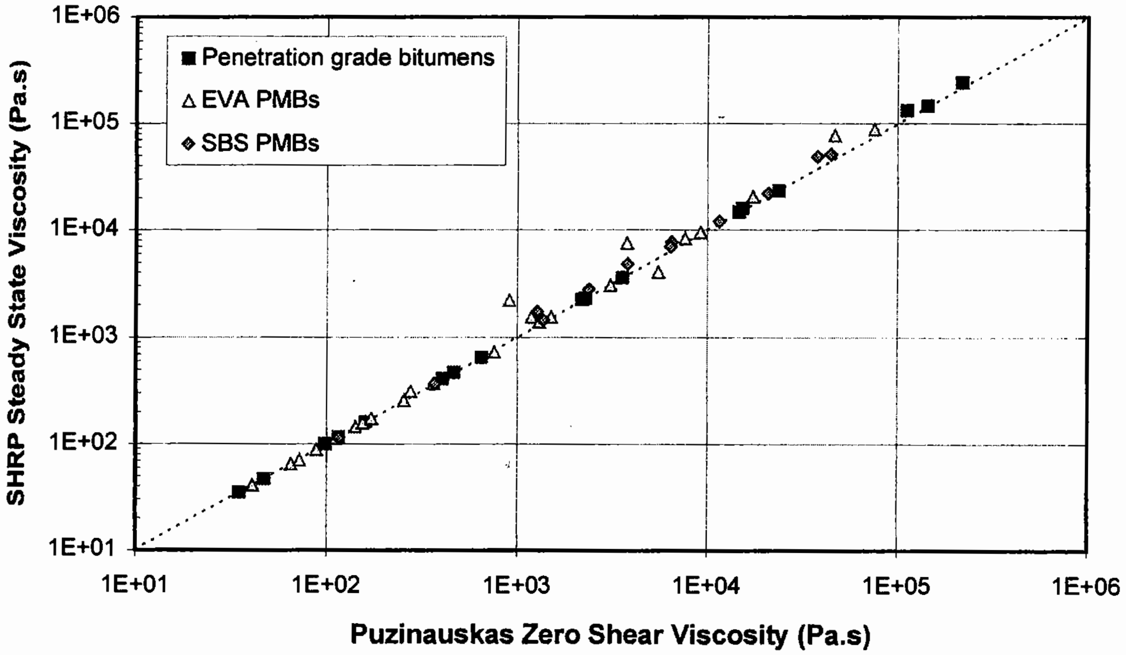

FIGURE 16 Correlation between Puzinauskas viscosity versus SHRP viscosity

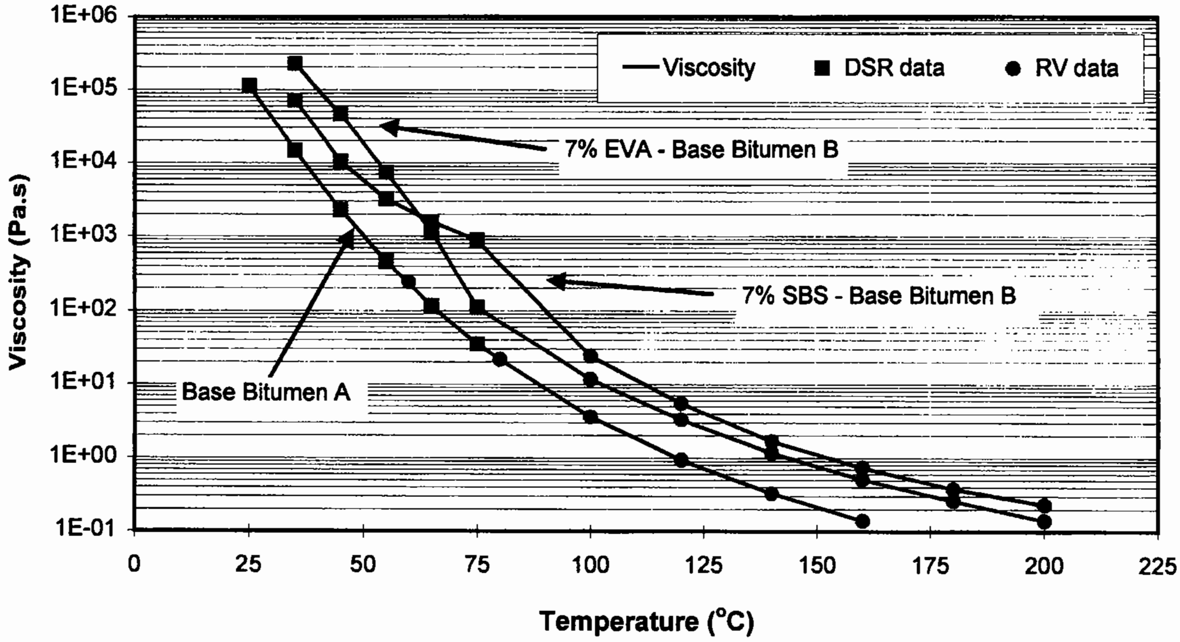

FIGURE 17 Viscosity-temperature relationship for Base Bitumen A, 7% EVA – Base Bitumen B and 7% SBS – Base Bitumen B

tionships of a number of penetration grade bitumens (Garrick, 1992).

The viscosity curve for the EVA PMB clearly indicates the melting (fusion) region of the EVA copolymer between 65°C and 75°C. This melting temperature range is consistent with the fusion temperature range identified for this PMB by means of differential scanning calorimetry (DSC) testing (Airey, 1999). The effect of the semi-crystalline copolymer can be seen to increase the viscosity of the PMB at temperatures below the fusion temperature of the copolymer. The viscosity-temperature relationship at temperatures above the EVA fusion temperature mirrors that seen for the penetration grade bitumen.

The viscosity-temperature relationship for the SBS PMB is once again different from that seen for the penetration grade and EVA modified bitumens. Compared to the EVA PMB, the melting temperature of the SBS copolymer occurs at a higher temperature of between 75°C and 100°C, corresponding to the glass transition temperature of the polystyrene (Whiteoak, 1990). The presence of the SBS polymer network allows an almost plateau-like viscosity behaviour to be seen within the temperature range of 55°C to 75°C.

The combination of dynamic oscillatory and rotational viscometry data in the form of viscosity-temperature plots allows the different rheological characteristics of penetration grade bitumens, semi-crystalline EVA and elastomeric SBS PMBs to be identified. The distinguishing characteristics of a smooth viscosity-temperature transition for Base Bitumen A, the sharp reduction in viscosity at the copolymer's fusion temperature for the EVA PMB and the plateau-like region for the SBS PMB are all clearly evident.

RHEOLOGICAL DATA PRESENTED IN BTDC

In addition to the conventional test data (Penetration, Softening Point and high temperature viscosity), zero shear viscosities (steady state viscosities) obtained

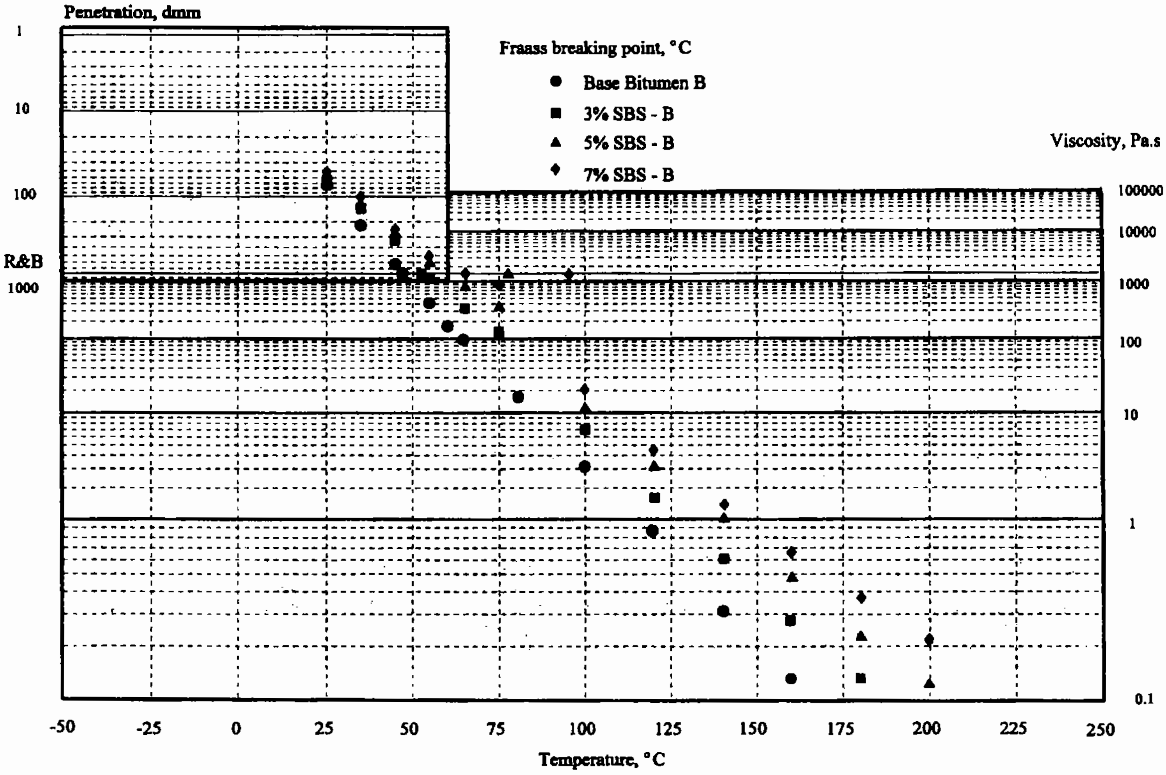

FIGURE 18 BTDC for SBS – Base Bitumen B PMBs

from DSR testing have been plotted in the form of BTDCs for a series of EVA and SBS PMBs. For purposes of brevity only a limited number of these BTDCs have been reproduced in this paper. Figure 18 shows the rheological data for Base Bitumen B together with the three SBS PMBs that have been produced by means of physical blending of the SBS polymer and base bitumen.

The BTDC shows a decrease in Penetration and an increase in Softening Point together with an increase in viscosity with increasing polymer modification. The rheological data presented in the form of Heukelom's BTDC depicts, as it has done in the illustrative chart in Figure 3, the advantageous increase in viscosity at high temperatures in terms of the material's high temperature permanent deformation resistance. However, the increased viscosity at high temperatures also has implications for the required mixing and compaction temperatures of the modified bituminous material.

In order to provide a clearer indication of the suitability of Heukelom's BTDC at quantifying the effect of polymer modification, the Penetration, Softening Point and viscosity data has been re-plotted for Base Bitumen B and the two highest polymer content EVA and SBS PMBs in Figures 19 and 20.

The charts are not meant to provide a fundamental analysis of the various PMBs, but do allow various observations to be made with regard to the suitability of conventional binder test data and the BTDC at describing the rheological characteristics of PMBs. The figures show that a straight line can be plotted through the Penetration, Softening Point and high temperature viscosities, together with the zero shear

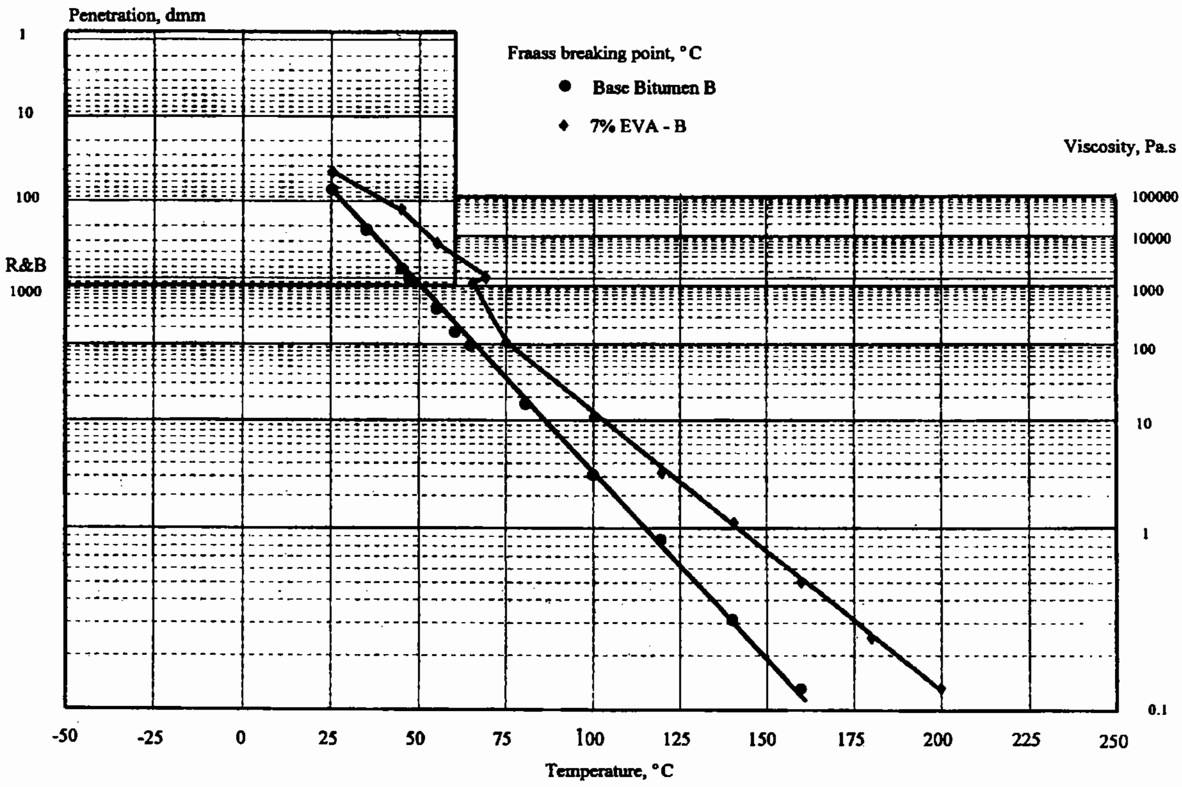

FIGURE 19 BTDC for 7% EVA – Base Bitumen B

viscosities, for the unmodified bitumen. This is consistent with the "S" type behaviour associated with the BTDC.

With regard to the PMBs, the viscosity-temperature relationship for the EVA and SBS PMBs are similar to that shown for the idealised modified binder in Figure 3, although the Softening Point temperatures are considerably greater for the thermoplastic rubber SBS PMB than for the EVA PMB. In terms of the utilisation of the essentially empirically-based BTDC to describe the polymer modification of a base bitumen, the results indicate that the charts are able to illustrate the benefits of polymer modification. However, the charts do indicate that the Ring-and-Ball Softening Points for PMBs tend to overestimate the benefits of polymer modification. This phenomenon has been identified by other researchers, with King *et al* (1993) finding that the correlation between Softening Point and rutting resistance for PMBs is extremely poor, particularly for styrene butadiene (SB) block copolymer modified PMBs.

The benefits of using Heukelom's BTDC for conventional binders is that it is possible to predict the viscosity-temperature characteristics of penetration grade bitumens, over a wide range of temperatures, using only routinely measured Penetration and Softening Point values. The charts then provide a means of selecting the appropriate operating temperatures and viscosity requirements for asphalt mixture manufacture and application. In addition, the charts provide a means of comparing the viscosity-temperature relationships and temperature susceptibilities of different binders.

For PMBs, the charts are unable to predict the viscosity-temperature characteristics from only the Penetration and Softening Point and therefore require

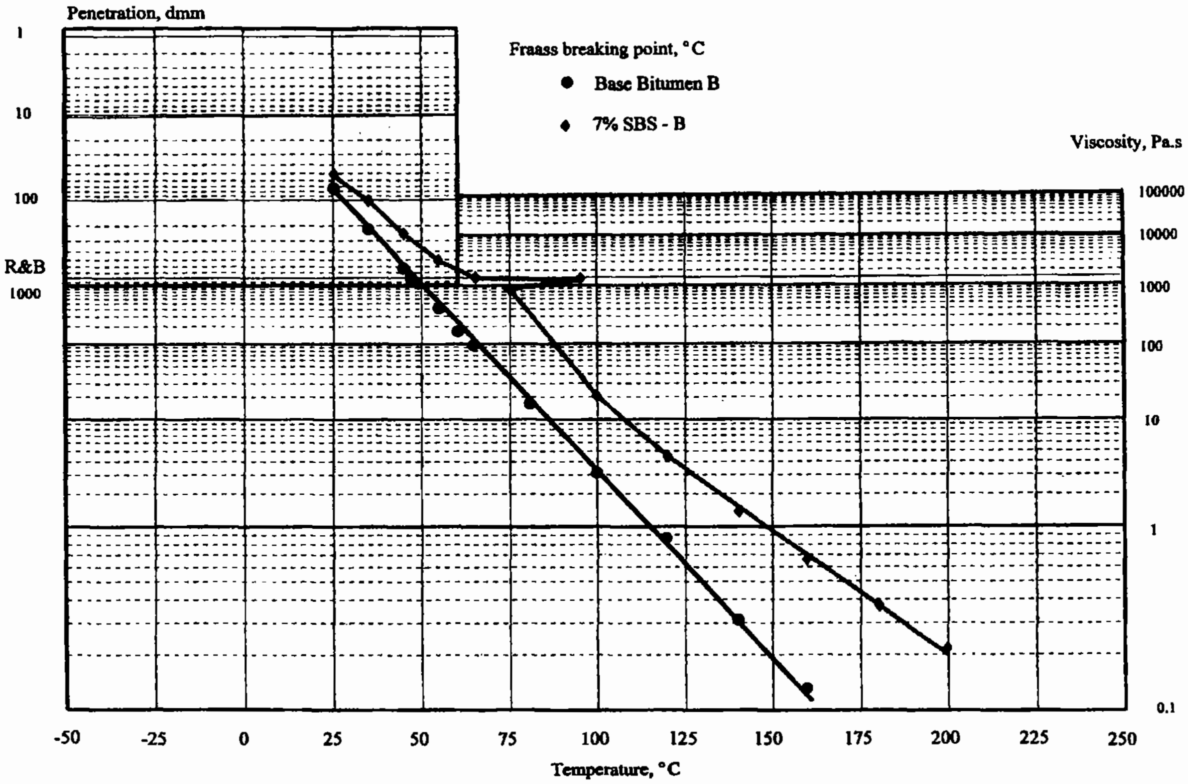

FIGURE 20 BTDC for 7% SBS – Base Bitumen B

addition rheological (viscosity) test data. In terms of characterising the viscosity-temperature properties of PMBs, the BTDCs do not provide any more information that can be obtained from the viscosity-temperature plots in Figure 17.

CONCLUSIONS

The objective of the paper was to evaluate the suitability of the BTDC, as well as conventional binder tests, at characterising the polymer modification of bituminous binders, particularly their viscosity-temperature characteristics. To achieve this a testing methodology was proposed whereby DSR test data was converted by means of two construction techniques, namely the SHRP and Puzinauskas methods, and combined with conventional binder data (Penetration, Softening Point and high temperature viscosity) in the form of viscosity-temperature plots and BTDCs.

The following conclusions can be drawn from this investigation:

- The testing methodology used in this study provides a convenient means of combining empirically-based binder data and fundamental rheological data in order to investigate the rheological characteristics of bituminous binders. In the context of this investigation, the conventional binder data (Penetration, Softening Point and high temperature viscosity) and the DSR data have been combined to evaluate the viscosity-temperature characteristics of the binders.
- Both the SHRP and the Puzinauskas construction methods can be used to calculate the zero shear viscosities, η_o, from oscillatory-type DSR test

data for unmodified, penetration grade bitumens. As the viscosity-frequency relationships for PMBs are similar to that obtained for penetration grade binders, the Puzinauskas construction method can also be used to determine η_o for EVA and SBS PMBs. However, the reliance of the SHRP method on the bitumen fulfilling the time-temperature superposition principle means that this method is unable to accurately predict η_0 for highly modified PMBs.

- The log viscosity versus temperature plots, constructed using high temperature rotational viscometry data and transformed DSR data, allow three distinctive viscosity-temperature relationships to be identified for the unmodified, EVA and SBS modified bitumens.
- The advantages of polymer modification in terms of increased viscosity at high service temperatures can be seen in the BTDCs once the Penetration, Softening Point and viscosity data has been plotted.
- The combination of transformed DSR zero shear viscosity and Ring-and-Ball Softening Point in the BTDCs indicates that the empirically-based Softening Point overestimates the benefits of polymer modification.
- Although the BTDC does provide the bitumen rheologist with a clear indication of polymer modification, the construction of the chart solely from empirically-based tests such as Penetration and Softening Point is not possible. This negates the advantage of the BTDC in terms of its easy construction and requires addition rheological test data to be measured and incorporated into the chart. In terms of characterising the viscosity-temperature properties of PMBs, the BTDC therefore does not provide any further information that can be obtained from conventional viscosity-temperature plots.

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