Determination of the continuous grade of a binder in the South African performance grade binder specification

TECHNICAL NOTE

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A Performance Grade (PG) Bitumen Specification, SATS-3208 (SATS 2019), was developed in South Africa during the period up to 2019. Since that time a period of implementation has begun on selected projects in South Africa. The implementation activities have included testing of data in accordance with the final anticipated standards. Formulation of a national standard is in the final stages and is expected to be published towards the end of 2024. The PG grade is specified using a high temperature number and a minimum temperature number that indicate the climate range within which a bitumen would be expected to perform. For example, a PG64-22 has a high temperature of 64°C and a minimum temperature of –22°C, from which intermediate and low operating temperatures are derived. A material meeting this grade will always have a performance range which is, ideally, just bigger than the specification grade and this is typically referenced as the continuous grade. A further definition is the difference between the two continuous grade numbers, referenced as the "Useful Temperature Interval" or UTI. As part of this implementation, it is required to determine the continuous grade for bitumen, including for modified binders, to ensure compliance with the specification. The UTI must be equal to or greater than 80°C. This technical note has been developed to demonstrate correct procedure to determine the continuous grade and UTI.

Keywords: PG grade, bitumen, binder performance, fatigue, rutting, ageing ratio, continuous grading temperature

INTRODUCTION

The Performance Grade (PG) Bitumen Specification in South Africa (SA) was discussed by Bredenhann *et al* (2019) and can be downloaded from **https://saice.org.za/journal/** and is defined in SATS-3208 (SATS 2019) – a technical specification that will be followed by the SANS 4001:BT10 final standard specification (this specification is in the final stages of completion).

Each binder grade is defined by a high and low temperature. It is desirable that a binder must be sufficiently stiff at high temperatures to resist permanent deformation (rutting) and sufficiently flexible at low temperatures to resist low temperature cracking. At intermediate levels the stiffness must be low enough not to be brittle, and with adequate relaxation properties to resist fatigue cracking. The maximum pavement design temperature T_{max} is the maximum annual seven-day average temperature at the 97.5% confidence level in the asphalt layer at a depth of 20 mm. If a base layer is considered, the depth is taken as 20 mm into the base layer plus the asphalt cover on the base layer. The minimum grading temperature is the maximum pavement design temperature less 80°C, i.e. $T_{min} = [T_{max} - 80]$°C. In effect, a minimum Useful Temperature Interval (UTI) of 80°C ensures optimal performance at both intermediate and low temperatures. At the intermediate temperatures it is important that the binder has good relaxation properties so that the material is not susceptible to cracking. This is particularly important when binder is used in a surface course mix which is more at risk to ageing.

Fatigue in the SA PG specification is controlled by the minimum UTI together with an Ageing Ratio (AR) to limit stiffness

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and prevent brittleness after ageing and thus fatigue cracking at operational intermediate temperatures.

Permanent deformation is controlled with the non-recoverable strain (J_{NR}) at a creep stress of 3.2 kPa. The J_{NR} is determined with the Multiple Stress Creep and Recovery (MSCR) test as described in ASTM-D7175 (ASTM 2015).

Cracking, either fatigue or low temperature, is controlled with the minimum UTI, the AR and the ΔT_C, defined as $T_{c,S} - T_{c,m}$ where the critical temperatures $T_{c,S}$ and $T_{c,m}$ are defined where stiffness S(60) = 300 MPa and m(60) = 0.3, as per ASTM-D7405 (ASTM 2020).

In the United States of America (USA) the rutting parameter implemented in 1994 was the |G*|/sinδ. This parameter has not been included in the SA PG specification, as it has been shown that |G*|/sinδ does not correlate well with field performance for modified binders and is slowly being replaced by use of the J_{NR}. G* and δ are, however, required to be reported for an unaged binder, as it is required for the calculation of the Ageing Ratio.

It is the purpose of this technical note to describe the correct procedure to determine the continuous grade of a binder. Such a continuous grade is based on the maximum/minimum temperatures where the binder value corresponds with the prescribed minimum/maximum specification requirement. The procedure for determining continuous grades is described in ASTM-D7643 (ASTM 2022).

STRATEGIC HIGHWAY RESEARCH PROJECT (SHRP) HIGH TEMPERATURE PARAMETER AND MSCR UPDATE

Gundla *et al* (2020) discuss the relationship between |G*|/sinδ and $J_{NR,}$ and it is shown that $|G^*|/\sin\delta = 7.997 \cdot (J_{NR})^{-0.85}$ with $R^2 = 0.994$. This relationship is generally valid for non-modified bitumen, but for modified binders this relationship does not apply. The work conducted by Gundla *et al* (2020) developed following analysis of earlier work by Kaloush *et al* (2019). Figure 1 shows the G*/sinδ and J_{NR} relationship graphically (the graph is reproduced with permission from data shared with the authors).

Figure 1 shows that a direct relationship exists between |G*|/sinδ and J_{NR} for non-modified binders. However, in the case of modified binders no such relationship was found. This supports the concept of grade bumping (i.e. specifying one to two grades higher than required by the environment) which has been used since the mid-1990s. However, as research was conducted with the MSCR and modified binders, it became clear that the concept of grade bumping, as applied with non-modified binders, cannot be applied in the same simplistic manner. With the MSCR test the same specification requirement is applied but at different values of J_{NR} specified at the given pavement temperature. This is the approach followed in the SA PG specification. Unfortunately, standard programs on the DSR equipment provide only the use of the USA standard of |G*|/sinδ, but this standard is not in the SA PG specification, so if used, the binders would be classified incorrectly. The correct approach to apply with the SA PG specification is discussed in this technical note.

Six samples of South African pen-grade bitumen were added to the database used by Gundla *et al* (2020) and are shown in Figure 2. Corresponding |G*|/sinδ and J_{NR} values for 70/100, 50/70 and 10/20 bitumen were included at 50–70°C. Only values

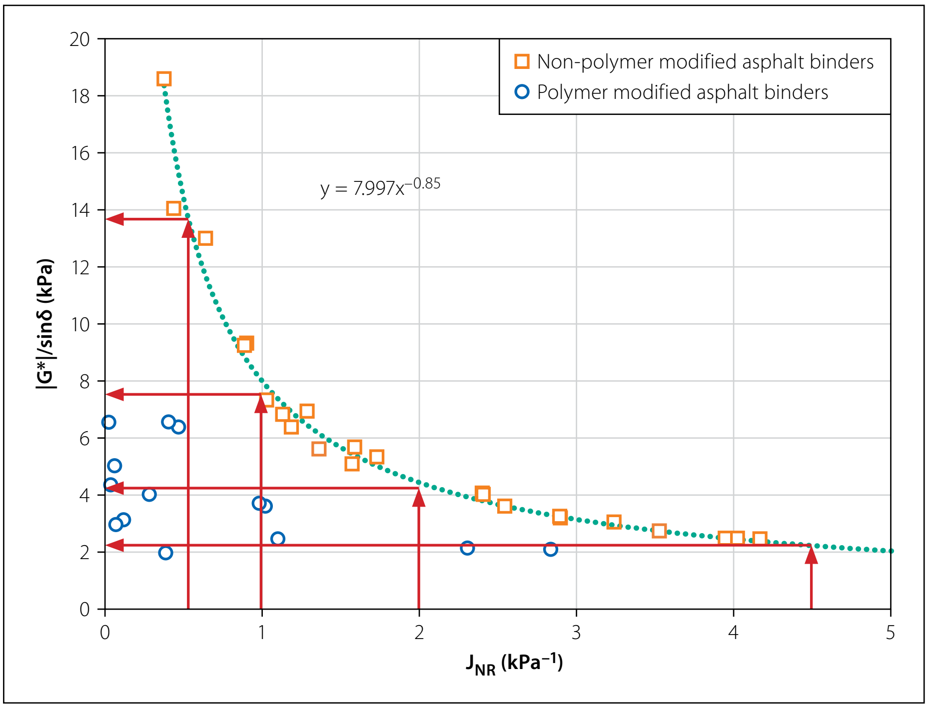

Figure 1 Relationship between SHRP rutting parameter |G*|/sinδ and JNR from MSCR test (RTFO-aged)

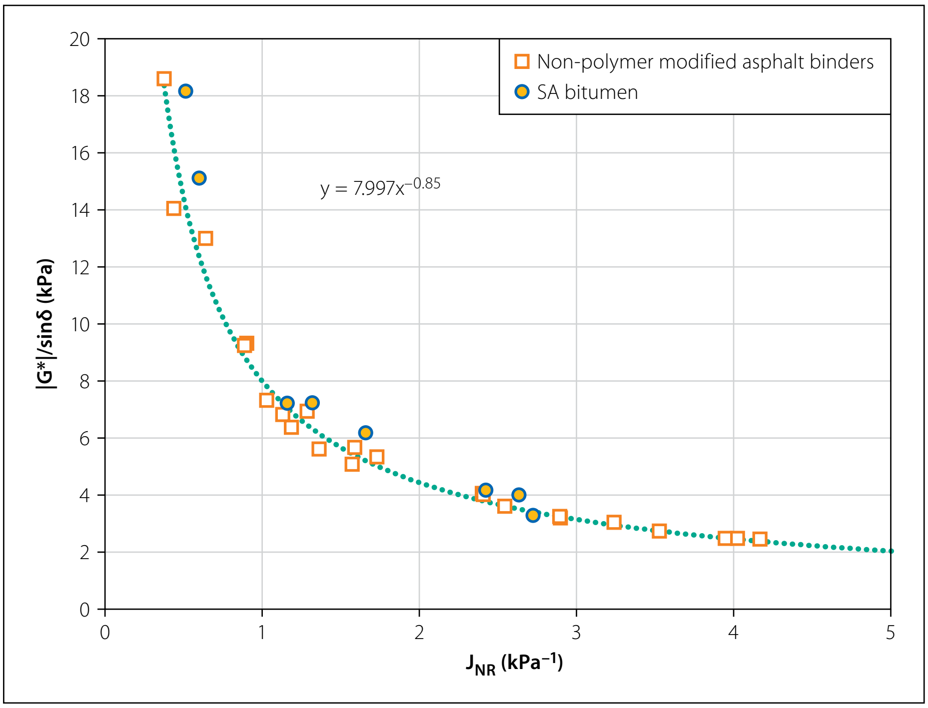

Figure 2 Relationship between SHRP rutting parameter |G*|/sinδ and J_{NR} from MSCR test (RTFO-aged) including 10/20, 50/70 and 70/100 pen-grade bitumen from South Africa

|G*|/sinδ < 20 and J_{NR} < 4.5 were included to keep the scale of the two graphs the same.

It is deduced from Figure 2 that unmodified bitumen from South Africa follows the same trend as those tested in the mentioned study in the USA.

THE SA PG REQUIREMENT FOR PERMANENT DEFORMATION

In Table 1 the nomenclature used to describe the severity of the traffic loading is summarised.

Table 1 Traffic classification based on traffic loading and travel speed

Traffic class	Traffic conditions	PG requirement
S	Standard conditions, speed > 80 km/h on open road	$J_{NR} \leq 4.5$ kPa^{-1}
H	Heavy traffic conditions and/or rolling terrain	$J_{NR} \leq 2.0$ kPa^{-1}
V	Very heavy traffic conditions and/ or slow-moving traffic	$J_{NR} \leq 1.0$ kPa^{-1}
E	Extreme traffic conditions, slow moving traffic at toll booths	$J_{NR} \leq 0.5$ kPa^{-1}

DETERMINATION OF HIGH TEMPERATURE CONTINUOUS GRADE

Four bitumen types are compared in Figure 3, in terms of the SANS 4001:BT1 classification that is familiar to the industry – a 50/70 bitumen, a 70/100 bitumen, a 10/20 bitumen (all refined in local refineries) and a very hard 10/20 bitumen (imported). Test results from three laboratories are shown in Figure 3 to demonstrate firstly the variability in test results, and secondly the extent to which hard binder (the 10/20 PEN) test temperatures must be increased to obtain results.

The continuous grading temperatures and continuous grade for a binder graded in accordance with the requirements specified in ASTM D6373 are based on the critical temperatures where $J_{NR} = 4.5$ kPa^{-1}, as demonstrated in Figure 3 – simply put, the exact temperatures at which $J_{NR} = 4.5$ kPa^{-1} are referred to as "true" high temperatures. The interpolation of

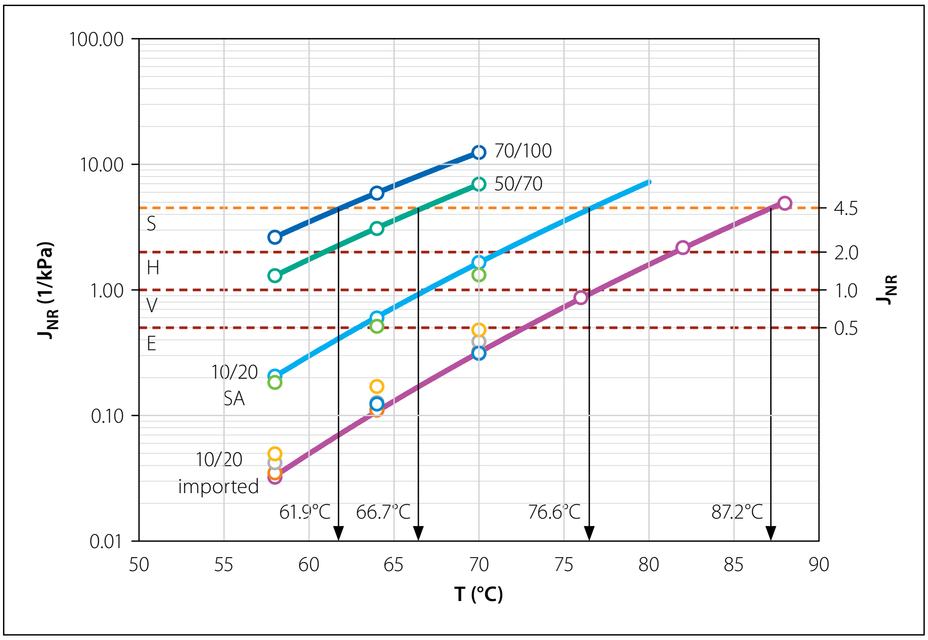

Figure 3 High temperature continuous grade bitumen test results from three laboratories

the continuous temperature is made by considering the log of the J_{NR} versus temperature expressed on a linear scale. The continuous grade is "*... a grade defined by the estimated upper and lower continuous grading temperatures while the continuous grading temperature Tc,n is the estimated temperatures at which the properties of an asphalt binder are equal to the specification requirement ...*" (ASTM-D7643) (ASTM 2022). The specification then refers to D6373 that will be SATS-3208 (SATS 2019) in the South African context where high temperature is defined with the MSCR test and low temperature with the BBR test.

PG grades are classified in 6°C intervals based on the finding that, for non-modified bitumen, for every 6°C increase/decrease the viscosity (therefore also shear modulus G*) will be halved/doubled. Continuous grades are rounded to the lower grade temperature.

The MSCR test is a destructive test, therefore a new binder sample is required for every temperature tested.

From Figure 3. it is deduced that continuous grades for the four bitumens are as shown in Table 2.

Table 2 Continuous PG binder grades

Bitumen (pen dmm)	Continuous high temperature grade (°C)	PG high temperature grade (°C)
70/100 SA	61.9	58
50/70 SA	66.7	64
10/20 SA	76.6	76
10/20 imported	87.2	82

PG grades as shown in Table 2 are typical of bitumen produced in South African refineries, except for the imported 10/20 shown with a one grade higher T_{max} than the locally produced bitumen. It should also be noted from Table 2 that the SA 10/20 bitumen continuous grade value was determined through extrapolation, as not enough MSCR tests were done. Extrapolation should preferably not be done; interpolation is more accurate, and it should be ensured that an adequate number of samples are prepared to do MSCR at high enough temperatures to ensure interpolation.

DETERMINATION OF LOW TEMPERATURE CONTINUOUS GRADE

Continuous low temperature grades are determined from BBR tests in accordance with ASTM-D6448 (ASTM 2007). The low temperature continuous grade is developed in a similar manner to that for $J_{NR,}$ with the exception that two parameters are considered rather than one. At a loading time of 60 seconds in the bending beam rheometer (BBR) the stiffness "S" and the magnitude of the slope of the log stiffness versus log time curve (m) are used in the interpolation. The stiffness is expressed on a log basis, while m is plotted on a linear basis against temperature. The highest (least negative) of the two numbers is considered to be the low temperature grade. Determination of the low temperature continuous grade is done in accordance with ASTM-D7643 (ASTM 2022) applying Equations 1 and 2 to determine the critical temperatures. The

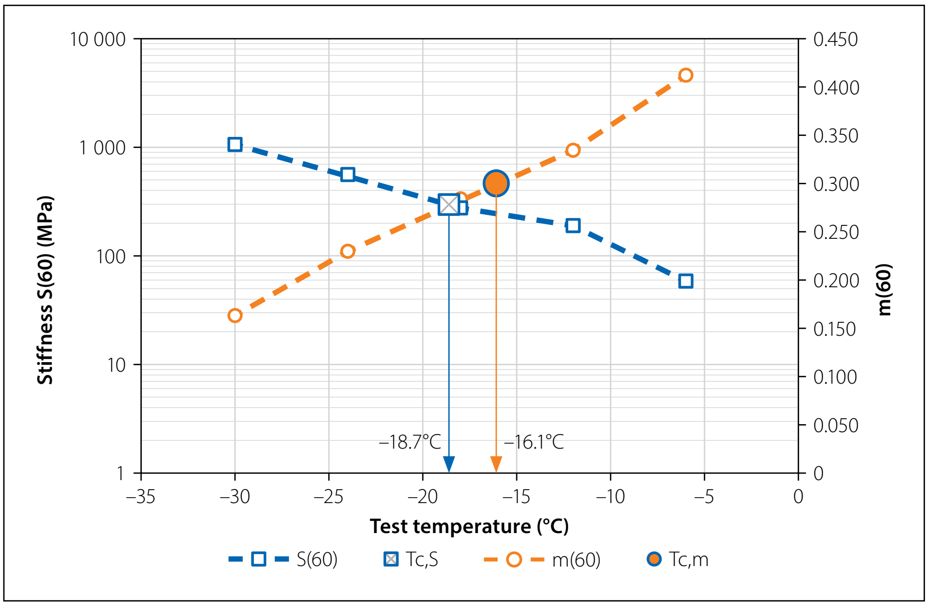

Figure 4 Determination of critical low temperature

parameter ΔTc is also calculated, from the equations (Equation 3) as follows:

$$Tc,S = T_1 + \left[\frac{\log(300) - \log(S_1)}{\log(S_2) - \log(S_1)}\right](T_2 - T_1) - 10 \quad (1)$$

$$Tc,m = T_1 + \left[\frac{0.300 - m_1}{m_2 - m_1}\right](T_2 - T_1) - 10 \quad (2)$$

$$\Delta T_c = T_S - T_m \quad \Delta T_c = T_{c,S} - T_{c,m} \quad (3)$$

Where:

$T_{c,S}$ = temperature at which the stiffness is 300 MPa

$T_{c,m}$ = temperature at which the m-value is 0.300

T_1, T_2 = two adjacent specification grading temperatures

S_1, S_2 = stiffness measurements at T_1, T_2 such that one value passes the specification requirement and one fails the requirement

m_1, m_2 = m-values at T_1, T_2 such that one value passes the specification requirement, and one fails the requirement.

For calculation purposes T_1 may be designated as the upper or lower temperature, as long as the corresponding specification test result (S or m) is used. It is good practice to use the S_1 as the value lower than 300 MPa and then select the corresponding T_1 temperature for consistency, and similar for the m values. Critical low temperature determination is illustrated in Figure 4 with:

$$T_{c,S} = -18.7°C - 10°C = -28.7°C$$

$$T_{c,m} = -16.1°C - 10°C = -26.1°C.$$

Table 3 Critical temperatures where S(60) = 300 MPa and m(60) = 0.300

Pen grade	Lab	Tc,S (°C)	Tc,m (°C)	ΔTc (°C)
70/100	L3d	–18.71	–17.14	–1.57
70/100	L3e	–14.12	–10.42	–3.70
50/70	L4b	–17.62	–14.17	–3.45
50/70	L4c	–14.07	–13.16	–0.91
10/20	L3a	–8.57	–6.71	–1.86
10/20	L3b	–8.52	–4.22	-4.30
10/20	L3c	–4.77	–6.27	1.50
10/20	L4a	–1.88	–2.46	0.58
10/20	L1c	–8.52	–2.58	–5.94

Table 4 Final PG grading of binders tested

Pen grade	Critical Tc low (°C)		Critical Tc high (°C)		UTI(°C)	PG grade
	T continuous	PG low grade	T continuous	PG high grade		
70/100+	–27.1	–22	61.9	58	89.0	PG58-22
70/100+	–20.4	–16	60.7	58	81.1	PG58-16
50/70+	–24.17	–22	66.7	64	90.9	PG64-22
50/70+	–23.16	–22	62.2	58	85.3	PG58-22
10/20*	–16.7	–16	84.1	82	100.8	PG82-16
10/20*	–14.2	–12	88.0	82	102.2	PG82-12
10/20	–14.8	–12	78.7	76	93.5	PG76-12
10/20	–11.9	–6	76.6	76	88.5	PG76-6
10/20*	–12.58	–12	87.2	82	99.8	PG82-12

Notes:
Bitumens marked * were imported; all other bitumens were from local refineries.
Bitumens marked + are from different refineries.

Critical temperatures for all tested bitumens are shown in Table 3. The test requirement $\Delta Tc = T_{c,S} - T_{c,m}$ is shown in Table 3, although it is not required to determine the continuous low temperature of a bitumen.

Critical temperatures $T_{c,S}$ and $T_{c,m}$ are reported at the test temperature that is 10°C higher than the actual temperature. All BBR tests are done at a temperature 10°C higher than the specified minimum temperature, e.g. for PG58-22 the isotherms are determined at –12°C to determine S(60) and m(60). The reason for this is that the original researchers who developed this test method considered the performance at two-hours loading time (7 200 seconds). This test time was considered too long and some calculations were performed, considering the time-temperature superposition princple, for typical binders in use to determine equivalencies to other temperatures. It was decided that testing at a loading time of 60 seconds and a ten-degree temperature shift provided the same test results based on the analysis.

FINAL CONTINUOUS GRADING

Finally, the high and low binder grades evaluated herein are reported in Table 4, indicating the final critical temperatures. The low temperature continuous grade reported in this table is the minimum of the values reported in Table 3 (Tc,S or Tc,m) with a correction of –10°C to arrive at the grade temperature.

Table 4 shows that all bitumen reported complies with the UTI ≥ 80°C requirement.

As a rule, the 10/20 bitumens have high UTI values nearly meeting the expectations for a polymer modified binder. The reasons for this phenomenon are beyond the scope of this technical note.

ACCURACY OF MEASUREMENT

Accuracy of testing is very important; the dataset shown in Figure 4 is an example of a dataset that is below standard and was included to demonstrate the importance of accuracy. Data quality can be improved by duplicate tests. The S(60) versus temperature and m(60) versus temperature should be a smooth function. From inspection it can be deduced that the –12°C datapoint is clearly problematic. Accuracy can be improved by preparing samples at the same time and test within an acceptable timeframe to avoid secondary influences such as steric hardening, especially for BBR tests that are done at low temperatures. As mentioned already, critical temperatures must be determined through interpolation, not extrapolation.

CONCLUSION

Continuous performance grades should be determined from requirements in the South African PG Specification SATS 3208 (SATS 2019) which is soon to be superseded by SANS 4001:BT10. High continuous grade is determined from RTFO-aged bitumen utilising the J_{NR} parameter as determined in the MSCR test, while the low temperature continuous grade is determined from the BBR tests, the higher critical temperature determined from S(60) = 300 MPa or m(60) = 0.300.

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