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TEMPERATURE SUSCEPTIBILITY OF SOUTH AFRICAN BITUMENS

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Abstract

The change in the SABS 307 specification for road bitumens from penetration based to viscosity based has meant that consistency is now mainly defined by viscosity testing. The temperature susceptibility of bitumen is discussed with reference to dynamic viscosity and penetration. Databases were used of South African bitumens from all refineries and all paving grades. Models were developed to interpolate consistency in the service and application temperature ranges, and to extrapolate between viscosity and penetration.

1 INTRODUCTION

The temperature susceptibility of bitumen is the rate at which its consistency changes with a change in temperature. It is determined by measuring the consistency at various temperatures. Bitumen is a thermoplastic material which softens on heating and stiffens on cooling i.e. its consistency changes. The viscosity of bitumen is known to be a function of temperature and shear rate. Work has been done concerning the general form of these relationships, however the specific nature of the dependency of the viscosity of bitumen on temperature and shear rate is still not well understood. In particular, a better system is needed for characterising the temperature susceptibility of bitumen.

The South African Bureau of Standards (SABS) Specification 307 for bitumens (1) is being amended from being penetration based to viscosity based. This was necessary because over the years the traffic loading and volumes have increased, to the extent that the spread in binder quality under the penetration based specification is no longer acceptable to the industry. The practitioner needs to have a more detailed knowledge of the performance of the bitumens available, and empirical parameters such as penetration and softening point are not adequate to supply this.

This paper will discuss the temperature susceptibility of SABS 307 bitumens with reference to both the penetration and viscosity based specifications. The results of several laboratory investigations will be presented, and models developed to predict consistency at various temperatures.

2 SPECIFICATION FOR ROAD BITUMENS IN SOUTH AFRICA

2.1 Penetration based specification

The SABS 307 penetration based specification for penetration grade road bitumens, used in South Africa prior to 1993/4, is summarised in Table 1.

Table 1 : Part of SABS 307 penetration grade bitumen specification

Property	Penetration grade				Test method
	40/50	60/70	80/100	150/200	
Penetration at 25°C/100g/5s, 0,1mm	40-50	60-70	80-100	150-200	IP 49
Softening point °C	49-59	46-56	42-51	36-43	IP 58
Other	Ductility, solubility, TFOT, spot test				

Despite the control offered by this specification, there were a number of perceived short comings in South African bitumen quality (Bergh and Green, 2) which may have occurred as a consequence of enforced changes in sources of crude oil processed at refineries during the period of sanctions (Vos, 3). In May 1988, the Bituminous Materials Liaison Committee, which represents the SA bituminous binder industry, appointed a task group to investigate and propose changes to the binder specification. They were to concentrate on the problems being encountered in the road construction industry that could be attributed to quality of the binder and to establish those which could not. For example the stripping of aggregate at the binder/aggregate interface would not necessarily be a failure of the binder itself, but ravelling of aggregate, with binder still attached, from the matrix of the road surface could indicate a lack of internal strength within the binder itself (cohesion).

The Task Group highlighted a number of failure conditions which could be attributed to binder quality, and/or inadequacy in the physical and rheological properties of the binder such as viscosity, brittleness, durability, cohesion, composition, tackiness, and ductility.

There were other shortcomings in the specification: it was based on empirical tests such as penetration and softening point, the test results did not correlate well with the performance at high road temperatures, the ductility test at 25°C did not distinguish well between binders since most had a ductility outside the range of the test apparatus, and control over the properties of aged bitumen was limited to the empirical measure of penetration.

Visc 60 RTFOT
Visc new

Low = good
high = bad

2.2 Viscosity based specification

The task group noted a worldwide trend in specifications of bitumen quality, away from empirical measurements such as penetration and softening point, and towards fundamental engineering properties such as viscosity, cohesion, durability, etc. The need to consider South African environmental conditions promoted the selection of tests that could determine the temperature susceptibility and ageing characteristics of the bitumen. These rheological properties contribute most significantly to the physical properties which give an indication of failure or distress of a road surfacing.

The task group accordingly suggested an amended, viscosity based, SABS 307 specification for road grade bitumens in South Africa. The penetration test at 25°C and softening point test are retained in the amended specification as a bridging parameter until experience with the viscosity specification can be obtained. The Rolling Thin Film Oven Test (RTFOT) is introduced as a conditioning process to simulate age hardening of the bitumen due to handling during mixing or spraying; the conditioned samples are then subjected to standard tests such as viscosity, ductility or penetration. The ductility test is retained, but the test temperature has been lowered from 25°C to either 10°C (B4 and B8) or 15°C (B12 and B24).

In the initial draft amendment dated January 1993, there were four grades proposed: B35, B20, B10, and B5. These grades were based on the midpoint of the acceptable viscosity range. As experience was gained with the initial draft amendment, it became apparent that there were inter-laboratory differences in testing results deriving from variations in interpreting the allowable equipment (spindles) to be used in the ASTM D4402 test procedure. A measurement assurance programme (MAP) was instituted to investigate this, and as a result, specific Brookfield test equipment was recommended (Zacharias and Emery, 4). This in turn led to changes in the viscosity test results for the same bitumens.

In late 1993, the first draft of the amended specification was replaced by the final version, with new viscosity ranges based on testing using the recommended spindle sizes (SC4-21, SC4-27, SC4-29). The viscosity ranges for the final amended specification SABS 307 are given in Table 2.

Table 2 : Part of proposed SABS 307 viscosity grade bitumen specification

Property	**Road grade** (equivalent penetration grade)				Test method
	B24 (40/50)	**B12** (60/70)	**B8** (80/100)	**B4** (150/200)	
Viscosity at 60°C, Pa.s[a]	170-300	105-165	55-100	25-50	ASTM D4402
Viscosity at 135°C, Pa.s, minimum[b]	0,27	0,22	0,15	0,12	ASTM D4402
Other tests include	Penetration, softening point, low temperature ductility, RTFOT (with various associated tests), spot test.				

Notes a: Ranges for first draft of amended specification were:
B35 250-480; B20 140-240; B10 60-130; B5 40-60 Pa.s

b: Using specified Brookfield RV viscometer using SC-4 type spindles and Thermosel system.

It should be noted that the refining process at the four South African refineries will not change as a result of the viscosity based specification, and so essentially the same products will be produced. The variations that do occur will be minor, and most bitumens produced to the viscosity based specification should meet the limits of the older penetration based specification. All four refineries were producing product to the viscosity based specification by 1 January 1994.

2.3 Performance based specification

The viscosity based specification represents an important step along the path to a fully performance based specification. In terms of the present state of knowledge and affordability, it is the logical step to have taken. The next step forward will be to full performance related test methods and specification with no empirical consistency parameters. This is the approach taken in the new Strategic Highway Research Programme (SHRP) bitumen specification, which sought to develop performance related test methods and specifications rather than continue to rely on empirical or consistency parameters.

In the low temperature range, SHRP researchers held that penetration and ductility tests were inappropriate as fundamental measurements for the characterisation of low temperature rheology, because the stress fields within the test specimens cannot be defined and the strains during the test are very large, vary within the test specimen, and cannot be easily modeled and calculated (Anderson et al., 5).

Their approach has been to develop three tests for bitumen:

- determination of dynamic shear resistance at 45°C,
- measurement of creep stiffness using a bending beam rheometer at -15°C,
- direct tension test at low temperatures to characterise failure limits.

The new SHRP binder specification is unique in that binder selection is allowed for on the basis of climate. The physical properties (such as creep) are constant among all the binder grades and what varies is the temperature at which the requirements must be met. This is an exciting concept, but they now need to amass the years of developmental experience before the approach can be considered sufficiently proven to be considered by South Africa. In practical terms, the high costs of the new testing equipment and tests are also problematic.

3 DETERMINATION OF THE TEMPERATURE SUSCEPTIBILITY OF BITUMEN

3.1 Rheology of bitumen

3.1.1 Fundamental characterisation

The rheology of bitumen is defined by its stress-strain-time-temperature response. Since bitumen is a visco-elastic material, fundamental rheological characterisation involves the determination of its viscosity and stiffness modulus under fixed

conditions of stress, strain, temperature and loading time. In considering the viscosity aspects, special attention must be paid to the shear rate dependence of the viscosity.

In general the viscosity will decrease with increasing shear rate. The maximum viscosity, measured at a shear rate approaching zero, is called the zero shear rate viscosity, or the Newtonian or absolute viscosity. The effect of shear rate on viscosity is dependent on the absolute viscosity level (which is dependent on the grade or penetration value), and the amount of 'structure' in the bitumen (which is associated with the penetration index, PI).

3.1.2 Newtonian and non-Newtonian fluids

The flow behaviour of bitumen can be divided into Newtonian and non-Newtonian. When it is behaving like a Newtonian fluid, the rate of shear is proportional to the shearing stress, and so the viscosity is independent of the shear rate. At 60°C and above, many bitumens are held to behave like Newtonian liquids (de Bats and van Gooswilligen, 6), although true Newtonian viscosity can only be assured above about 90°C.

For convenience, the temperature range relevant to road grade bitumens can be divided into a service temperature range with an upper limit for South Africa of 60°C (a typical high road temperature in summer), and an application temperature range with a lower limit of 60°C (the viscosity of bitumen at elevated temperatures is important for the applications of pumping, mixing and spraying).

Below about 60°C, bitumens exhibit non-Newtonian behaviour in which the rate of shear is not proportional to the shearing stress. Thus at most road service temperatures, bitumens display non-Newtonian characteristics and their viscosity depends on the rate of shear. Under these conditions, the measured viscosity is not a unique material property, and depends on the bitumen, the test apparatus and test conditions. Comparisons between non-Newtonian viscosity values can only be made for similar viscometers under similar conditions of shearing stress and shear history.

3.1.3 Measurement

There are standardised instruments available for the measurement of viscosity. For Newtonian fluids measured at 60°C and above, the methods available determine the Newtonian viscosity in good approximation (de Bats and van Gooswilligen, 6). These include the Brookfield, Haake, Cannon-Manning and reverse flow U-tube viscometers. For non-Newtonian fluids measured below 60°C, the viscosity is measured by methods such as the Shell sliding plate microviscometer and the Asphalt Institute cone and plate viscometer, but these are slow and expensive tests. It is common to use empirical measures of consistency in this range such as penetration and softening point.

The use of a standard method such as the Brookfield apparatus for measuring viscosity within a specification means that the problems of shear rate dependency below 60°C, and possibly below about 90°C, fall away to a large extent. However their repeatability lies in using only the equipment (spindles) specified in the test method.

3.1.4 Effect of wax in the bitumen

The effect of wax can be seen from the Bitumen Test Data Chart (BTDC), developed by Shell (Heukelom, 7). It provides a means of describing both penetration and viscosity as functions of temperature.

Three classes of bitumens can be distinguished by the BTDC plot, with each class showing a specific type of behaviour. The standard class is the 'Class S' which comprises a large group of residual and cracked bitumens of different origin with a limited wax content. This would be represented by a straight line on the BTDC. The waxy class - 'Class W' - comprises bitumens with a high wax content which would show a discontinuity between the penetration and viscosity portions of the BTDC plot, although the two portions would be essentially parallel. The blown class - 'Class B' - comprises bitumens substantially hardened through air blowing and the slope of the low temperature BTDC plot is flatter than the high temperature plot.

The discontinuity in the BTDC plot of waxy bitumens occurs over much of the service temperature range, say from 15 to 85°C, although this depends on the nature of the wax and the thermal history of the bitumen. The problem is that it is not possible in practice to assess how the bitumen viscosity at 60°C has been influenced by the effects of wax since the specification does not indicate the shape and position of the discontinuity. To do so would require additional testing and this is not economically practical since the only way to determine the temperature susceptibility free from any influence of wax would be test viscosity at several temperatures above say 90°C.

In Figure 1, a waxy bitumen has been plotted on the BTDC, and the possible scatter of viscosity results at 60°C in the discontinuity range can be seen. If 60°C is within the discontinuity range, the calculated temperature susceptibility from testing at 60°C and 135°C will be overestimated. More importantly, the high temperature results cannot be extrapolated back to determine consistency in the service temperature range (such as estimating penetration from viscosity results). In practical terms, if experience shows that a bitumen needs a certain penetration in a certain climate for hotmix asphalt to be sufficiently stiff to perform or to resist rutting, then estimating this from the viscosity results will be misleading if the bitumen is a Class W.

The penetration/road grade bitumens in South Africa typically have a very low wax content, increasing with increasing softness, although most can be expected to be Class S. A sample of each penetration grade (40/50, 60/70, 80/100, 150/200) from each of the four South African refineries (except Calref 60/70) was tested in this research and all were found to be Class S according to Heukelom's definition (7). However viscosity at 60°C was used to determine the viscosity portion of the BTDC plot which means that the result may still have been slightly affected by wax, and possibly some bitumens should have been classed as 'Class W'. With the data at hand, this could not be proven and further research would be needed to quantify the extent and significance of waxy bitumens in South Africa.

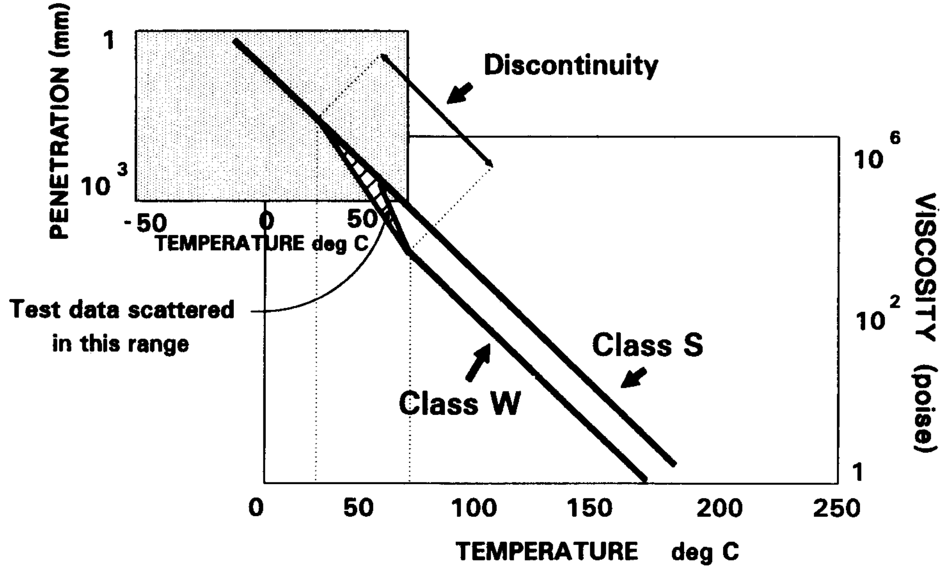

Figure 1 : Bitumen Test Data Chart for a Class W bitumen

3.2 Temperature susceptibility of bitumen

The temperature susceptibility of bitumen is defined as the change in consistency with temperature. There are a number of computed measures available to quantify the temperature susceptibility of bitumen.

In practice though, the cost and difficulty of some tests limits their use outside the research laboratories. The generally available data to quantify temperature susceptibility are penetration and softening point and viscosity at 60°C and 135°C. The viscosity based bitumen specification SABS 307 provides all this data, and the associated methods of determining the temperature susceptibility are discussed below.

3.2.1 Penetration Index

The common method of determining temperature susceptibility of bitumen is Penetration Index (PI), which is based on the BTDC (Heukelom, 7; also discussed briefly in the Shell handbook, 8). The BTDC shows the plot of consistency with temperature over the full temperature range from application to service. As such it gives an extremely useful picture of the temperature susceptibility of bitumen. For road grade bitumens in South Africa, the variation in PI values is usually small, say between -1,3 and 0,3. However the extremes for worldwide bitumens of all grades (not just road grades) are reported between -3,0 and +8,0; the higher PI values representing Class B bitumens (de Bats and van Gooswilligen, 6).

Bitumens of lower and negative PI soften more readily than those with higher PI. Bitumens with higher and positive PI are more rut resistant, but can lead to difficulties with mixing, laying and particularly compaction and fatigue performance. Using SABS 307 data, PI can be determined from the penetration at 25°C and the softening point (as measured by ASTM D36, not IP58).

3.2.2 Bitumen temperature susceptibility (BTS)

BTS is a general definition of temperature susceptibility for penetration and viscosity regions of class S bitumens. It is valid over their entire penetration/viscosity range (de Bats and van Gooswilligen, 6), but is not suited to class W or class B bitumens. It is based on the original PI definition of Pfeiffer and Van Doormaal (9) and the underlying principles of the BTDC, but extending those such that BTS is determined for both the penetration and viscosity ranges. For the penetration range, BTS_{pen} = PI. For the viscosity range, BTS_{vis} is given by equation 1:

$$BTS_{vis} = \frac{30}{0{,}4\,(C_1 - C_2)\,(T_2 - T_1)^{-1} + 1} - 10 \qquad (1)$$

$$\textit{Where} \quad C_{1,2} = \frac{1310 * \log_{10} Viscosity@T_{1,2}}{4{,}35 + \log_{10} Viscosity@T_{1,2}}$$

Viscosity in poise $\quad T = \textit{Temperature}\,°K$

3.2.3 Viscosity temperature sensitivity (VTS)

The viscosity at temperatures above 60°C can be calculated using VTS, which is based on viscosity measurements at 60°C and 135°C. There are several forms of the equation (such as de Bats and Gooswilligen, 6; De Kock, 10; and Garrick, 11). The form used here in equation 2 is similar to the Garrick equation (11) which gives consistency with his rheological grouping addressed below. This is equation used by the Asphalt Institute and by McLeod (12).

$$VTS(T_1 - T_2) = \frac{\log(\log_{10}(V_2)) - \log(\log_{10}(V_1))}{\log_{10}(T_1) - \log_{10}(T_2)} \qquad (2)$$

Where T_1, T_2 = *temperature* °K
V_1, V_2 = *viscosity centipoise at* T_1, T_2

As discussed above, slight inaccuracies may occur if the bitumen is more waxy than is used in South African bitumens, because the dynamic viscosity at 60°C would still be in the waxy range, giving a slightly steeper gradient, but in practical terms these inaccuracies can be ignored.

3.2.4 Rheological grouping

The concept that bitumens can be grouped by like rheological properties has been proposed by Garrick (11). Analysis of 118 bitumens in America showed that they could be placed into ten distinct rheological groups, defining their viscosity-temperature and viscosity-shear rate relationships. These groups are delimited by VTS, PVN(25-135) [which is the same as the Pen-Vis number or PVN of McLeod, as shown in his Appendix A, 12] and PVN'(25-60), respectively equations 2, 3, and 4.

$$PVN(25\text{-}135) = \frac{-1{,}5\,(A - \log_{10}(V135))}{A - B} \qquad (3)$$

Where
$A = 4{,}25800 - 0{,}79674\,\log_{10}(P25)$ $\qquad B = 3{,}46289 - 0{,}61094\,\log_{10}(P25)$

$V135$ = *viscosity cSt at* 135 °C $\qquad P25$ = *penetration* 0,1*mm at* 25 °C

$$PVN'(25\text{-}60) = \frac{-1{,}5\,((6{,}4890 - 1{,}5900\,\log_{10}(P25) - \log_{10}(V60))}{1{,}0500 - 0{,}2234\,\log_{10}(P25)} \qquad (4)$$

Where $V60$ = *viscosity, Poise at* 60°C $\qquad P25$ = *penetration,* 0,1*mm at* 25°C

Although each bitumen has a unique viscosity/temperature relationship, the relationship for bitumens in the same rheological group are almost identical, and can be modelled by equation 5. The limits for the group parameters, as well as the equation 5 constants for each group, are given in Table 3. When the group constants are used to estimate the viscosity of a given bitumen, the maximum error is about 10% at temperatures above 60°C and 50% at lower temperatures which is related to the non-Newtonian characteristics at lower temperatures (Garrick, 11).

$$\frac{\log(100\eta_T)}{\log(100\eta_{333})} = 1 + G^m\,(T^{-m} - 333^{-m}) \qquad (5)$$

Where
η_T = *viscosity at temperature T, Poise*
η_{333} = *viscosity at* 60°C (333°K), *Poise*
T = *temperature,* °K $\qquad G, m$ = *constants*

4 TESTING PROGRAMME

4.1 Test methods and data sources

The main source of data [i] used in this paper was from 302 samples which were both routine and experimental samples tested at the laboratories of the four South African refineries (Table 4). The routine samples were from refinery production to the penetration based SABS 307 specification, but since the refining process has not changed with the change from penetration to viscosity based specification, these will be similar to bitumen produced under the viscosity based specification. The testing was generally performed in accordance with the methods specified in the penetration and viscosity based SABS 307, save that IP58 was used for the softening point.

Table 3 : Range of temperature susceptibility values for Garrick's rheological groups

Group	VTS (60-135) Equation 2	PVN (25-135) Equation 3 (also McLeod, 12)	PVN' (25-60) Equation 4	Eqn 5 constants	
				m	G
A	3,55 to 3,70	-0,15 to -0,60	+0,10 to -0,35	4,0	327,0
B	3,35 to 3,55	+0,15 to -0,35	+0,20 to -0,30	4,3	322,0
C	3,75 to 3,85	-1,00 to -1,20	-0,60 to -0,75	4,1	329,0
D	3,35 to 3,55	-0,15 to -0,55	-0,30 to -0,75	4,7	319,0
E	3,50 to 3,70	-0,60 to -1,00	-0,30 to -0,75	4,7	321,0
F	3,90 to 4,10	-1,40 to -1,80	-0,80 to -1,50	4,4	328,5
G	3,60 to 3,80	-0,90 to -1,30	-0,75 to -1,20	4,9	321,0
H	3,40 to 3,60	-0,50 to -0,80	-0,75 to -0,90	5,1	317,5
I	3,55 to 3,65	-0,90 to -1,60	-1,20 to -1,80	5,4	318,0
J	3,45 to 3,55	-1,30 to -1,50	-1,80 to -2,10	6,6	315,0

Source: Garrick (11)

The second source of data [ii] were 15 bitumens comprising a sample from each of the four refineries (Calref, Genref, Natref, Sapref) for each of the four penetration grades (40/50, 60/70, 80/100, 150/200); one 60/70 sample was not available from Calref. This testing was conducted by the laboratory at Sapref in South Africa, as an extension to the testing being conducted under the MAP 7 programme (13). Again, the testing was performed in accordance with the methods specified in the penetration and viscosity based SABS 307, and the softening point was conducted in accordance with IP58. Additional viscosity testing on these samples was undertaken in Amsterdam by Shell Research laboratories using the ASTM D2170 reverse flow U-tube method at 135°C and the ASTM D2171 Cannon-Manning vacuum method at 60°C. Shell Research also calculated a number of consistency and BTDC parameters using their proprietary software.

The third source of data [iii] was from multiple testing on 4 bitumen samples, comprising a sample of each of the four grades from one refinery, which was undertaken at the University of Stellenbosch and Engen laboratories (de Kock, 10). This included the same penetration and viscosity testing as the main data source, with additional penetration testing at 30°C, 35°C and Shell sliding plate rheometer viscosity testing at 25°C.

Table 4 : Descriptors of main data source [i]

Grade (no. of samples)		Range of results: minimum; average; maximum			
		Penetration[a]	Softening point[b]	Viscosity 60°C[c]	Viscosity 135°C[d]
40/50	(82)	40; 45; 50	48,5; 51; 54	165; 215; 331	0,27; 0,35; 0,85
60/70	(91)	60; 66; 84	45; 49; 53	105; 133; 175	0,23; 0,29; 0,48
80/100	(70)	77; 91; 125	43; 46; 50	57; 90; 132	0,17; 0,24; 0,42
150/200	(16)	152; 171; 199	40; 43; 51	25; 37; 42	0,11; 0,15; 0,18
n.s.[e]	(43)	26; 86; 213	36; 48; 54	30; 142; 334	0,12; 0,24; 0,46

Notes a: Penetration at 25°C/100g/5s, 0,1mm : ASTM D36
b: Softening point (ring and ball) : IP58
c: Viscosity at 60°C Pa.s : Brookfield : ASTM D4402, spindles either SC29 or SC27
d: Viscosity at 135°C Pa.s : Brookfield : ASTM D4402, spindles either SC21 or SC27
e: Experimental bitumens, not made to fit a particular grade

4.2 Calculated temperature sensitivity parameters

For the main data source [i] with 302 samples, the parameters of VTS, PVN(25-135), PVN'(25-60) and PI were calculated (Table 5).

Table 5 : Bitumen temperature sensitivity parameters

Grade	Range of results: minimum; average; maximum			
	VTS[a] Equation 2	PVN(25-135)[a] Equation 3 Mcleod's PVN (12)	PVN'(25-60)[a] Equation 4	PI
40/50	2,96; 3,63; 3,83	-1,40; -1,16; -0,74	-1,51; -1,17; -0,09	-1,29; -0,72; -0,18
60/70	3,16; 3,60; 3,80	-,140; -1,11; -0,57	-1,41; -1,10; -0,17	-1,08; -0,50; +0,32
80/100	3,23; 3,61; 3,86	-1,44; -1,04; -0,42	-1,53; -1,08; -0,04	-1,55; -0,26; +1,34
150/200	3,52; 3,64; 3,82	-1,57; -1,03; -0,95	-1,34; -1,15; -0,68	-0,45; +0,86; +3,15
Non-spec.	3,54; 3,72; 3,81	-1,52; -1,10; -0,30	-1,53; -1,31; -0,9	-1,58; -0,38; +2,13

Notes a: Defined in section 3.2.4

5 PREDICTORS OF TEMPERATURE SUSCEPTIBILITY OF SOUTH AFRICAN BITUMENS

Predictors of temperature susceptibility have been determined for South African bitumens, based on the data available from the viscosity based bitumen specification SABS 307: penetration at 25°C, softening point, and viscosity at 60°C and 135°C.

5.1 Prediction within the service temperature range up to 60°C

5.1.1 Use of PI for South African bitumens

PI is the common predictor of temperature susceptibility in the service temperature range, and this was calculated for each of the 302 samples from the main data source [i]. Because the testing was performed in accordance with the penetration based SABS 307 specification using the IP58 test method, and the calculation of PI is based on the softening point determined by ASTM D36, a value of 1,5°C was added to the IP 58 results before calculation (Shell, 8). The viscosity based SABS 307 specification provides for softening point to be determined using the ASTM D36 method, and so future results will not need correction. The calculated PI was $PI_{pen/R\&B}$ which assumes that the penetration is 800 at the softening point; this is slightly less accurate than $PI_{pen/pen}$ (Heukelom, 7), but adequate for Class S bitumens.

The results showed that 85% of the bitumens had a PI between -1 and 0, and 12% were less than -1 and 3% greater than 0. There is a difference between grades, with the harder bitumens slightly more temperature susceptible than the softer bitumens in the service temperature range ($F=32,8$; significant at 99,99% level) (Table 6). Interestingly the PI did not vary significantly by refinery ($F=2,0$; not significant at 95% level).

Table 6 : Variation of PI by bitumen grade

Grade	Mean PI	Number of samples
150/200 or B4	+0,86	16
80/100 or B8	-0,26	70
60/70 or B12	-0,50	91
40/50 or B24	-0,72	82

5.1.2 Prediction of viscosity at 60°C

With PI determined, the consistency in the service temperature range can be predicted from the BTDC equation/plot (Heukelom, 7). However this is not sufficient to accurately predict viscosity at 60°C if the bitumen is waxy. This is because the effect of wax causing a discontinuity in the BTDC plot near the 60°C mark must also be taken into account. To quantify the significance of the waxy discontinuity for South African bitumens, the measured dynamic Brookfield

viscosity at 60°C was compared with the viscosity predicted from the penetration side of the BTDC plot (Figure 2) using equation 6 (Heukelom, 7) and data set [ii].

$$\frac{-5{,}42\ \log_{10}\dfrac{\eta(Pa.s)}{1300}}{8.5\ +\ \log_{10}\dfrac{\eta(Pa.s)}{1300}} = A(T - T_{800\ pen}) \qquad (6)$$

Where η = *dynamic viscosity Pa.s at temperature* T = 60°C
$T_{800\ pen} = T_{R\&B}$ = *softening point °C ASTM D36*
A is as determined during the calculation of PI

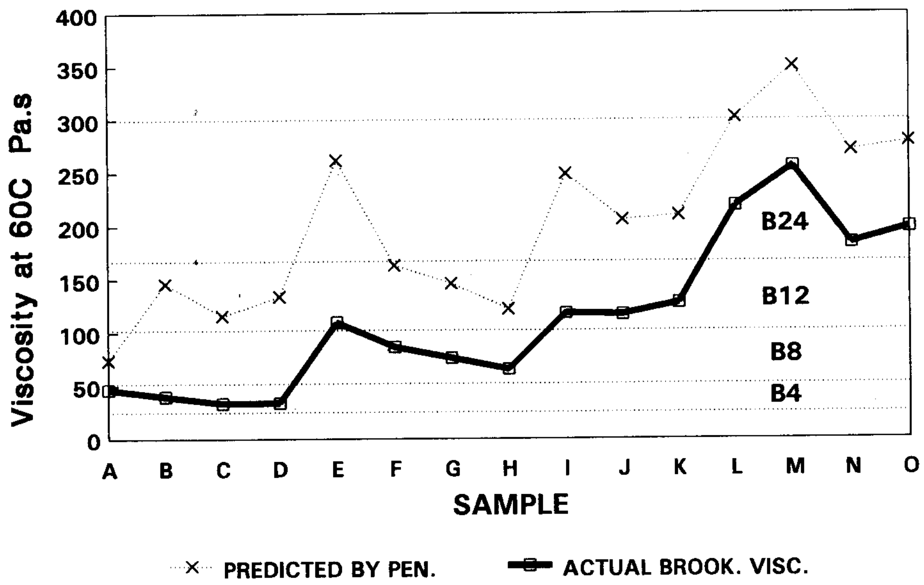

Figure 2 : Comparison of actual and predicted viscosity at 60°C

The errors were significant, and the viscosity predicted from $PI_{pen/R\&B}$ was substantially different from the measured viscosity. Often the error would be enough to change the grade classification of the bitumen under the viscosity based SABS 307 specification. However Figure 2 indicates that some sort of relationship may exist, although it must be emphasized that data set [ii] is limited in extent.

An equation was developed to relate the two, but is not published here because it was developed from such a limited data set that it could be unreliable in practice.

Since PI is generally not a reliable predictor of consistency at high service temperatures, use of the viscosity based SABS specification will improve the understanding of consistency at high service temperatures.

The available data from the main source [i] enabled two equations (7, 8) to be developed to predict viscosity at 60°C from penetration data, which will be of use in extrapolating the behaviour of South African penetration grade bitumens.

$$\eta_{60} = -1492 * \log_{10}(\log_{10}Pen) + 532 \qquad (7)$$
$$R^2 = 0{,}86 \quad \textit{standard error of estimate} = 24{,}6$$

$$\eta_{60} = 38{,}62\ T_{R\&B} - 117{,}12\ PI + 2{,}59\ Pen - 2015 \qquad (8)$$
$$R^2 = 0{,}90 \quad \textit{standard error of estimate} = 20{,}9$$

Where η_{60} = *Dynamic viscosity at 60°C, Pa.s ASTM D4402*
Pen = *penetration at 25°C/100g/5s, 0,1mm ASTM D5*
$T_{R\&B}$ = *softeningpoint °C ASTM D36* *PI* = *Penetration index*

Other equations were developed to predict penetration (9) and softening point (10). Different forms of models, both linear and logarithmic, were tried but no improvement could be found. The model form suggested by de Kock (10) was tried as equation 11, but a poor correlation was found using this much larger data set, and so the model was expanded to equation 12.

$$Pen = -1648 * \log_{10}(\log_{10}(1000*\eta_{60})) + 1240 \qquad (9)$$
$$\textit{with } R^2 = 0{,}88 \quad \textit{standard error of estimate} = 12{,}1$$

$$T_{R\&B} = 11{,}53 * \log_{10}(1000*\eta_{60}) - 10{,}4 \qquad (10)$$
$$\textit{with } R^2 = 0{,}73 \quad \textit{standard error of estimate} = 1{,}57$$

Where *Pen* = *penetration at 25°C/100g/5s, 0,1mm*
η_{60} = *Viscosity at 60°C Pa.s D4402*
$T_{R\&B}$ = *Softening point °C ASTM D36*

5.2 Prediction within the application temperature range

BTS_{vis} or VTS can be used to predict viscosity in the application temperature range, by first using viscosity at 60°C and 135°C to establish BTS_{vis} or VTS, and then extrapolating or interpolating using equations 1 and 2.

$$\log_{10}\left(\frac{Pen}{T_{R\&B}}\right) = -0{,}004496 \log_{10}\left(\frac{\eta_{60}}{\eta_{135}}\right) + 3{,}789 \qquad (11)$$
$$\textit{with } R^2 = 0{,}56 \quad \textit{standard error of estimate} = 0{,}58$$

$$\log_{10}\left(\frac{Pen}{T_{R\&B}}\right) = 0{,}001334 \log_{10}\left(\frac{\eta_{60}}{\eta_{135}}\right) - 49{,}22 \log_{10}(\log_{10}(\eta_{60})) + 35{,}7 \qquad (12)$$
$$\textit{with } R^2 = 0{,}87 \quad \textit{standard error of estimate} = 0{,}314$$

Where *Pen* = *penetration at 25°C/100g/5s, 0,1mm*
η_{60} = *Viscosity at 60°C Pa.s D4402*
η_{135} = *Viscosity at 135°C Pa.s D4402*
$T_{R\&B}$ = *Softening point °C ASTM D36*

5.3 Prediction across the temperature ranges

5.3.1 Prediction of viscosity at 135°C using PI

Surprisingly, PI can be used as a predictor of viscosity at 135°C for South African penetration grade bitumens by assuming that BTS_{vis} = PI. That there are only moderate errors is probably due to the logarithmic nature of the BTDC and the fact that South African bitumens tend to be Class S.

There was no direct correlation between PI and BTS using data source [i]: the correlation coefficient was -0,221. Data source [ii] had more extensive consistency testing, and using this, a second attempt was made to correlate PI and BTS; no suitable correlation between them could be found (maximum R^2 was 0,49).

However the errors in using PI to predict viscosity at 135°C are only moderate. For the bitumens from data source [ii], the error in using PI and viscosity at 60°C to predict temperature at which the viscosity would be 0,2 Pa.s (middle of the mixing range) was in the order of 4 to 7°C. Alternatively the error in predicting viscosity at a temperature of 135°C using PI and viscosity at 60°C was about 0,05 Pa.s.

It is even possible to approximately predict viscosity at 135°C using equation 7 or 8 to predict viscosity at 60°C, and PI to extrapolate that to 135°C, but the errors would become rather large.

5.3.2 General viscosity-penetration model

The non-linear nature of temperature susceptibility together with the waxy discontinuity near 60°C makes the development of a general consistency prediction model for bitumen difficult. The PVN approach by McLeod (12) offers some advantage here but needs more research for South African bitumens. The Garrick rheological groups (11) were seen to be the best approach since they accurately model viscosity-temperature and viscosity-shear rate relationships. Using the parameters VTS, PVN(25-135) and PVN'(25-60) calculated for the main data source [i] (Table 5), it was found that the South African bitumens only fell into two of Garrick's groups: Group G (29%) and Group I (18%). There were one or two samples that fell into other groups, but the bulk (52%) lay outside the ten groups.

The most likely explanations for this result are firstly that testing errors or differences in methods or apparatus could have caused slight differences in measured viscosities due to possible non-Newtonian behaviour at 60°C and/or the slightly waxy nature of South African bitumens. The second explanation is that there are more groups than the ten of Garrick, which could be true if the crude oil source and/or processing of South African bitumens was different to those tested by Garrick.

The likelihood of testing errors or differences was examined by a re-run of the analysis in which all the upper and lower group limits of Garrick were widened by 0,05, which is quite substantial and enough to include most expected errors or differences. On the re-analysis, 25% of the results still lay outside the ten groups, and so it was concluded that testing errors or differences was insufficient to explain the result.

Since there were probably more than the ten rheological groups, further analysis was attempted to identify these new groups, but there were insufficient data sets from the South African testing to get a accurate shape of the viscosity-temperature curve for each bitumen. It was only possible to try and cluster the bitumens into new groups (using both statistical and graphical clustering processes) which was done, and various tentative limits for the new group(s) were found.

This suggested that two new groups are feasible: K and L (Table 7), which in addition to groups G and I identified earlier, makes a total of four groups of like rheological behaviour for South African bitumens. There was no trend for bitumens lying outside or inside the groups to vary by grade, but there was a slight trend by refinery: certain refineries had a high proportion of their outputs in certain groups.

Table 7 : Tentative range of temperature susceptibility values for new rheological groups

Group	VTS (60-135)	PVN (25-135)	PVN' (25-60)	% data source [i]
K	3,45 to 3,65	-1,20 to -0,80	-1,30 to -0,90	24%
L	3,65 to 3,85	-1,55 to -1,20	-1,30 to -0,90	18%
Garrick's Group G				30%
Garrick's Group I				18%
Bitumens samples still outside the 12 groups				10%

However the new groups are considered only provisional, and their number, constants, trends and definition need to be established by additional research on South African bitumens.

6 CONCLUSIONS

The temperature susceptibility of South African bitumens can be assessed in view of the change from the penetration based SABS 307 specification to the viscosity based specification. Several sources of data were used to examine existing temperature susceptibility measures and to develop new prediction equations. In particular it was concluded that:

1. Viscosity at 60°C could not be reliably predicted using the Bitumen Test Data Chart and PI approach alone, probably due to the slightly waxy nature of South Africa road bitumens.

2. New models have been developed that predict:
    - Viscosity at 60°C from penetration, PI, and/or softening point (this was better able to model the slightly waxy nature of South African bitumen),
    - Softening point from viscosity at 60°C.

3. A new model was developed that predicted penetration at 25°C from viscosity at 60°C and/or 135°C. However the accuracy is only fair, and so the SABS 307 specification will have to continue to provide for penetration testing until further research can develop a better model of the temperature susceptibility in the cooler temperature range.

4. A tentative classification has been made of South African bitumens into four Groups of like rheological behaviour in order to model viscosity-temperature and viscosity-shear rate relationships over a wide range of temperature and shear conditions. These Groups correspond to two of ten groups previously found in American research and two new ones for South African bitumens. The only tests needed to determine rheology Group are penetration at 25°C, and viscosity at 60°C and 135°C, all of which are included in the new viscosity based SABS 307 specification for road grade bitumens. Further research is needed here.

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6TH CONFERENCE ON ASPHALT PAVEMENTS FOR SOUTHERN AFRICA

QUALITY ASSURANCE AND CONSTRUCTION TECHNIQUES FOR HOT RECYCLED ASPHALT WITH HIGH CONTENT OF RECLAIMED MATERIALS

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Abstract

This paper presents the experience gained during the production of a recycled asphalt subbase, containing an unusually high proportion of recovered material. The stockpiling techniques used to cater for the highly variable material recovered from the existing road are described together with the modifications to the mixing plant required to cope with the unusual mix. The properties of the recycled asphalt and bitumen recovered from the mix are compared to those of an asphalt base mix, using all new materials, produced through the same plant. The economics and environmental implications of the use of recycled asphalt are discussed.

1. INTRODUCTION

The rehabilitation of a 9,3km section of National Route 3 : Section 2 between Key Ridge and Nchanga, in Natal, included the removal and re-use, to form a subbase under a 235mm thick concrete pavement, of approximately 53 000 tons of the existing asphalt pavement. This section of road had been built progressively between the mid 1950's and 1975. During this time the specifications for the asphalt layers used had been modified as techniques developed, resulting in several different asphalt mixes. During the last 10 years of its life, the pavement had undergone a high degree of stress, necessitating maintenance and a major holding action, which included a modified bitumen seal.

2. ABBREVIATIONS

The following abbreviations are used in this paper :

RAP :	Recovered Asphalt Pavement
HMRA:	Hot Mixed Recycled Asphalt
BRD :	Bulk Relative Density
MTD :	Maximum Theoretical Relative Density