A COMPARISON OF BINDER TESTS THAT RELATE TO ASPHALT MIXTURE DEFORMATION

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ABSTRACT

The deformation (or rutting) susceptibility of asphalt mixtures is governed by the interaction of a large number of parameters such as volumetric composition and constituents properties e.g. aggregate size/shape, nature and flow behaviour of the bitumen.

For asphalt mixtures made with standard, unmodified bituminous binders, the contribution to deformation by the bitumen can be accurately described in terms of traditional bitumen properties that are relatively easy to determine, such as softening point, viscosity or stiffness at 60 °C.

Bitumen modification introduces complexity in the rheology of the binder (i.e. the way it flows) and consequently how it influences rutting susceptibility of the asphalt mixture. The physical binder properties that relate to the deformation susceptibility of asphalt mixtures with complex binders are deemed to be low shear viscosity (LSV), zero shear viscosity (ZSV) and/or non-recoverable creep compliance (Jnr) from multiple stress creep recovery test.

In this paper we present results of a study comparing ZSV and Jnr with traditional bitumen properties of a range of modified and unmodified binders. In this study asphalt rutting of one asphalt mix, assessed with a (small scale) laboratory wheel tracking test, is compared with the traditional and non-traditional bitumen properties.

Keywords: asphalt rutting propensity, rheological simple binders, rheological complex binders, MSCR test, high temperature bitumen property

1.0 INTRODUCTION

Over recent years significant research effort has been aimed at finding reliable relationships between asphalt mixture performance and binder characteristics. Numerous binder rheological characteristics, ranging from simple penetration value, softening point, (zero shear rate) viscosity to more complex characteristics such as stiffness modulus, were reported for prediction of the end-performance – rutting resistance of asphalt mixture. Plenty of correlations have been established but often for only limited sets of binders depending on type, modification etc. For practical and specification purposes it is important to find a "general" correlation between binder property and asphalt rutting performance that can be applied for a wide range of binders irrespective of type, modification, manufacturing process and/or additives used.

The main purpose of this study is to determine which binder rheological characteristic(s) best correlates with results of a standard laboratory asphalt mixture rutting test. The binders investigated comprise a wide spectrum ranging from standard penetration grade bitumen to highly modified binders and hard grade bitumen with different manufacturing routes or raw materials and additives used.

This paper reports our experience and results with Zero Shear Viscosity (ZSV), Non-recoverable Creep Compliance (J_{nr}) in comparison with results of common quality methods (Penetration, Softening Point) including the SHRP value $G^*/\sin\delta$. Binder rheology parameters are compared with asphalt mixture rutting results.

The outcome of this study will contribute to help finding the appropriate rheological method and parameter to describe the binder contribution to asphalt mixture rutting and to help further standardisation and implementation of these methods.

2.0 TEST PROGRAM

2.1 Materials

This study includes twenty different bituminous binders used in a continuous graded asphalt mixture. Table 1 gives a brief description of these binders. They include five normal paving grade bitumens (NPG), eleven polymer modified binders (PMB), two "low viscosity" binders (NV) and two special bitumens (SP).

Table 1 : Binder sample set

Sample	Type	Class	Additional information
NPG1	Normal paving grade	EN 12591; 30/45	
NPG2	Normal paving grade	EN 12591; 50/70	
NPG3	Normal paving grade	EN 12591; 70/100	
NPG4	Normal paving grade	AASHTO MP1; PG 64-22	
NPG5	Normal paving grade	EN 13924; 10/20	
PMB1	Polymer modified	EN 14023; 25/55-55	Plastomeric PMB; > 4% additives
PMB2	Polymer modified	EN 14023; 65/105-80	Elastomeric PMB; > 4% additives
PMB3	Polymer modified	EN 14023; 25/55-55	Elastomeric PMB; < 4% additives
PMB4	Polymer modified	EN 14023; 45/80-55	Elastomeric PMB; < 4% additives
PMB5	Polymer modified	EN 14023; 45/80-65	Elastomeric PMB; < 4% additives
PMB6	Polymer modified	EN 14023; 45/80-80	Elastomeric PMB; > 4% additives
PMB7	Polymer modified	AASHTO MP1; PG 64-28	Elastomeric PMB; < 4% additives
PMB8	Polymer modified	AASHTO MP1; PG 76-22	Elastomeric PMB; < 4% additives
PMB9	Polymer modified	EN 14023; 45/80-80	Elastomeric PMB; > 4% additives
PMB10	Polymer modified	AASHTO MP1; PG 76-22	Elastomeric PMB; < 4% additives
PMB11	Polymer modified	AASHTO MP1; PG 76-22	Elastomeric PMB; < 4% additives
NV1	FT wax modified		70/100; < 4% additives
NV2	FT wax modified	EN 14023; 25/55-70	Elastomeric PMB; > 4% additives
SP1	Multigrade		35/45
SP2	Normal paving grade	AASHTO MP1; PG 70-16	H3PO4 modified

The binders are incorporated in a continuous graded hot rolled asphalt mixture at identical binder content. The asphalt mixture chosen is a 35 % coarse aggregate (35/14) hot rolled asphalt (HRA) surface course mixture. Asphalt concrete constituents and binder content are shown in the Table 2.

Table 2 : Asphalt mixture composition - design

Material	**Type**	**Weight [%] (aggregate)**	**Weight [%] (mix)**	**Specific Gravity [kg/m^3]**	**Volume [%] (mix)**
6/14 mm	CYH	40.2	37.4	2,680	32.7
0.063-4 mm	Gelligaer dust	18.3	17.0	2,740	14.5
0.063-2 mm	Channel sand	36.5	34.0	2,650	30.0
Filler (<0.063 mm)	Limestone	5	4.7	2,710	4.0
Binder	(various)		**6.9**	1,020	15.8
Air voids					3.0

2.2 Measurements

The asphalt mixtures are tested in the "small" laboratory wheel track equipment at 45 and 60 °C according to BS EN 12697-22:2003 Part 6.3 Small size devices [6]. 50 mm thick specimens slabs are subjected to dynamic wheel loading for 2,700 s (45 minutes) or until 11 mm of deformation (rut depth) occurred. Rut depth (when required extrapolated) [mm] and rut rate [mm/s] are determined from the rut depth measurements. This method is well accepted to assess the rutting tendency of asphalt mixtures and is part of the European asphalt mixture specification.

Fresh and RTFOT aged binders are tested for Penetration at 25°C, Softening Point, Superpave high temperature parameter $G^*/\sin\delta$, Zero shear viscosity (ZSV) at 45 and 60 °C and creep compliance (J_{nr}) from Multistress Creep Recovery (MSCR) at 45 and 60 °C. Table 3 lists the methods used. Conditions for MSCR are: load applied for 1s followed by recovery for 9s (10 test cycles in total) at four different stress levels (30, 100, 300, 1000 Pa).

The rheological characteristics are evaluated for all samples on fresh binders and aged binders under influence of heat and air (RTFOT, EN-12607-1).

At very low shear rates, structures deform so slowly that they can adapt continuously thus maintaining a situation close to equilibrium and not build up any structural changes. At these conditions and a given temperature, the viscosity of a visco-elastic liquid has a limiting value – Zero Shear rate Viscosity (ZSV, η_0) – Newtonian dynamic viscosity [1]. According to the European draft Technical Specifications prCEN/TS 15324&15325:2006 ZSV can be determined in creep or in oscillation mode (low frequencies) [2]. The creep test is preferably performed at temperatures where $\eta_0 <$ 50000 Pa.s and $\eta_0 >$ 100 Pa.s. In this study ZSV is measured in "controlled-stress" creep mode (stress range 20 – 50 Pa) at 45 and 60°C using parallel plates of 25 mm diameter and 2 mm gap. The test temperatures correspond to the temperatures at which the laboratory rutting tests are performed.

The ZSV test consist of two steps: step 1 - stress sweep is performed under conditions close to steady-state. In case of an unknown binder this step gives information about (non-) Newtonian character of the bitumen and allows the appropriate stress level selection (Figure 1). This step was skipped for all unmodified binders (i.e. NPGs and SPs) as they are known to behave Newtonian at the recommended stress level of 50 Pa. While some polymer modified binders show Newtonian behaviour over the whole stress range (i.e. PMB 1, PMB 7, PMB 10), the flow curve of PMB 4, PMB 5, PMB 6 and PMB 11 presents more non-Newtonian character while the existence of a Newtonian plateau is complete absent for NV 2.

Table 3 : Methods for characterisation of binders

Property	**Test Method**	**Unit**
Penetration @25°C	EN 1426	1/10 mm
Softening point (Spt)	EN 1427	°C
Dynamic shear $G^*/\sin\delta$	AASHTO T315	kPa
ZSV @45°C and 60°C	prEN 15325	kPa.s
MSCR (J_{nr}) @45°C and 60°C	ASTM Draft 3*	1/kPa
RTFOT ageing @163°C	EN 12607-1	

* a modified test method was applied which is described below

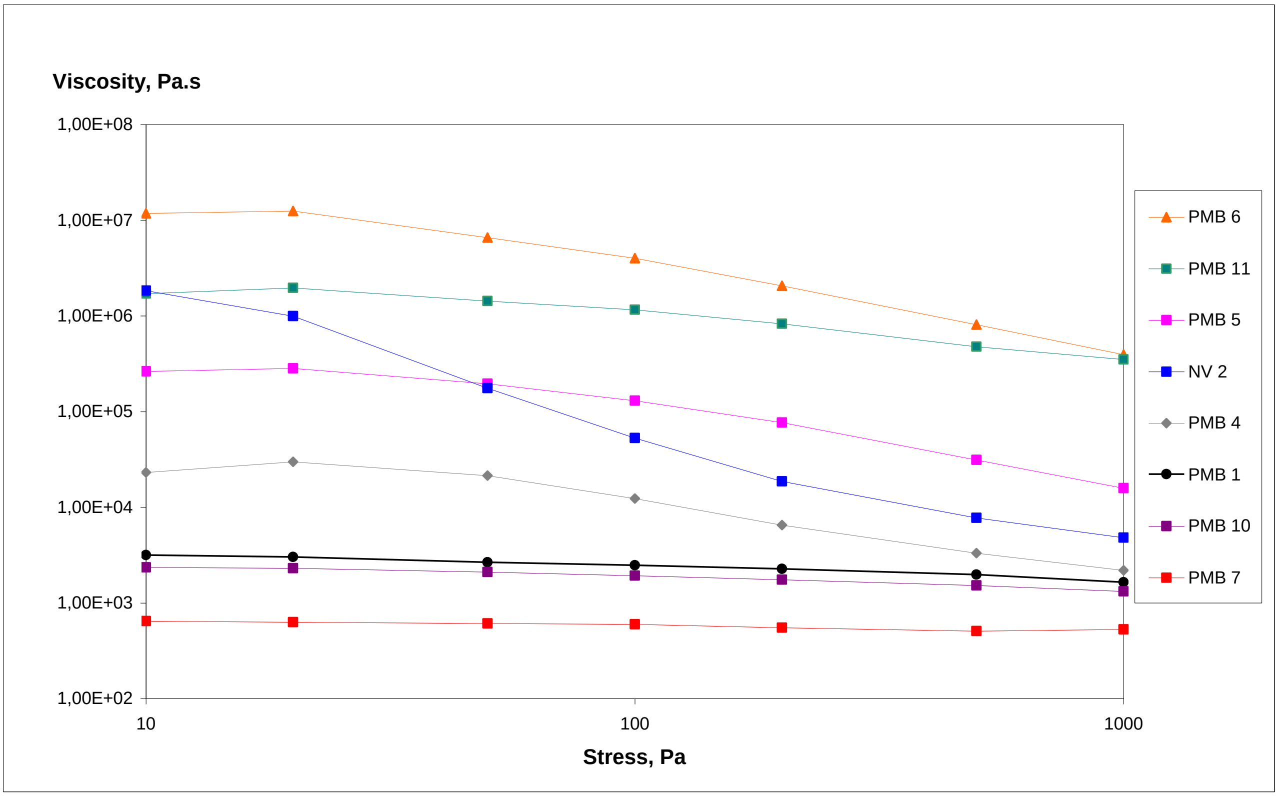

Figure 1 : ZSV test Step 1 for polymer modified binders (60°C)

In the second step of the ZSV test creep flow is determined at the stress level chosen from step 1. It is critical that a low enough stress level is chosen to remain within the linear viscoelastic response of the binder. For this study the binders are tested at a stress between 20 and 50 Pa. Shear rate should preferably be above 10^{-4} s^{-1}, but for some highly modified binders, e.g. NV 2 and PMB 6, the shear rate at 20 Pa is close to 10^{-6} s^{-1}. For these binders the measurements are not performed within the linear domain. To ensure a steady state flow the total creep times are chosen to be 3,600 s (1 hour) for non modified and 14,400 s (4 hours) for polymer modified binders. The average viscosity is computed over the last 900 s (15 minutes) with the precision difference < 5%. Final ZSV values are determined at a given temperature and at a single (low) stress value.

The MSCR procedure captures the non-recoverable creep compliance J_{nr} (1/kPa) and percentage of recovery during a loading cycle and is used to assess the elastic response of bitumen under shear creep and recovery at different stress levels [3]. The MSCR test can be applied to modified and unmodified bitumen [4]. For this study the “Standard Test method for MSCR Draft 3” [3] is followed. The tests are performed with a Gemini Dynamic Shear Rheometer (Fa. Bohlin) with a 25 mm parallel plate geometry and 1 mm gap setting. The sample is loaded at constant stress for 1s and allowed to recover for 9s. At each stress level (i.e. 30, 100, 300 and 1000 Pa) ten creep and recovery cycles are run. The tests are done at 45 and 60 °C. Non-recoverable creep compliance at each stress is calculated (Figure 2).

The Superpave parameters G* and sin δ at 1.59 Hz (10 rad/s) are obtained from frequency sweep measurements at 45 and 60°C. Measurements of complex shear modulus (G*, Pa) and phase angle (δ, °) are performed in frequency sweep mode according to EN 14770. The first step - selection of the linear region for each binder allows determining the appropriate deformation level for the next step - measurements in equally spaced logarithmic steps of frequency within the range 0.1 Hz to 10Hz. Each sample (fresh and aged) is tested with the two geometries 8 mm and 25 mm from 80 °C down to 5°C.

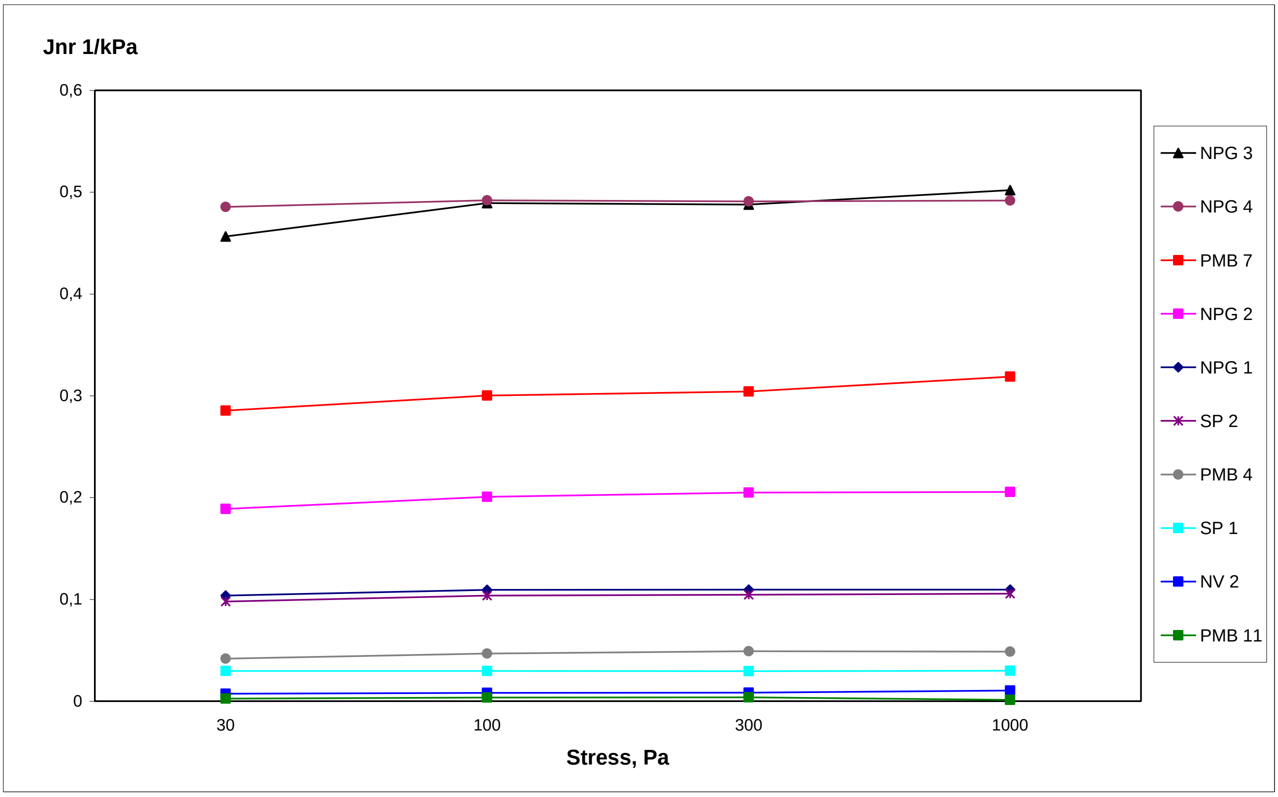

Figure 2 : Non-recoverable creep compliance J_{nr} in the range of 30 Pa to 1000 Pa (45°C)

3.0 RESULTS

Wheel-tracking results are presented in Table 4. The rut rate is calculated as defined in paragraph 8.1 of BS 598-110:1998. For specimens that reached a deformation of 11 mm before 2,700 s (45 minutes), the reported rut depth is derived by extrapolation using linear regression through a log-log plot of the deformation data. There is an excellent correlation between rut depth and rut rate independent of the test temperature and binder type that extends over more than two decades, see Figure 3. It is therefore sufficient to take only one of these parameters into account to describe the susceptibility to rutting of the asphalt mixture. For this study rut rate is selected for further analysis and comparison with the measured bitumen properties.

The precision of the wheel-tracking rut rate according to BS 598-110:1998 is 40% for laboratory prepared specimens. Extrapolation of some test results will have introduced some more imprecision. Furthermore wheel-tracking results are considered increasingly less sensitive for values below approximately 0.25 10^{-3} mm/s. This needs to be kept in mind when assessing trends and correlations with bitumen properties.

Table 4 : Results wheel-tracking tests

Bitumen	Rut depth @ 45°C [mm]	Rut rate @ 45°C [10^{-3} mm/s]	Rut depth @ 60°C [mm]	Rut rate @ 60°C [10^{-3} mm/s]
NPG1	4.8	0.73	15*	3.33
NPG2	5.7	0.75	20*	4.17
NPG3	10.2*	1.97	53*	15.7
NPG4	9.1	1.55	56*	17.2
NPG5	0.9	0.13	2.6	0.38
PMB1	1.7	0.17	7.5	1.61
PMB2	1.5	0.15	3.7	0.51
PMB3	2.8	0.33	7.3	1.45
PMB4	2.3	0.28	7.8	1.95
PMB5	1.6	0.17	4.1	0.67
PMB6	1.0	0.06	3.3	0.50
PMB7	6.4	1.03	29*	7.14
PMB8	2.9	0.38	15*	3.28
PMB9	2.2	0.17	5.5	1.00
PMB10	3.6	0.62	17*	4.28
PMB11	3.2	0.33	9.8	2.03
NV1	5.2	0.70	20*	4.53
NV2	1.9	0.17	7.9	1.64
SP1	1.8	0.33	8.8	1.98
SP2	8.2	1.28	25*	5.94

*: extrapolated results

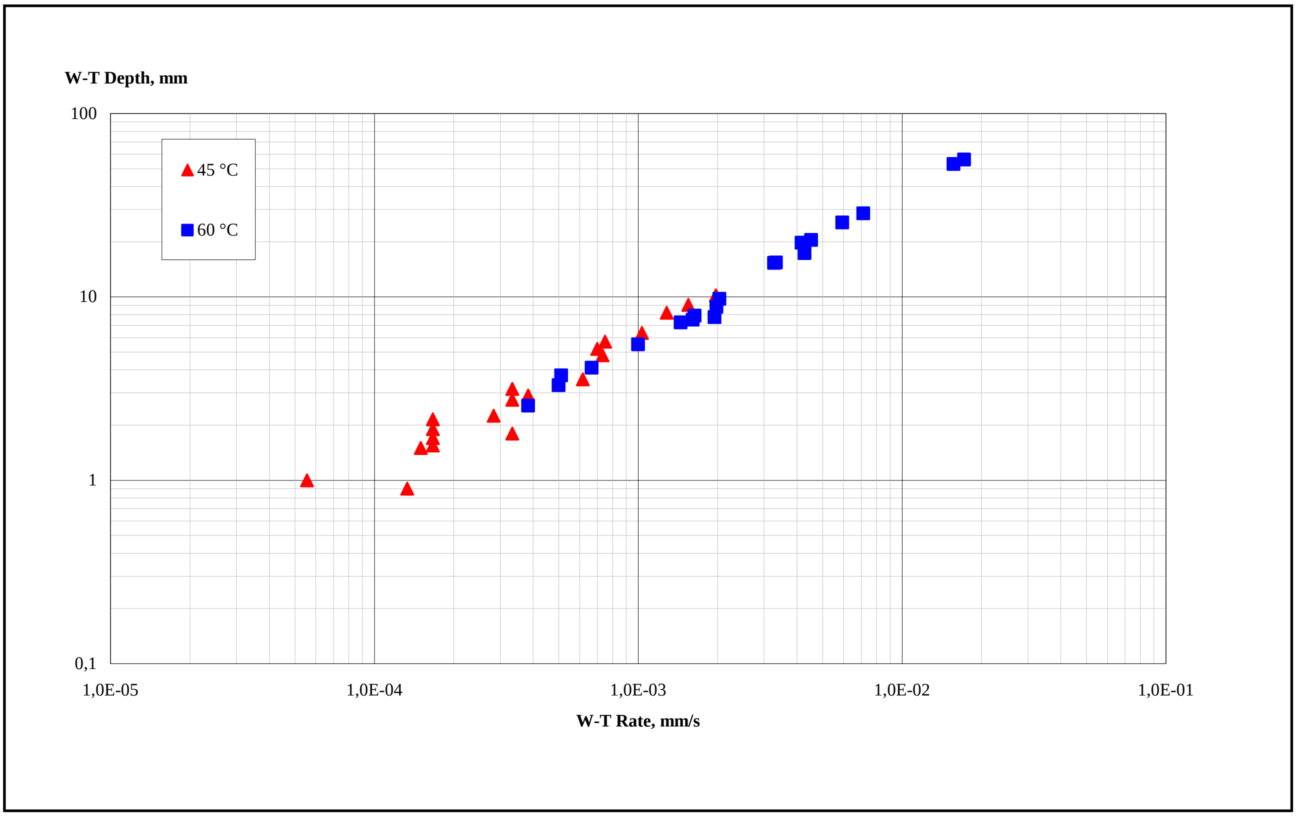

Figure 3 : Wheel-tracking rut depth against rut rate

3.0 DISCUSSION

Figure 4 shows the relationship between wheel tracking rut rate at 60 °C and Softening Point of the fresh binders. As is known this correlation is very poor (R^2=0.68) when considering all binders. However, when looking only at the five normal paving grades (NPGs) and the two special bitumens (SPs) one can distinguish an almost perfect correlation (R^2=0.95). A similar picture develops when Softening Point after RTFOT ageing is used. Apparently the more complex rheological nature of the modified bitumens removes the straight forward traditional correlation between rutting and Softening Point. Interestingly, for highly modified PMBs and FT wax modified bitumen, Softening Point underestimates the actual rutting propensity of these binders when compared with normal paving grades. The Softening Point of some PMB with low modification appears to coincide with the NPG correlation suggesting they do follow the "normal" trend. This confirms that for unmodified binders and some low polymer content PMBs the contribution to deformation susceptibility can be accurately described by Softening Point.

Figure 5 shows the relationship between wheel tracking rate and ZSV for unaged binders. There is no correlation (R^2=0.49) when considering all binders. However, considering only rheological simple binders, NPGs and SPs, a very good correlation (R^2=0.93) is found. This correlation is furthermore independent of temperature.

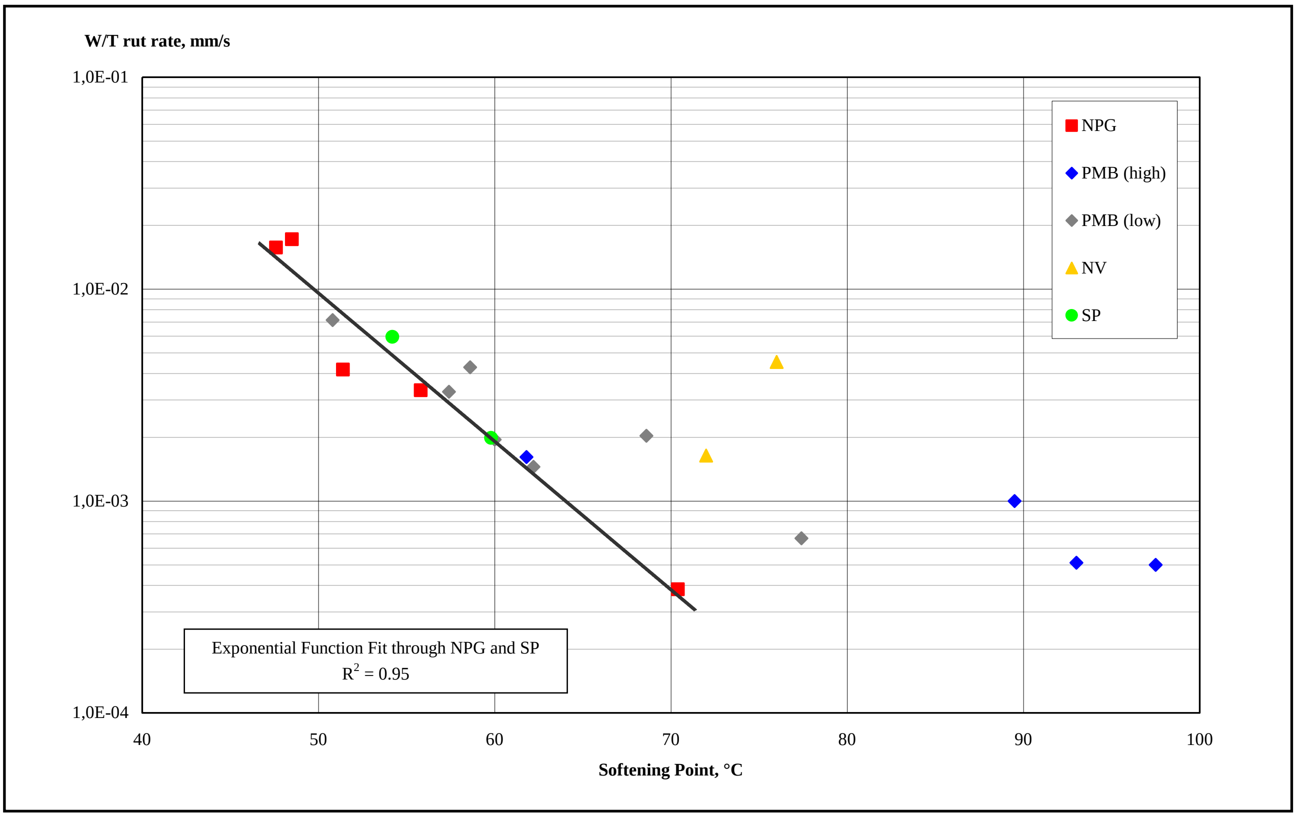

Figure 4: Wheel tracking rut rate at 60ºC vs Softening Point of unaged binder

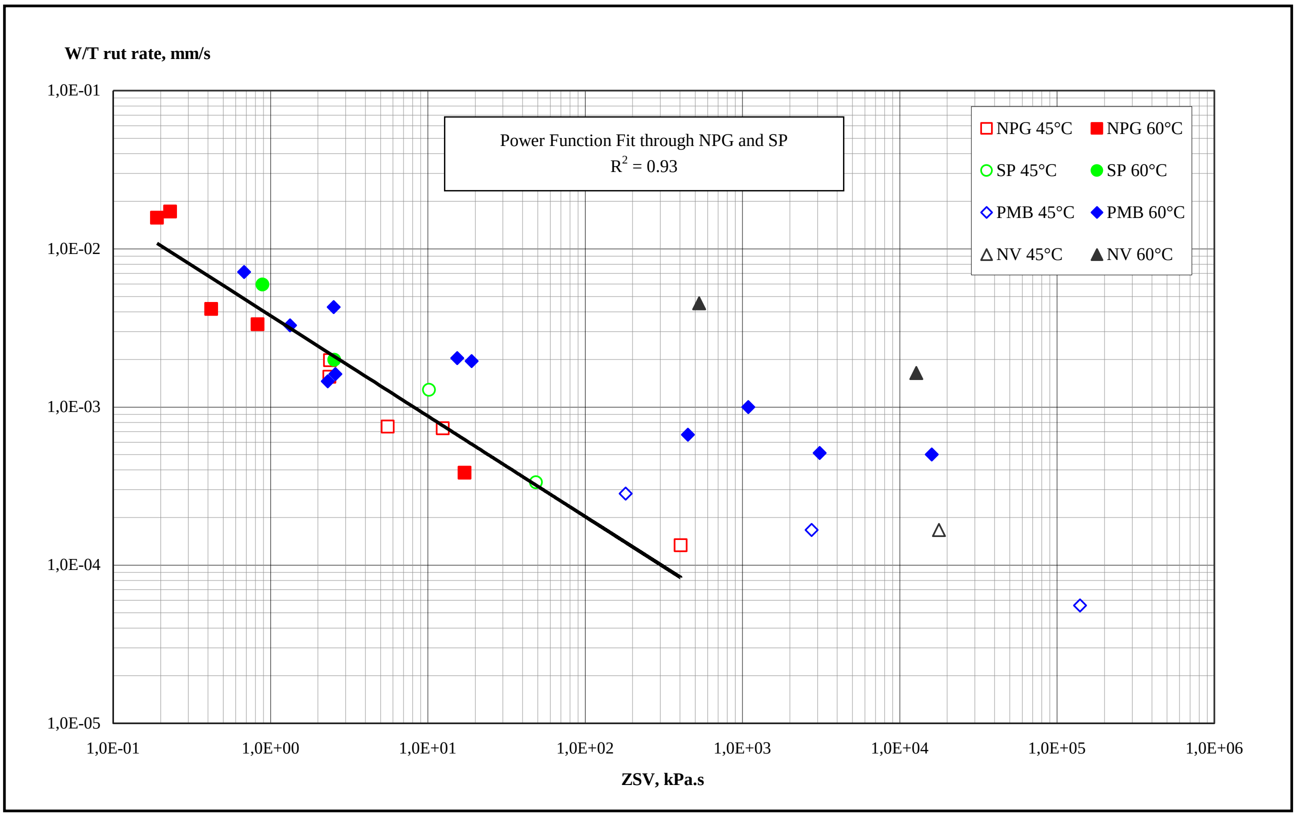

Figure 5: Wheel tracking rut rate vs ZSV of unaged binders at 45 and 60ºC

The relationship between wheel-tracking rut rate and Stiffness Modulus G^* (1.59 Hz) at 45 and 60 °C of the original binders is shown in Figure 6. For unmodified (rheological simple) binders G* correlates well with rut rate (R^2 = 0.94). However, for rheological complex binders (i.e. most PMBs) there is clearly no correlation between rut rate and G^*. In fact the contribution of these binders to rutting resistance is generally largely underestimated by G*. For example PMB3, which is a commonly used binder in Germany, has at 60 °C the same value for G^* as NPG1 (± 7 kPa) but a factor 2 lower rut rate. PMB5 with a lower value for G* at 60 °C (± 4 kPa) has even a factor 6 lower rut rate than NPG1. This trend/picture remains when G*/sinδ or data of the short term aged binder is plotted.

From the above we conclude that for rheological simple binders (NPG, SP) Softening Point, ZSV and G* correlate well with rut rate but as expected this breaks down for rheological more complex materials.

Figure 7 and 8 present wheel tracking rut rate against J_{nr} at 45 and 60 °C of unaged and RTFOT aged binders respectively. There appears a single good correlation for all binders independent of temperature. The correlation is even better when aged properties are considered (R^2 = 0.79 unaged vs 0.90 aged).

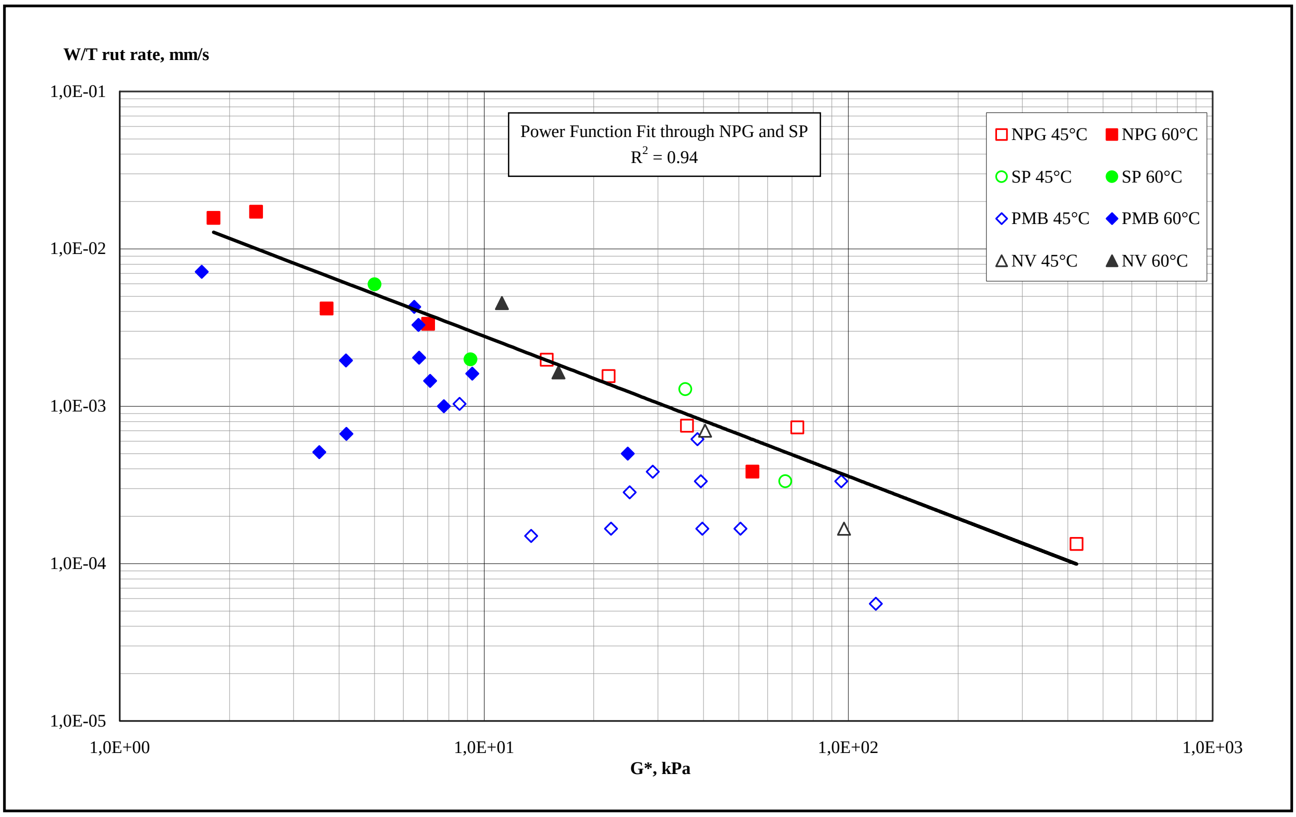

Figure 6 : Wheel tracking rut rate vs stiffness modulus G^* (1.59 Hz) of unaged binders at 45 and 60°C

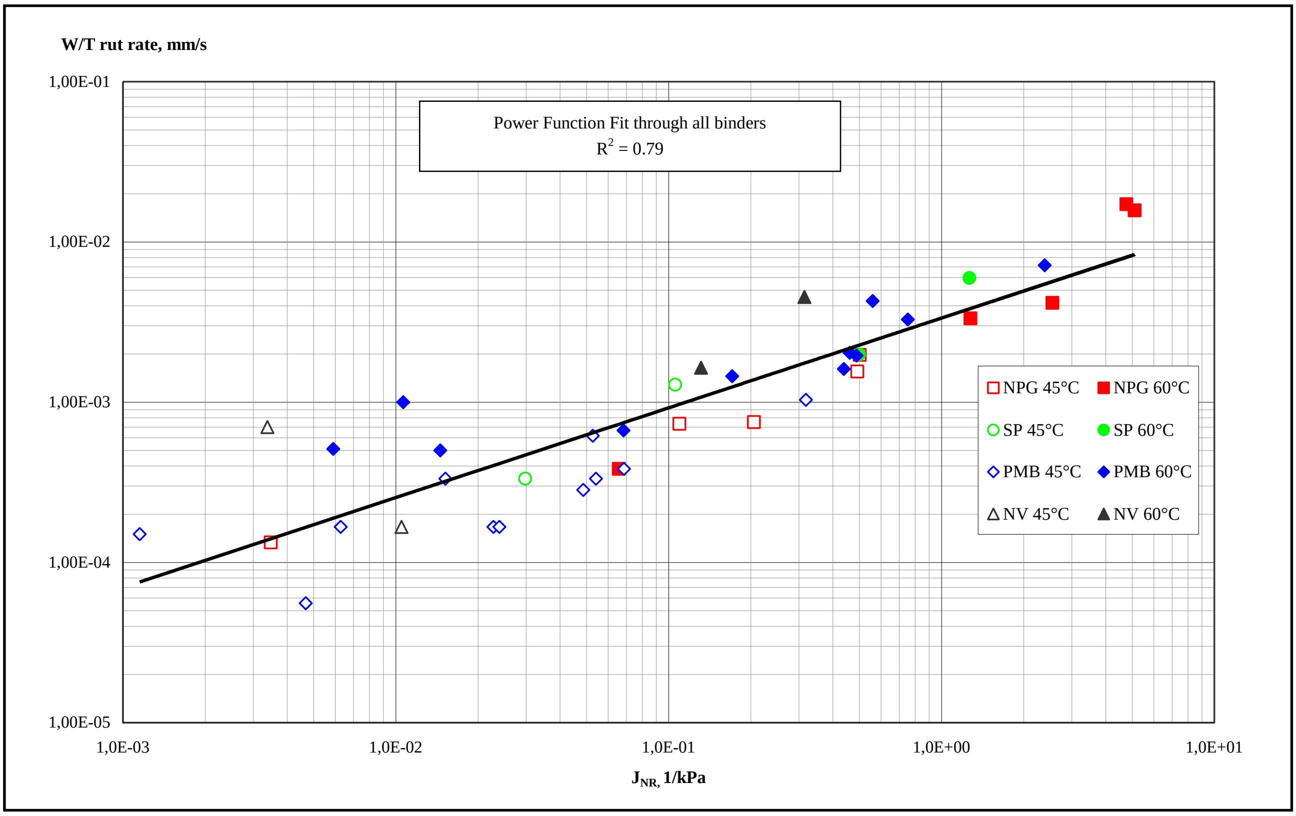

Figure 7: Wheel tracking rut rate against J_{nr} of unaged bitumen at 45 and 60 °C

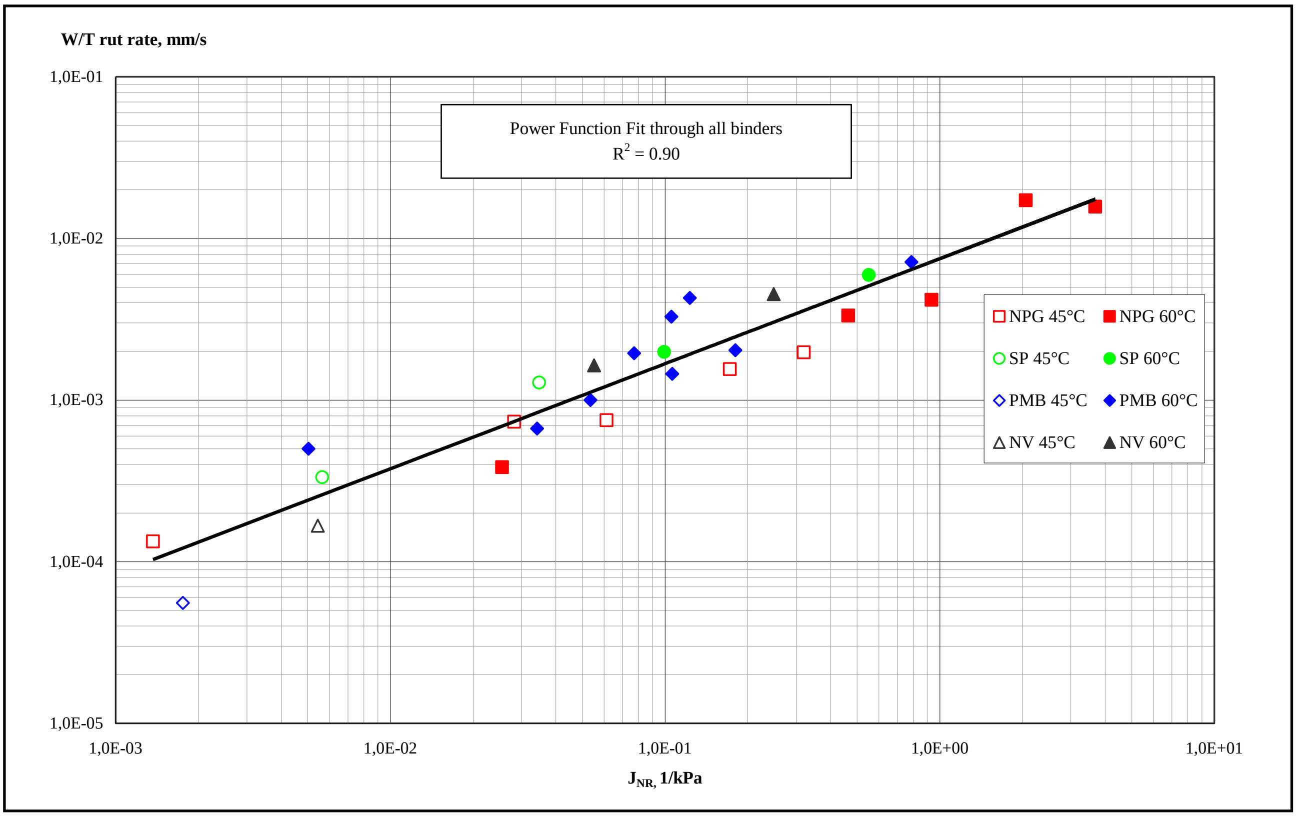

Figure 8 : Wheel tracking rut rate vs J_{nr} of RTFOT aged bitumen at 45 °C and 60 °C

5.0 CONCLUSIONS AND RECOMMENDATIONS

The rutting propensity of the asphalt mixture used in the study containing rheological “simple” binders (e.g. normal paving grade bitumen) is adequately described by the traditional Softening Point. Consequently, to understand their sensitivity to rutting there is no need for more complex rheological characterisations. Conversely, the rutting propensity of asphalt mixtures made with rheological more “complex“ binders is NOT at all correlated to Softening Point.

There is a very good correlation (R^2>0.9) between the rutting propensity of asphalt mixtures made with rheological “simple” binders and any of the more complex rheological parameters such as G*, ZSV and J_{nr}. This is independent of the state of ageing or test temperature of the binders used. This can simply be explained by the fact that all “simple” binders are in a “simple” state of linear Newtonian flow during these asphalt mixture and binder tests. For this state Softening Point, G*, ZSV and J_{nr} are all measures of simple Newtonian flow and are therefore well correlated.

There are very poor correlations (R^2<0.7) between the rutting propensity and G*, G*/sinδ and ZSV when examining all asphalt mixtures including those with “complex” binders such as most polymer modified bitumens. This is independent of the state of ageing. None of these parameters are therefore suitable predictors for rutting of complex binders.

There is a reasonable (R^2=0.79) and good (R^2=0.9) correlation between rutting propensity and J_{nr} for respectively fresh and short term aged binders. This is independent of test temperature. This confirms that J_{nr} is the most suitable rheological parameter to assess the contribution of the binder to rutting of the asphalt mixture and supports the approach proposed in the US to include J_{nr} in future Superpave specifications as high temperature bitumen characterisation. Furthermore it underlines the necessity to adopt the MSCR test method for European standardisation. The fact that the correlation is (much) better after short term ageing suggests inclusions of an appropriate ageing step when considering using J_{nr} for specification purposes.

6.0 ACKNOWEDGEMENT

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