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Functional Durability-related Bitumen Specification (FunDBitS)

Correlations between bitumen and asphalt properties

Permanent Deformation (rutting)

Deliverable D2 b
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Czech Technical University in Prague (CTU), Czech Republic
University of Kassel (UoK), Germany
Belgian Road Research Centre (BRRC), Belgium
Slovenian National Building & Civil Engineering Institute (ZAG), Slovenia
Transport Research Laboratory (TRL), UK
École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
European Asphalt Paving Association (EAPA), Belgium
Laboratório Nacional de Engenharia Civil (LNEC), Portugal
ASMUD, Turkey
Vienna University of Technology (TU Vienna), Austria
Nynas NV, Belgium

CEDR Call 2013: Energy Efficiency – Materials and Technology

FunDBitS
Functional Durability-related Bitumen Specification

Correlations between bitumen and asphalt properties

Permanent Deformation (rutting)

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Authors of this deliverable:
Fátima Batista & Margarida Sá da Costa, LNEC, Portugal
Bernhard Hofko, HTU Vienna, Austria
Joëlle De Visscher & Tine Tanghe, BRRC, Belgium

PEB Project Manager: Gerhard Eberl (ASFINAG), Austria

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Executive summary

In the FunDBitS project, the data that has become internationally available since the BiTVal project are being reviewed in order to develop performance-based bitumen characteristics which may be introduced into bitumen specification standards EN 12591, EN 14023 and EN 13924.

The relevant information available in the literature was already reviewed and possible correlations between the bitumen and asphalt properties were identified. For this, the following five main asphalt properties were considered: permanent deformation (rutting); stiffness; low temperature cracking; fatigue cracking and binder/aggregate interaction. As a result of the work performed, the interim report of the FunDBitS project, deliverable D.1, presents a description on identified correlations between bitumen and the referred five asphalt properties.

Later on, possible correlations between the bitumen and asphalt properties were reviewed in terms of the extent to which the bitumen affects the asphalt, in particularly its durability and service life, with due consideration for the reliability of the test methods and presence of other factors on the asphalt properties. Deliverable D.2 of the FunDBitS project presents the review of the correlations between the referred five asphalt properties and bitumen tests/properties.

The present report is a part of deliverable D.2, which deals specifically with the correlations between asphalt resistance to permanent deformation and bitumen tests/properties.

The relevant asphalt tests on permanent deformation are described in deliverable D.1, as follows:

- in Europe
  - Wheel Tracking test, WTT (EN 12697-22)
  - Cyclic compression test, CCT (EN 12697-25)
- in the USA
  - SUPERPAVE shear tester, SST
- other used tests
  - Simple Performance Tests, SPT (e.g. Dynamic modulus test; Flow Number; Flow Time)
  - Coaxial Shear Test, CAST
  - Carleton in-situ shear strength test, CISST

In the present report, the review of the identified correlations between bitumen relevant properties and the resistance to permanent deformation of bituminous mixtures is addressed by type of bitumen properties, i.e. bitumen tests are grouped by the type of property they provide. The relevant bitumen properties related to asphalt behaviour in terms of permanent deformation were identified in deliverable D.1, namely in the table on “Elevated service temperatures [bitumen] properties” of the “Data form”. Taking into consideration deliverable D.1, particularly in its “Permanent deformation (rutting)” chapter, the following bitumen properties are addressed:

- Viscosity
  - Capillary Viscometer Test
  - Coaxial Cylinder Viscosity Test
  - Cone and Plate Viscosity Test
  - Creep Zero/Low Shear Viscosity

  - Oscillation Zero/Low Shear Viscosity
- Softening point
  - Ring and Ball (R&B) Test
- Elastic and recovery properties
  - Multiple Stress Creep and Recovery (MSCR) Test
  - Elastic Recovery Test
- Complex modulus and phase angle
  - Dynamic Shear Rheometer (DSR) Test
- Performance Grading
  - Performance Grade (PG) classification

Among the addressed bitumen properties and its relation with the permanent deformation of bituminous mixtures, the most promising tests are the Zero/Low Shear Viscosity (ZSV/LSV) by creep or oscillation test method and the “non-recoverable compliance” (J_{nr}) from the MSCR test method.

1 Introduction

More than 80 % of the European Road Network is paved with asphalt materials. Energy efficient asphalt pavements can be built by using durable pavement materials in order to avoid or postpone maintenance and rehabilitation works. In order to improve the durability of asphalt materials, performance-based specifications were introduced for relevant asphalt mixtures. The asphalt types consist of aggregate particles in a specific grading and bitumen, the viscoelastic properties of which largely predetermine the mechanical asphalt properties.

Although the durability of asphalt mixtures is highly dependent on the properties of the bituminous binder, these are specified based on empirical test procedures (Softening Point Ring and Ball, penetration). It is well known that these test methods do not allow a prediction of asphalt mix performance, particularly for polymer-modified binders which are often used in heavily-loaded asphalt materials. In addition, the ageing of bitumen (which has a crucial effect on binder properties and thus on pavement performance), its durability and recyclability are not taken into account by European specifications in terms of performing functional testing after short-term or long-term ageing. To cover these aspects, functional performance-based bitumen test procedures have been developed over last years, but performance-based bitumen specifications are still not implemented in the first issued bitumen European standards, such as EN 12591 (paving grade bitumens), EN 14023 (polymer modified bitumens) and EN 13924 (hard paving grade bitumens). In EN 14023 latter, standard specific performance-based test methods are discussed only as a guideline.

During the BitVal project, an extended study was performed in order to evaluate correlations between bitumen and asphalt mixture properties. Resulting from that research, bitumen characteristics were researched for which good correspondences with performance-based asphalt mixture properties could be found. However, due to the limited number of research results available and discrepancies between the test conditions in both the bitumen and asphalt test procedures, it was too early to draw firm conclusions for specifications from those results.

In the meantime, performance-based asphalt test procedures were applied Europe-wide in order to evaluate the mechanical properties of asphalt mixtures. Since the introduction of performance-based test methods in the EN 12697-series, in particular, Parts 12 (water sensitivity), 24 (fatigue), 25 (rutting resistance), 26 (stiffness) and 46 (low-temperature cracking) have harmonised the relevant test methodologies within Europe.

In order to find correlations between binder and asphalt mixture properties, a lot of research has been conducted internationally since then which should allow stronger proposals to draft specifications for paving grade and polymer-modified bitumens that will broadly improve the durability, and thus the energy efficiency, of asphalt pavements. Furthermore, asphalt producers who improved the asphalt mixture properties during mix design were also forced to conduct tests on bitumen performance characteristics in order to establish quality control for their products. Therefore, data from the asphalt industry are available which will allow the correlation of asphalt and binder performance-based characteristics to be determined.

In the FunDBitS project, the data that has become internationally available since the BiTVal project are being reviewed in order to develop performance-based bitumen characteristics which may be introduced into bitumen specification standards EN 12591, EN 14023 and EN 13924.

The relevant information available in the literature was already reviewed and possible correlations between the bitumen and asphalt properties were identified. For this, the following five main asphalt properties were considered: permanent deformation (rutting); stiffness; low temperature cracking; fatigue cracking and binder/aggregate interaction. As a result of the work performed, the interim report of FunDBitS project, deliverable D.1, presents a description on identified correlations between bitumen and the referred five asphalt properties.

Later on, possible correlations between the bitumen and asphalt properties were reviewed in terms of the extent to which the bitumen affects the asphalt, in particularly its durability and service life, with due consideration for the reliability of the test methods and presence of other factors on the asphalt properties. Deliverable D.2 of FunDBitS project presents the review and analysis of the correlations between the referred five asphalt properties and bitumen tests/properties.

The present report is a part of deliverable D.2, which deals specifically with the correlations between asphalt resistance to permanent deformation and bitumen tests/properties.

2 Permanent deformation (rutting)

2.1 Introduction

Permanent deformation (rutting) is defined as the irreversible structural change in an asphalt layer caused by high pressure on the surface at elevated service temperatures.

The relevant asphalt tests on permanent deformation are described in the interim report of FunDBitS project deliverable D.1 – "Identified correlations between bitumen and asphalt properties" (2015), as follows:

- in Europe
  - Wheel Tracking test, WTT (EN 12697-22)
  - Cyclic compression test, CCT (EN 12697-25)
- in the USA
  - SUPERPAVE shear tester, SST
- other used tests
  - Simple Performance Tests, SPT (e.g. Dynamic modulus test; Flow Number; Flow Time)
  - Coaxial Shear Test, CAST
  - Carleton in-situ shear strength test, CISST

The rutting process in asphalt mixtures under repeated loads develops in three stages (Figure 2-2), which can be described as follows: the primary stage, that exhibits a fast increase of rutting (with a decreasing rate), due to an initial densification of the material; a secondary phase, with a constant rate of rutting; and a tertiary stage, characterized by accelerating rutting that leads to complete failure. In repeated load permanent deformation tests, primary and secondary stages are usually observed, but tertiary stage is only achieved in some type of tests (e.g. Flow Number test).

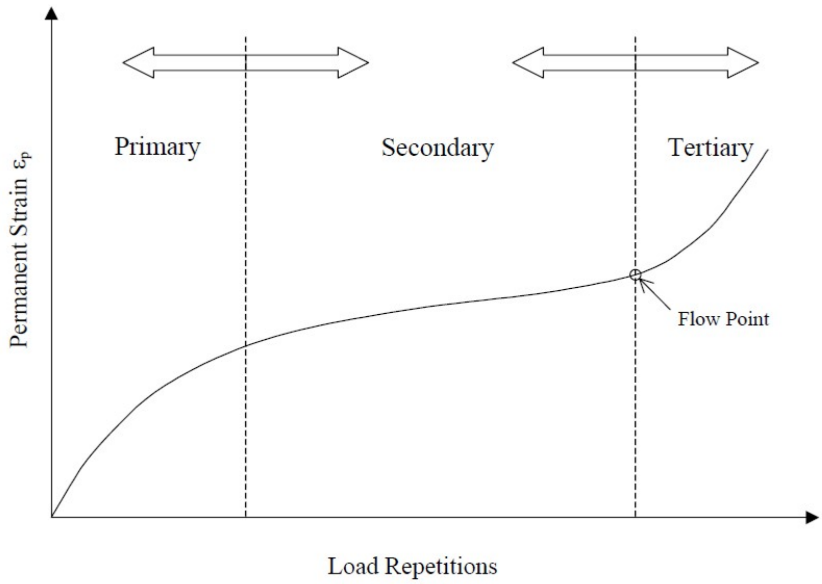


Figure 2-1: Typical repeated load permanent deformation behaviour of bituminous materials [NCHRP, 2004]

The analysis of the possible relationship between bitumen relevant properties and the permanent deformation behaviour of asphalt mixtures is addressed, in this report, by type of bitumen properties, i.e. bitumen tests were grouped by the type of property they provide.

The relevant bitumen properties related to asphalt behaviour in terms of permanent deformation were identified in deliverable D1, namely in the table on "Elevated service temperatures [bitumen] properties" of the "Data form".

Taking into consideration deliverable D1, particularly in its "Permanent deformation (rutting)" chapter, the following bitumen properties are addressed in next sections:

- Viscosity
  - Capillary Viscometer Test
  - Coaxial Cylinder Viscosity Test
  - Cone and Plate Viscosity Test
  - Creep Zero/Low Shear Viscosity
  - Oscillation Zero/Low Shear Viscosity
- Softening point
  - Ring and Ball (R&B) Test
- Elastic and recovery properties
  - Multiple Stress Creep and Recovery (MSCR) Test
  - Elastic Recovery Test
- Complex modulus and phase angle
  - Dynamic Shear Rheometer (DSR) Test
- Performance Grading
  - Performance Grade (PG) classification

2.2 Relationship found between bitumen viscosity properties and asphalt resistance to permanent deformation

Regarding relationships between bitumen viscosity properties and mix resistance to permanent deformation, the following bitumen test methods were investigated (number of relevant papers found in brackets):

- Capillary Viscometer Test (1)
- Coaxial Cylinder Viscosity Test (0)
- Cone and Plate Viscosity Test (0)
- Creep Zero/Low Shear Viscosity (4)
- Oscillation Zero/Low Shear Viscosity (2)

From the total number of relevant papers found for this bitumen parameter (7), it is obvious that conclusions are based on a limited set of data.

2.2.1 Capillary Viscometer Test

One relevant paper was found in this case, i.e. Paper 558 (Reyes-Lizcano *et al.*, 2009). This paper investigates the effect of polymer modification on HMA performance. Mixes were prepared with binders with 1 %, 3 % and 5 % (based on binder mass) of SBS. Capillary viscometer tests on all binders were compared to results from dynamic tests using the Nottingham Asphalt Tester (NAT) to determine the resistance to permanent deformation according to EN 12697-25 (Figure 2-2). Tests were run at +40 °C with a lower stress level of 10 kPa and an upper stress level of 100 kPa for up to 3,600 load cycles.

No correlation between kinematic viscosity of tested binders and accumulated axial strain of the asphalt mixes were found.

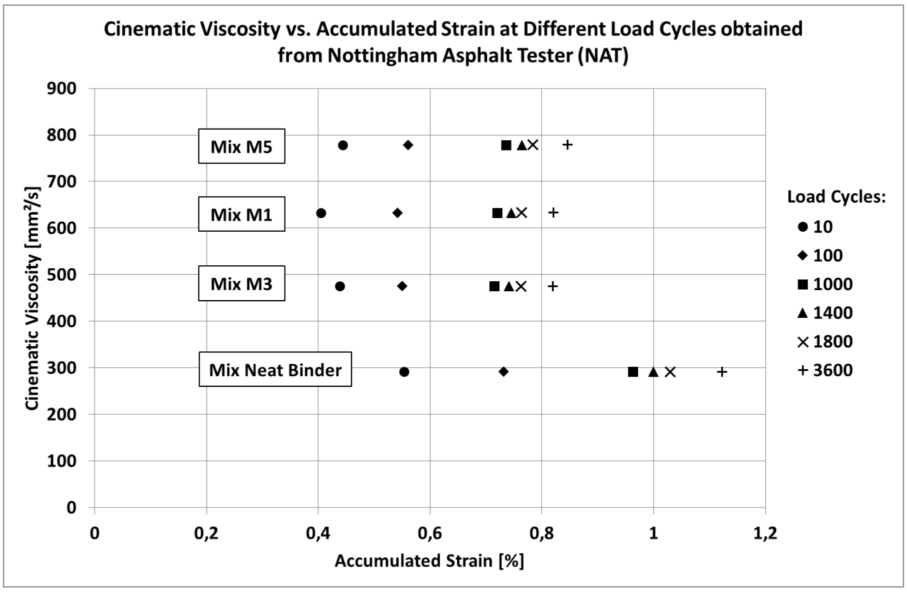


Figure 2-2: Kinematic viscosity *vs.* accumulated strain [Paper 558: Reyes-Lizcano *et al.*, 2009]

2.2.2 Coaxial Cylinder Viscosity Test

No relevant papers were found.

2.2.3 Cone and Plate Viscosity Test

No relevant papers were found.

2.2.4 Creep Zero/Low Shear Viscosity (ZSV/LSV) Test

Four relevant papers were found for creep ZSV: Paper 023 (Dueñas *et al.*, 2012), Paper 042 (Robertus *et al.*, 2012), Paper 043 (Morea, 2012) and Paper 047 (Gungor & Sağlik, 2012).

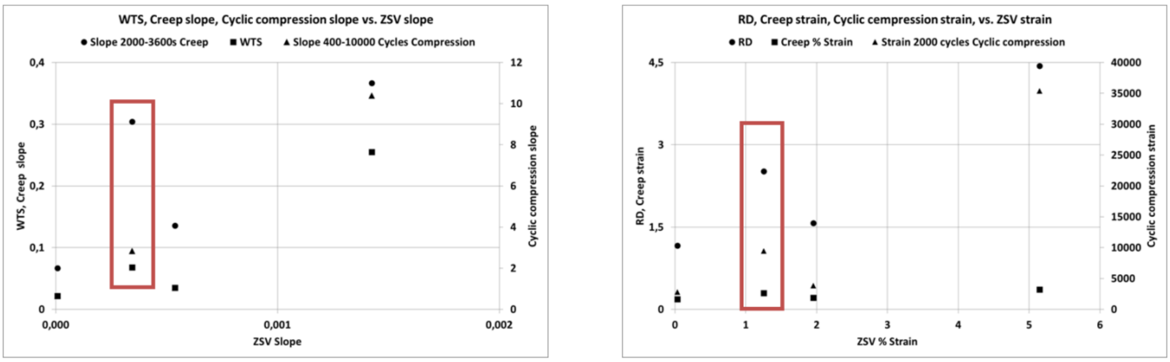


Figure 2-3: Relations between Wheel tracking mix test, cyclic compression mix test and binder creep test (ZSV slope & ZSV % strain) [Paper 023: Dueñas *et al.*, 2012)]

Paper 023 (Dueñas *et al.*, 2012) worked with a small set of samples, 4 different binders (a paving grade bitumen, 50/70; a polymer-modified binder, PMB 45/80-60; a highly-polymer-modified binder, hvPMB 45/80-75; and a crumb rubber binder). It compares ZSV carried out according to TS 15325 at +60 °C to results from wheel-tracking tests according to EN 12697-22, small device, Procedure B, from cyclic compression tests according to EN 12697-25 and to creep tests (Figure 2-3). The mix tests were carried out on AC 16 mixtures at +60 °C. Due to the small number of test samples and the fact that the presented trends always show at least one deviation from the overall trend, **no statistically valid conclusion can be** drawn from this paper.

Paper 042 (Robertus *et al.*, 2012) shows a large set of samples with 20 different binders, including 4 paving grade bitumens, 11 polymer modified binders, 2 low-viscosity binders and two "special binders". ZSV were run in controlled-stress creep mode at +45 °C and +60 °C. Creep times for non-modified binders were set to 1 hour, for modified binders to 4 hours. The average viscosity was computed over the last 15 min. On the mix level, wheel tracking tests were carried out at +45 °C and +60 °C. The relationship between wheel tracking rate and ZSV for unaged binders was assessed (Figure 2-4). **A correlation was found between the ZSV and the rutting rate, using a power function. The coefficient of correlation R^2 is low ($R^2 = 0,49$; n = 30) when all binders are considered. However, there is a good correlation ($R^2 = 0,93$; n = 14) when only rheological simple binders are considered.**

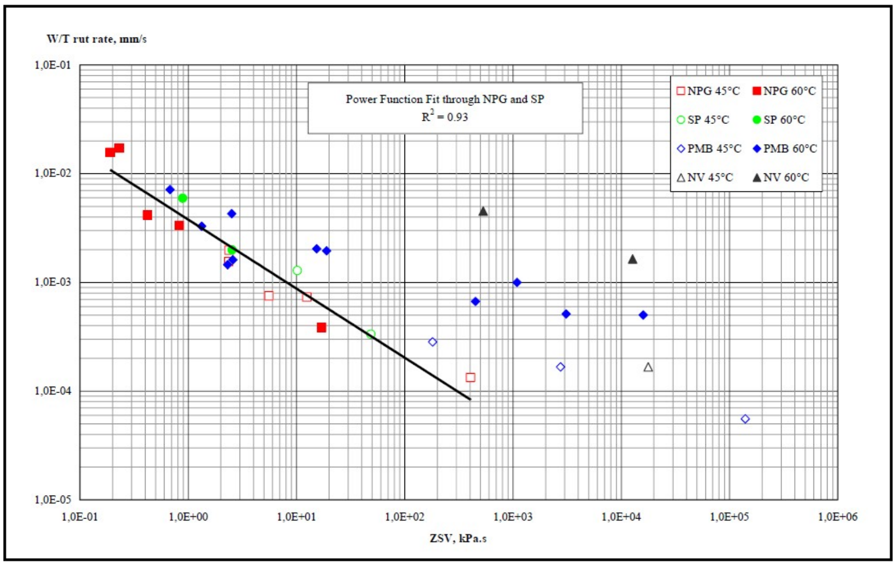


Figure 2-4: Wheel tracking rut rate vs. ZSV [Paper 042: Robertus *et al.*, 2012]

Paper 043 (Morea, 2012) addresses relationships between the LSV of bitumen and bituminous mixes resistance to permanent deformation (Figure 2-5). The study contains non-modified and SBS-modified binder in unaged and RTFOT-aged state. LSV and wheel tracking tests were carried out at temperatures ranging from 50 °C to 80 °C. **A good correlation between rutting rate [µm/min] derived from load cycle 2 000 to load cycle 2 500 and the LSV was found. Correlation function is given for unaged and RTFOT-aged state as well as coefficient of correlation.**

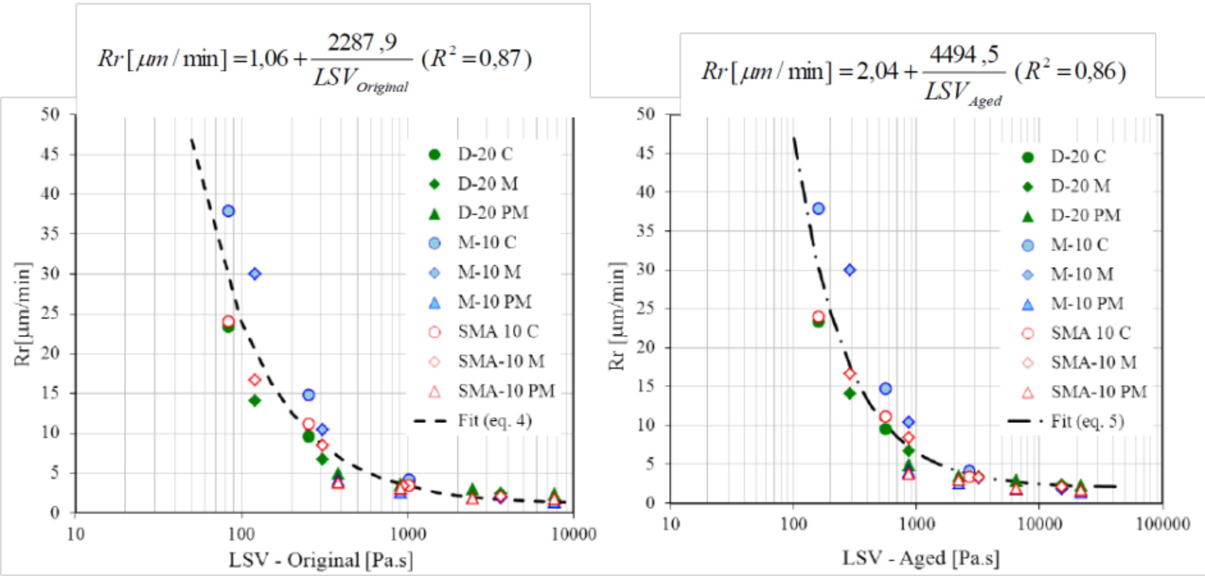


Figure 2-5: Rutting performance (Rr, WTT) *vs.* accumulated strain [Paper 043: Morea, 2012]

Paper 047 (Gungor & Sağlik, 2012) presents a study on 12 different binders, 4 paving grade bitumens and modified binders by adding SBS and Elvaloy modifier. ZSV was determined on RTFOT-aged samples at 6 different temperatures ranging from +35 °C to +60 °C according to TS 15325 with creep times of 30 min for unmodified binders and 7 h for modified one and recovery times of 30 min. and 1 h, respectively. On asphalt mix level triaxial cyclic compression tests (TCCT) were run according to EN 12697-25 with a constant confining pressure of 100 kPa and axial load amplitude of 300 kPa at a frequency of 2,5 Hz. TCCTs were run at +40 °C and +50 °C. Graphics relating ZSV-strain and permanent deformation results are drawn for the referred temperatures (Figure 2-6). **There is a good correlation for all binders at both temperatures using a power function to describe accumulated axial strain at 10,000 load cycles *versus* ZSV (R^2 = 0,84 at 40 °C and R^2 = 0,92 at 50 °C, n = 12). However, the test methods take up to 10 hours for a modified binder to reach steady-state and some materials fail before steady-state is reached.**

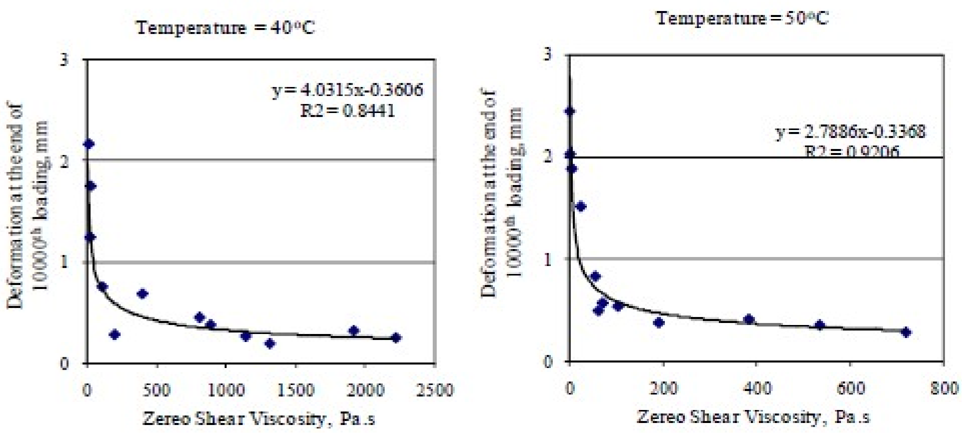


Figure 2-6: ZSV *vs.* permanent deformation at 40 ºC and 50 ºC [Paper 047: Gungor & Sağlik, 2012]

2.2.5 Oscillation Zero/Low Shear Viscosity (ZSV/LSV) Test

Two papers were found that work on oscillation ZSV, Paper 067 (Guericke, & Schlame, 2008) and Paper 499 (De Visscher & Vanelstraete, 2009).

For Paper 067 (Guericke, & Schlame, 2008), 11 different non-modified and polymer-modified binders were employed in the study. ZSV was measured on the RTFOT-aged binder samples at +60 °C in oscillation mode at low shear rate and extrapolated to zero to obtain ZSV. Hamburg wheel tests were carried out at +40 °C, +50 °C and +60 °C on SMA mixtures made from the investigated binders (Figure 2-7). **A power function correlates rut depth [mm] to the ZSV with high coefficient of determination (R^2 = 0,91 at +60°C, n = 11; R^2 = 0,91 at +50°C, n = 6; R^2 = 0,81 at +40°C, n > 25). Thus, there seems to be a good correlation between the Hamburg wheel test and oscillating ZSV for both, non-modified and polymer-modified binders.**

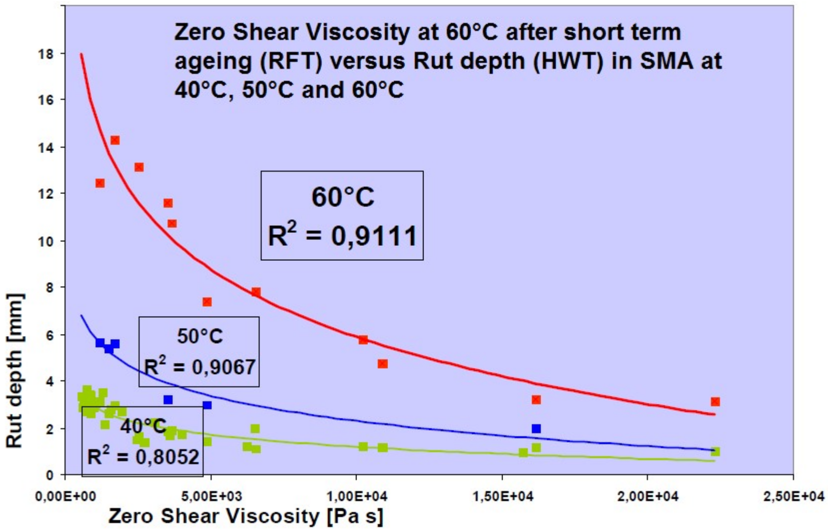


Figure 2-7: Ruth depth in stone mastic asphalt (SMA) in Hamburg Wheel tracking test [Paper 067: Guericke, & Schlame, 2008]

Paper 499 (De Visscher & Vanelstraete, 2009) works with 12 different binders, 6 unmodified binders, 1 wax-modified binder and 5 polymer-modified binders. LSV tests are carried out according to CEN/TS 15324 to obtain both, the equiviscous temperature 1 (EVT1) and the equiviscous temperature 2 (EVT2). In addition, tests on asphalt mixes (AC 16) were carried out as well. These tests include the wheel tracking test (WTT) according to EN 12697-22 (large device) and the triaxial cyclic compression test (TCCT) according to EN 12697-25, part B. The WTT was carried out at a frequency of 1 cycle per second, the TCCT at the same frequency with a haversine loading pulse of 0,4 sec, followed by a rest period of 0,6 sec. Asphalt mix tests were carried out at +50 °C. Linear trends were used to correlate proportional rut depth (PRD) after 30,000 cycles and the creep rate from TCCT between load cycle 2000 and 8000 to EVT1 and EVT2, respectively (Figure 2-8 and Figure 2-9). **With regard to PRD and EVT1, a good correlation is found for the complete set of binders (R^2 = 0,83, n =11) as well as for the unmodified binders (R^2 = 0,86, n = 6). For PRD and EVT2, only the correlation for unmodified binders is sufficient enough (R^2 = 0,85, n =6). With regard to the creep rate *versus* EVT1 and EVT2, all correlations show an R^2 > 0,75. In general, EVT1 seems to work better to predict permanent deformation behaviour of asphalt mixes.**

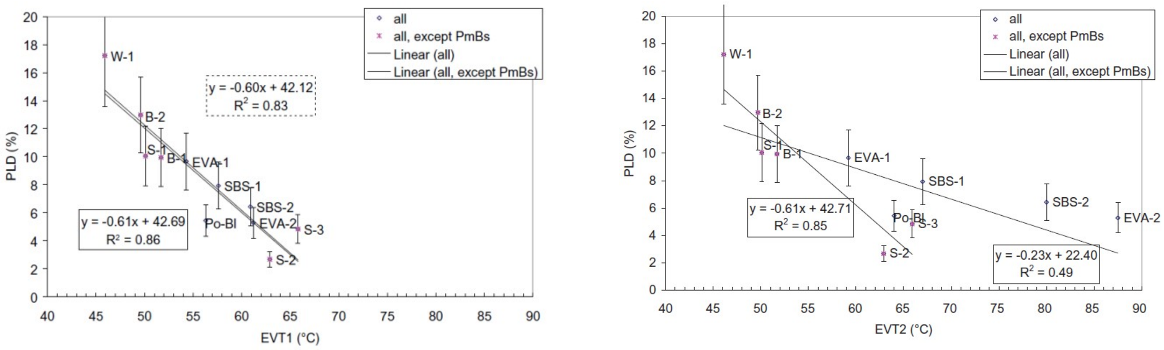


Figure 2-8: Proportional rut depth (after 30,0000 cycles) versus EVT1 & EVT2 [Paper 499: De Visscher & Vanelstraete, 2009]

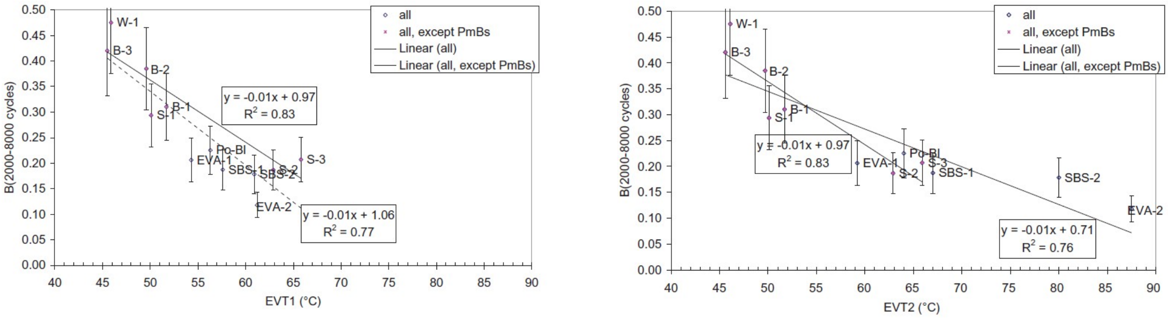


Figure 2-9: Slope of the accumulated strain curve of the triaxial compression test versus EVT1 & EVT2 [Paper 499: De Visscher & Vanelstraete, 2009]

2.2.6 Papers analysis sum up

The following conclusions can be drawn from the paper review:

- In general, only a small number of studies (7) are available on correlating bitumen viscosity properties to asphalt mix permanent deformation.
- The four studies on creep ZSV show that the correlation between binder viscosity and wheel tracking parameter is good when only non-modified binders are used. However, when the axial strain from TCCT is linked to ZSV, a good correlation can be achieved even when modified binders are taken into consideration.
- The two studies on oscillation ZSV reveal that the rut depth seems to be linked to the ZSV with high coefficient of determination and that the equiviscous temperature 1 (EVT) according to CEN/TS 15324 is linked to the proportional rut depth and the creep rate from TCCT with good correlation.
- Although ZSV shows good potential to link binder to mix properties, more studies are needed to be able to draw stronger conclusions.
- Also, test conditions for ZSV vary strongly from one paper to the next. A more detailed standardization of the test conditions would be beneficial for the next series of standards.
- Creep ZSV measurements on polymer-modified binders take a long time (up to 10 hours) to reach a steady state. Therefore, it seems that oscillation ZSV can be run more efficiently than creep ZSV.

Table 2-1 summarizes the correlations found between bitumen binder viscosity properties and permanent deformation behaviour of bituminous mixtures.

Table 2-1: Correlations found between binder viscosity and permanent deformation behavior of asphalt mixtures

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	R^2	*Comment*
Paper 042 (Robertus *et al.*, 2012)	WT Rut Rate (mm/s) *vs.* ZSV (kPa*s)	Power (y= a.x^b)	14	N/A	N/A	0.93	U / UA
			30	N/A	N/A	0.49	U & PMB
Paper 043 (Morea, 2012)	WT rut rate (µm/min) vs. LSV (Pa*s)	y=a+b/x	29	1,06	2287,9	0,87	U & PMB / UA & A
				2,04	4494,5	0,86	
Paper 047 (Gungor & Sağlik, 2012)	Axial deformation [mm] from TCCT *vs.* ZSV [Pa*s]	Power (y= a.x^b)	12	2.7886	-0,3368	0.92	U & PMB / A (TCCT@40ºC)
			12	4.0315	-0.3606	0.84	U & PMB / A (TCCT@50ºC)
Paper 067 (Guericke & Schlame, 2008)	HWT Rut Depth (mm) *vs.* ZSV [Pa*s]	Power (y= a.x^b)	25	N/A	N/A	0.81	U & PMB / A (WTT at +40°C)
			6	N/A	N/A	0.91	U & PMB / A (WTT at +50°C)
			11	N/A	N/A	0.91	U & PMB / A (WTT at +60°C)
Paper 499 (De Visscher & Vanelstraete, 2009)	PRD [%] *vs.* EVT1 [°C]	Linear (y= a + bx)	6	-0.61	42.69	0.86	U
			11	-0.6	42.12	0.83	U & PMB
	PRD [%] *vs.* EVT2 [°C]	Linear (y= a + bx)	6	-0.61	42.71	0.85	U
			11	-0.23	22.4	0.49	U & PMB
	Creep rate [µm/m/n] *vs.* EVT1	Linear (y= a + bx)	6	-0.01	0.97	0.83	U
			11	-0.01	1.06	0.77	U & PMB
	Creep rate [µm/m/n] *vs.* EVT2	Linear (y= a + bx)	6	-0.01	0.97	0.83	U
			11	-0.01	0.71	0.76	U & PMB

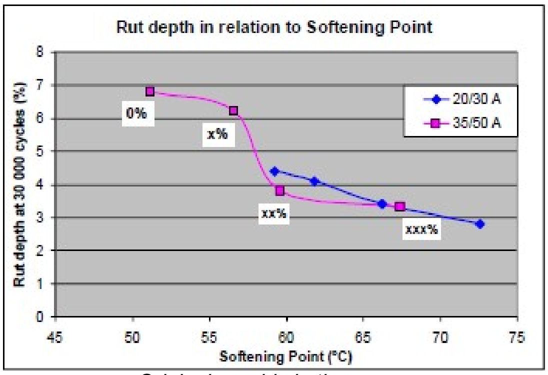
LEGEND: U - Unmodified bitumen; PMB - Polymer Modified Bitumen;
A - Aged bitumen; UA – unaged bitumen;
PRD – percentage of rut deformation in wheel tracking tests;
ZSV – Zero Shear Viscosity; EVT1 – equiviscous temperature 1; EVT2 – equiviscous temperature 2;
HWT - Hamburg Wheel tracking Test; TCCT – Triaxial Cyclic Compression Test; WT – Wheel tracking Test; PRD – Percentage of Rut Depth.

2.3 Relationship found between bitumen softening point and asphalt mix resistance to permanent deformation

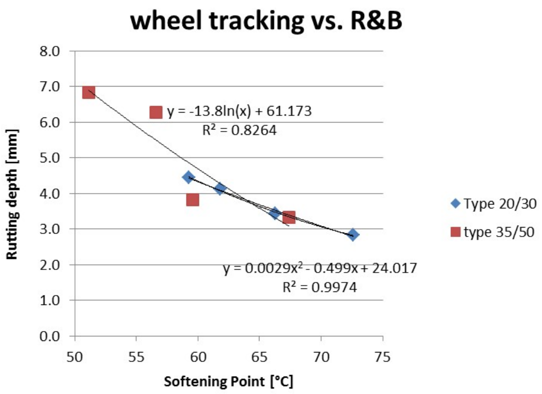
The Ring and Ball (R&B) test is considered as a traditional test method with a large background in data. However, there are concerns that this test may not be suitable for any modified bituminous binder. Correlation analysis between R&B and asphalt mix testing was found in 7 of the reviewed papers: Paper 026 (Eckmann *et al.*, 2012), Paper 042 (Robertus *et al.*, 2012), Paper 067 (Guericke & Schlame, 2008), Paper 425 (Dreessen & Pascal, 2009), Paper 504 (Tusar *et al*., 2009), Paper 532 (Renken, 2012) and Paper 558 (Reyes-Lizcano *et al*., 2009).

2.3.1 Ring and Ball (R&B) Test

Paper 026 (Eckmann *et al*., 2012) correlates results from R&B tests on bituminous binder samples with different polymer contents to the rut depth from wheel tracking tests according to EN 12697-22 (French device) after 30,000 load cycles (Figure 2-10). Two base binders (20/30 and 35/50) were employed in the study. **The results show that for each of the binders, a good linear correlation between softening point and rut depth [%] is obtained (R^2 > 0,80, n = 4). However, the set of samples is low and it is obvious that the correlation only works for each binder source by itself.**



Original graphic in the paper



Processed graphic in order to obtain correlation of softening point with rutting

Figure 2-10: Rut depth *vs*. Softening Point [Paper 026: Eckmann *et al*., 2012]

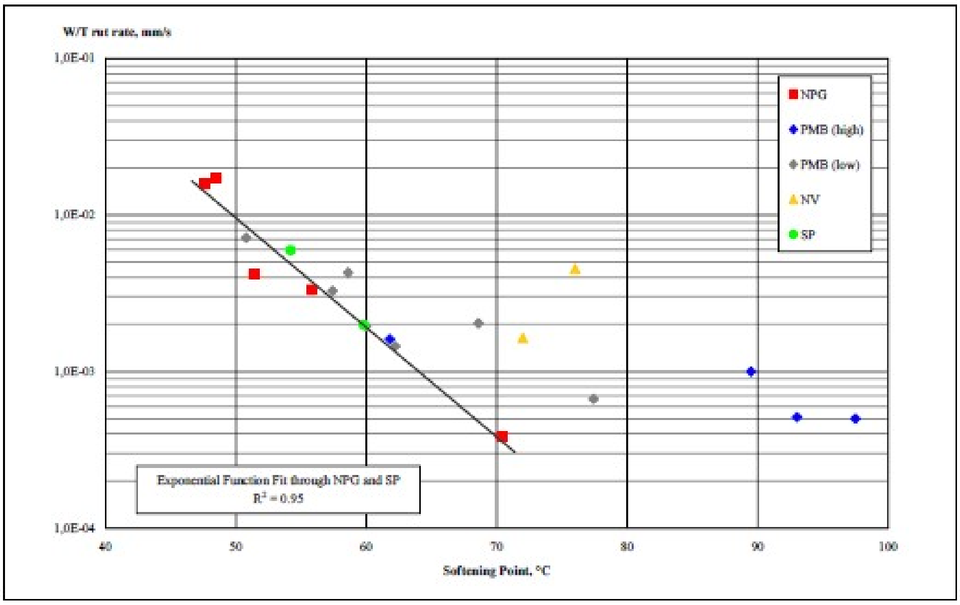
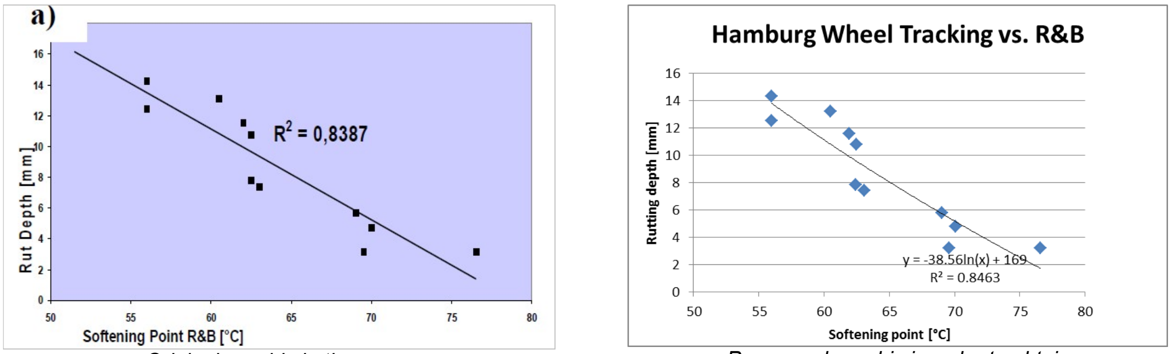


Figure 2-11: Wheel tracking rut rate at 60°C *vs*. Softening Pont of unaged binder [Paper 042: Robertus *et al*., 2012]

Paper 042 (Robertus *et al*., 2012) shows a correlation between R&B and the wheel tracking rut rate at +60 °C (Figure 2-11). Non-modified and polymer-modified binders were used. **A rather poor linear correlation was found (R^2 = 0,68; n = 19) when all binder samples**

were considered. The coefficient of determination increased to 0,95 (n = 7) when only non-modified and lowly modified binders were taken into consideration.

Paper 067 (Guericke & Schlame, 2008) correlates rut depths [mm] to the R&B results of 11 different unmodified and polymer-modified binders and SMA mixtures (Figure 2-12). **A decent linear correlation (R^2 = 0,83; n = 11) was found.**



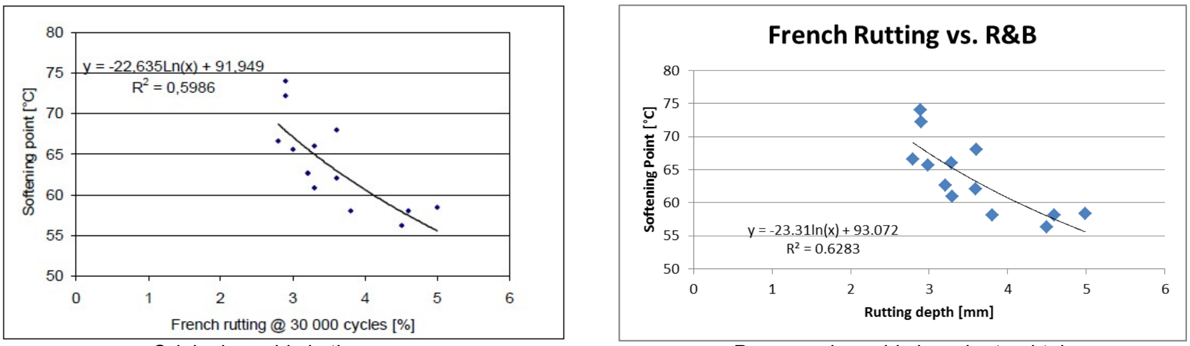
Original graphic in the paper

Processed graphic in order to obtain correlation of softening point with rutting

Figure 2-12: Rut depth (Hamburg Wheel-tracking Test) in SMA at 60 °C *vs.* Softening point R&B after short-term ageing (RFT) [Paper 067: Guericke & Schlame, 2008]

Paper 425 (Dreessen & Pascal, 2009) investigates R&B results of polymer modified binders (Styrelf®) with polymer contents ranging from 2 M% to 5 M%. Correlations from R&B of different binders (7 pure, 6 polymer modified and 2 specials binders) and results of wheel tracking tests (WTT) according to EN 12697-22 (French device) were studied (Figure 2-13).

A weak correlation was found, which corresponds to a coefficient of determination of 0,60 for a logarithmic trend (n = 13).



Original graphic in the paper

Processed graphic in order to obtain correlation of softening point with rutting

Figure 2-13: Correlation between softening point (R&B) and rutting (WTT) [Paper 425: Dreessen & Pascal, 2009]

In paper 504 (Tusar *et al.*, 2009), 7 binders, 3 non-modified bitumens and 4 polymer modified binders were employed. Wheel tracking tests (WTT) results were correlated to R&B results (Figure 2-14). **A logarithmic regression (correlation) between rutting depth [mm] and softening point was found with a high correlation (R^2 = 0,91; n = 7), even though the study contained non-modified and polymer-modified binders.**

Paper 532 (Renken, 2012) works with 12 different binders and asphalt concrete used for binder layers (AC 16 BS) and for surface layers (AC 11 DS). R&B results were investigated in combination with results from wheel tracking tests (WTT) according to EN 12697-22 (Figure 2-15). **No correlation between R&B and rut depth [mm] was found (n =14).**

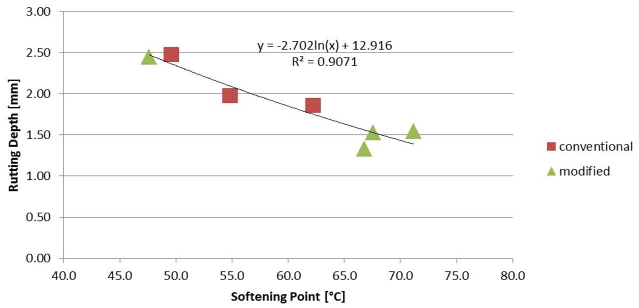


Figure 2-14: Correlation between softening point (R&B) and rutting (WTT) [Paper 504: Tusar *et al.*, 2009]

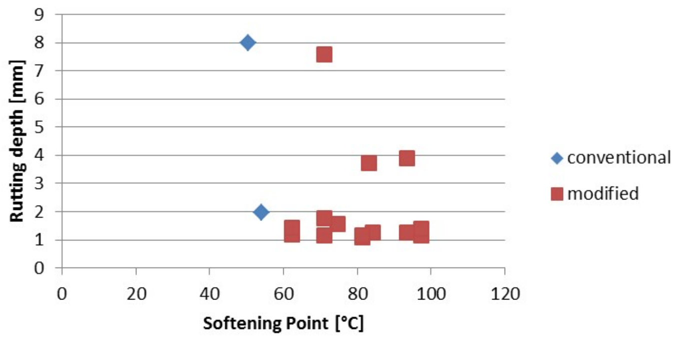


Figure 2-15: Correlation between softening point (R&B) and rutting (WTT) [Paper 532: Renken, 2012]

Furthermore, Paper 532 (Renken, 2012) assesses the influence of 3 different additives on the bitumen properties and bituminous mixture resistance to permanent deformation. R&B results were investigated in combination with results from uniaxial dynamic compression tests according to TP Asphalt-StB, Part 25 B1 (based on EN 12697-25, part B, but without the radial stress) (Figure 2-16). The resistance against permanent deformation is positively influenced by the use of additives that change the viscosity of the binder. **However, the set of samples is low and it is obvious that the correlation only works for each binder by itself.**

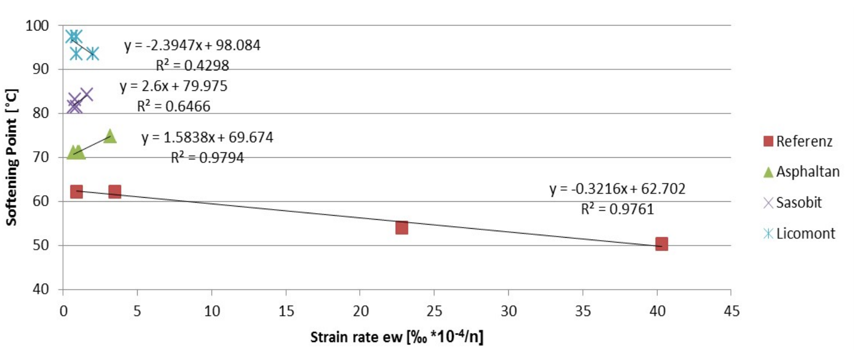


Figure 2-16: Correlation between softening point (R&B) and rutting (uniaxial dynamic compression tests) [Paper 532: Renken, 2012]

Paper 558 (Reyes-Lizcano *et al.*, 2009) studied binders from one bitumen source using the non-modified sample and polymer-modified samples with 3 % to 13 % (in mass) of polymer in the binder. Repeated uniaxial loading tests were carried out on asphalt mixes produced with these binders by using the Nottingham Asphalt Tester (NAT) according to EN 12697-25 at +40 °C. **A correlation analysis between accumulated axial strain [%] after 3 600 load cycles and the softening point was carried out** (Figure 2-17)**. The coefficient of determination is poor (R^2 = 0,54; n = 9).**

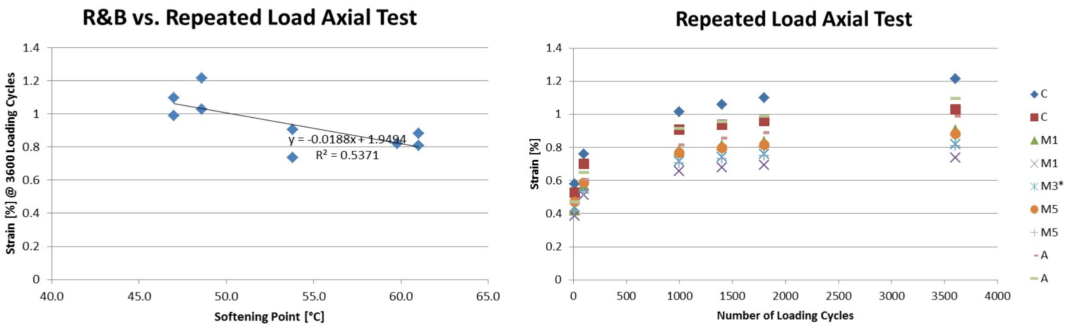


Figure 2-17: R&B test *vs.* Repeated Load Axial Test results [Paper 558: Reyes-Lizcano *et al.*, 2009]

2.3.2 Papers analysis sum up

In Figure 2-18, all data from the examined papers are collected and illustrated. It is evident, that the correlation of some isolated data cannot be applied on a global validity.

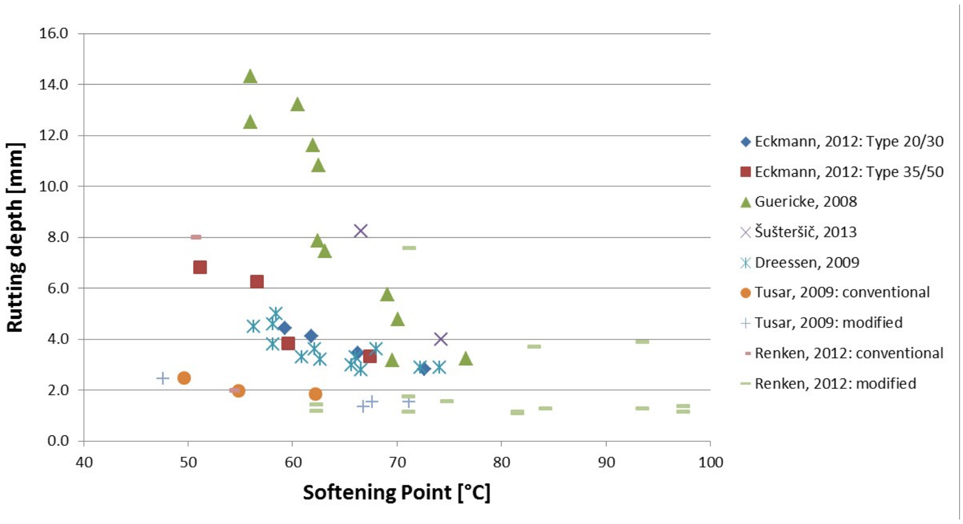


Figure 2-18: Correlations between softening point (R&B) and rutting (WTT)

Figure 2-19 shows the correlation between the softening point and dynamic stability from papers 259 (Kim *et al*., 2013) and 308 (Tan *et al*., 2014). The relationship of the two parameters is approximately linear. The R^2 value for fitting the relationship between dynamic stability and softening point is 0,65.

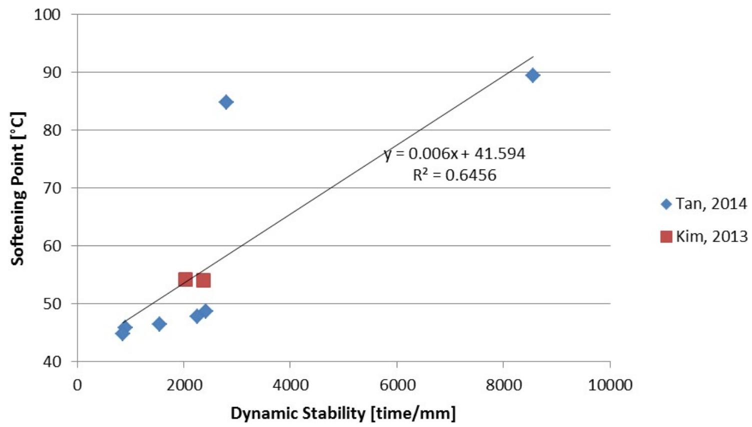


Figure 2-19: Correlations between softening point (R&B) and rutting (dynamic stability)

Table 2-2 summarizes the correlations found between binder R&B and permanent deformation behaviour of bituminous mixtures.

Table 2-2: Correlations found between binder R&B and permanent deformation behavior of bituminous mixtures

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	*R^2*	*Comment*
Paper 026 (Eckmann *et al.*, 2012)	Rut depth [mm] *vs.* softening point [°C]	Linear (y= a + bx)	4	-0.2323	18.695	0.82	U (20/30 pen grade) + PMB
			4	-0.1221	11.642	0.99	U (35/50 pen grade) + PMB
Paper 042 (Robertus *et al.*, 2012)	Rut rate [mm/s] *vs.* softening point [°C]	Linear (y= a + bx)	19	N/A	N/A	0.68	U + PMB
			7	N/A	N/A	0.95	U
Paper 067 (Guericke & Schlampe, 2008)	Rut depth [mm] *vs.* softening point [°C]	Linear (y= a + bx)	11	0.5893	46.523	0.84	U + PMB
Paper 425 (Dreessen & Pascal, 2009)	Softening point [°C] *vs.* rut depth [mm]	Logarithmic (y= a lnx + b)	13	-22.635	91.949	0.60	U + PMB
Paper 504 (Tusar *et al.*, 2009)	Rut depth [mm] *vs.* softening point [°C]	Logarithmic (y= a lnx + b)	7	-2.702	12.916	0.91	U + PMB
Paper 532 (Renken, 2012)	Rut depth [mm] *vs.* softening point [°C]	Non correlation found	N/A	N/A	N/A	N/A	N/A
Paper 558 (Reyes-Lizcano *et al.*, 2009)	Accumulated axial strain [%] *vs.* softening point [°C]	Linear (y= a + bx)	9	-0.0188	1.9494	0.54	PMB

LEGEND: U - Unmodified bitumen; PMB - Polymer Modified bitumen;
A - Aged bitumen; UA – Unaged bitumen;

The following conclusions can be drawn from the paper review:

- From the seven papers with relevant data, six of them correlate R&B results to results from wheel tracking tests and one to results from TCCT.
- Some papers find a decent correlation between R&B and wheel tracking results, even when polymer-modified binders are used for testing. But these studies are limited to samples from the same binder source, i.e. one unmodified bitumen-base was used to produce the polymer-modified samples. When a mix of unmodified and modified binders is used that are not from the same base bitumen, poor correlations were found.
- The R&B test is a method with long tradition and large data background. However, it does not give good correlation between bitumen and asphalt mix level when polymer-modified binders are used.

2.4 Relationship found between bitumen elastic and recovery properties and asphalt resistance to permanent deformation

There were 43 papers on Multiple Stress Creep and Recovery (MSCR) test retrieved from the literature database, but only a limited number of them discuss correlations with asphalt permanent deformation. With respect to Elastic Recovery test, there were no papers found on correlations between the bitumen properties and asphalt permanent deformation.

2.4.1 Multiple Stress Creep and Recovery (MSCR) Test

In Paper 023 (Dueñas *et al.*, 2012) a set of 4 binders is considered: B50/70, PMB 45/80-60, PMB 45/80-75 and a crumb rubber modified (CRM) binder. Correlations were studied with both the wheel tracking test (EN 12697-22) and the cyclic compression test (EN 12697-25), all tests performed at 60 °C (Figure 2-20). Although the number of binders is small, Figure 2-20 shows **a fairly good correlation between J_{nr} of the binder, and both the compliance in the cyclic compression test and the rut depth in the wheel tracking test.** Only the crumb rubber modified binder (CRM) showed more permanent deformation in both asphalt tests as expected from the J_{nr} result in the MSCR test. There was also **a good correlation between % recovery in the MSCR test and % recovery in the cyclic compression test** on asphalt.

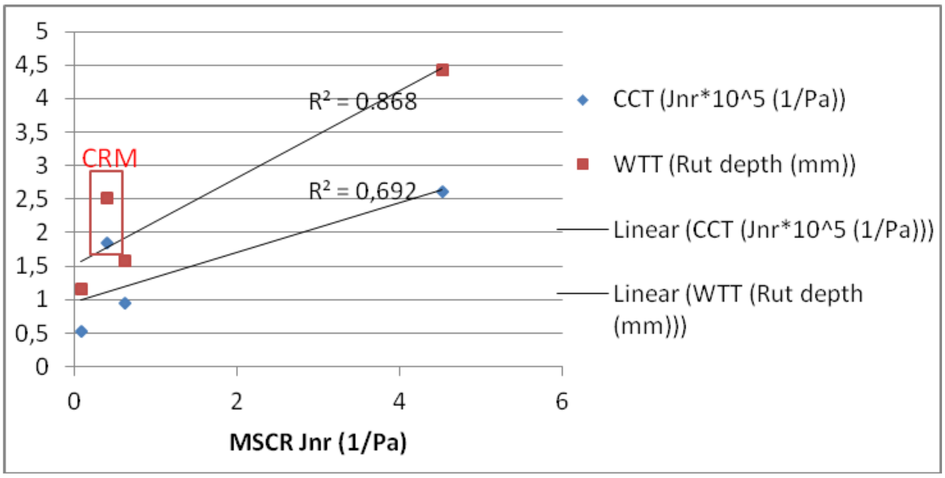


Figure 2-20: Correlations between J_{nr} and permanent deformation in two asphalt tests (Cyclic compression test CCT and wheel tracking test WTT) [based in data from Paper 023]

In Papers 425 (Dreessen & Pascal, 2009), 501 (Dreessen *et al.*, 2009) and 035 (Dreessen & Gallet, 2012) the correlation between J_{nr} and the rut depth in the wheel tracking test (large size device) is investigated. All tests (MSCR and wheel tracking tests) were performed at 60 °C. J_{nr} was measured at various stress levels, up to 25 600 Pa. Table 2-3 shows the correlation between J_{nr} at the various stress levels and the rut depth at various cycles, based on a set of 15 binders (7 pure, 6 PmB and 2 special). **The authors conclude that the higher stress levels lead to better correlations and propose a stress level of 12 800 Pa.**

Table 2-3: R^2 of correlations between J_{nr} (at various stress levels) and rut depth (at various cycles) [Papers 035, 425 and 501]

Rut cycles / Jnr [Pa-1]	1000	3000	10000	30000
100	0,2186	0,1857	0,1074	0,3604
800	0,3642	0,3571	0,2756	0,3547
1600	0,3441	0,3468	0,2925	0,3028
3200	0,6350	0,6374	0,4916	0,4453
6400	0,8498	0,9025	0,8483	0,5674
12800	0,8787	0,9008	0,8050	0,7149
25600	0,8475	0,8059	0,6410	0,7711

Paper 042 (Robertus *et al*., 2012) examined correlations between various binder tests and the rut rate in a small size wheel tracking device. A large set of 20 binders, including PmBs and special binders, was tested at both 45 °C and 60 °C (Figure 2-21). **A good correlation was found between the wheel tracking rut rate (small size device) and J_{nr} from the MSCR test. The correlation was much better than with all other investigated binder properties. The correlation was also better with aged binders (R^2=0,90) than with fresh (unaged) binders (R^2=0,79).**

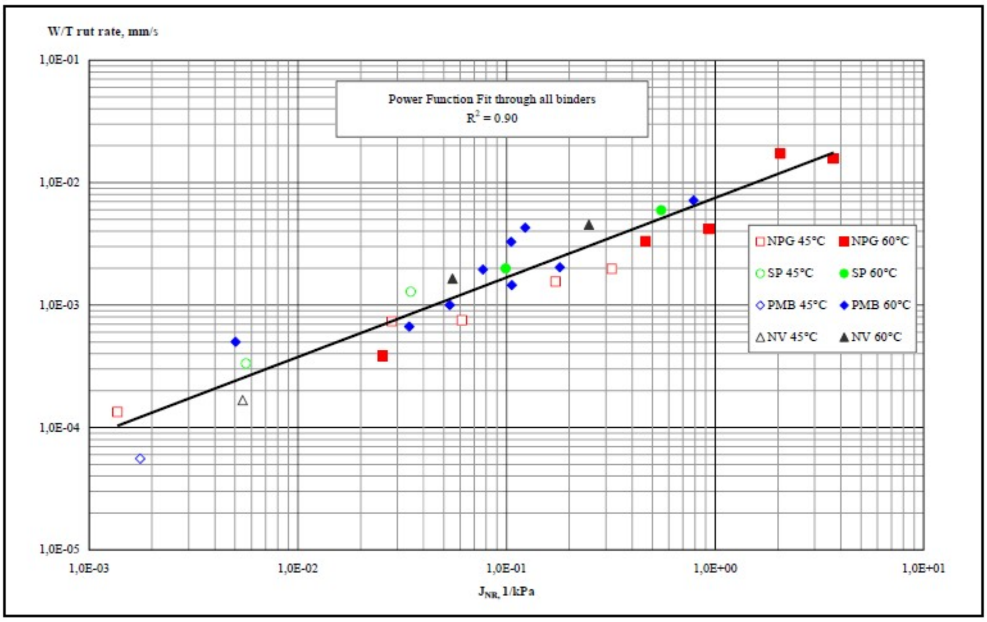


Figure 2-21: Wheel tracking rut rate vs. J_{nr} of aged binders at 45 °C and 60 °C [Paper 042: Robertus *et al*., 2012]

Paper 185 (D'Angelo *et al*., 2007) presents the correlation between J_{nr} from the MSCR test and rut depth in the ALF (Accelerated Load Facility) of the US FHWA. The paper also studied the correlation between J_{nr} and rut depth measured on test sites after 6 years of service. **In both studies, the correlations were good and better than the correlations with G*/sinδ.**

In Paper 330 (Bower *et al*., 2014), four WMA techniques are compared to HMA with same "additives": MSCR (J_{nr} at 64 °C and 3,2 kPa) is compared to rutting tests on a Hamburg wheel tracking device on field cores and early stage field cores. **It was noted that the binder test results may not be consistent with the mixture test results. The tests on extracted and recovered binders evaluated the effects of WMA on the binder only.** However, between different WMA technologies, the test results on the binder are more consistent than those on mixtures.

Paper 456 (Bennert & Martin, 2010) addresses the impact of PPA in a binder as partial substitution of SBS: in the MSCR binder test, the pure polymer modified binder (SBS) performs better than the binder with SBS and PPA, especially in recovery. But **in asphalt performance, no difference between the binders could be observed**.

In Paper 516 (Laukkanen *et al*., 2014), it was found that the non-recoverable creep compliance parameter (Jnr at 3,2 kPa) has a superior capability of predicting asphalt mixture rutting compared to other rheological binder rutting indicators, such as G*/sinδ at different frequencies, high PG grade, ZSV, *etc*. In the study, paving grade binders as well as PMB and wax modified binders were evaluated. The MSCR test also demonstrates that highly modified binders, and especially binders modified with synthetic wax, are more stress sensitive compared to unmodified and moderately modified binders. A study on the creep-recovery data revealed that the modification of bitumen significantly changes the way the material response develops under repeated creep-recovery loading. These kinds of changes in material response are not captured by the standard MSCR test parameters**, but do so with the creep-recovery data. These can provide a deeper understanding of the influence of different modifiers and their microstructural characteristics on the binder rutting performance**.

In Paper 562 (Tabatabaee & Tabatabaee, 2010), MSCR test was done at different temperatures, but only values measured at 64 °C were compared to G*/sinδ at 64°C and to a mix permanent deformation test (unconfined dynamic creep test) run at 40 °C. The paper deals with crumb rubber modified bituminous binders. The MSCR test showed that rubber caused a significant increase in binder elastic recovery, reducing permanent deformation and thus improving rut resistance. A comparison of the two stress levels showed that **CRM binders were stress sensitive**, showing less recovery at 3,200 Pa for each binder but more improvement as rubber content increased. **J_{nr} from the MSCR correlated well with the compliance from the mixture test results**.

2.4.2 Elastic Recovery Test

No relevant papers were found on correlations with asphalt tests.

2.4.3 Papers analysis sum up

The MSCR test is mostly compared to wheel tracking tests: either the French wheel tracking device (large size device), or Hamburg wheel tracking device (small size device). The temperature is either 45 °C, 50 °C or 60 °C, depending on the country/region.

Table 2-4 summarizes the correlations found between MSCR test results (J_{nr} or % recovery) and permanent deformation behaviour of bituminous mixtures.

Table 2-4: Correlations found between MSCR test results (Jnr or % recovery) and permanent deformation behaviour of bituminous mixtures

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	*R^2*	*Comment*
Paper 023 (Dueñas *et al.*,2012)	WTT, rut depth *vs.* J_{nr} (T=60 ºC; τ=3,2 kPa)	Linear (y= a + bx)	4	N/A	N/A	0,87	U, PmB and Crumb Rubber Modified
	Compliance in CCT *vs.* J_{nr} (T=60 ºC; τ=3,2 kPa)	Linear (y= a + bx)	4	N/A	N/A	0,69	U, PmB and Crumb Rubber Modified
	% recovery in CCT *vs.* % recovery MSCR (T=60 ºC; τ=3,2 kPa)	Linear (y= a + bx)	4	N/A	N/A	0,96	U, PmB and Crumb Rubber Modified
Paper 035 (Dreessen & Gallet, 2012), paper 425 (Dreessen& Pascal, 2009) and paper 501 (Dreessen *et al.*, 2009)	WTT large size device, rut depth *vs.* J_{nr} (T=60 ºC; τ=3,2 kPa)	Linear (y= a + bx)	15	N/A	N/A	0,44	7U, 6 PmB and 2 special All RTFOT
	WTT large size device, rut depth *vs.* J_{nr} (T=60 ºC; τ=25,6 kPa)		15	N/A	N/A	0,77	7U, 6 PmB and 2 special All RTFOT
Paper 042 (Robertus *et al.*, 2012)	WTT small size, rut rate *vs.* J_{nr} (T=45 and 60 ºC; τ=1 kPa)	logy=a*log x	20	N/A	N/A	0,79 UA 0,90 RTFOT	5U, 11 PmB,2 wax modified, 2 special
Paper 185 (D'Angelo *et al.*, 2007)	ALF of FHWA *vs.* J_{nr} (T=64 °C; τ=25,6 kPa)	Linear (y= a + bx)	6	-0,112	0,493	0,81	U and PmB
	Field rutting (after 6 yrs) *vs.* J_{nr} (T=64 °C; τ=0,8 kPa)	Linear (y= a + bx)	7	0	0.0116	0,77	U and PmB

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	R^2	*Comment*
Paper 516 (Laukkanen *et al.*, 2014)	WTT large size device *vs.* J_{nr} (τ= 3200 Pa)	Linear (ax+b rut rate	9	N/A	N/A	0,98	U&PMB/UA
		Parameter b from the power law: linear	9	5,94	0,84	0,98	U&PMB/UA
Paper 562 (Tabatabaee& Tabatabaee, 2010)	unconf. cyclic creep test *vs.* J_{nr} (τ= 3200 Pa)	not clear ?	6	N/A	N/A	0,83	U&CMB / A
		Linear ?					U.D.C. at 40°C

LEGEND: U - Unmodified bitumen; PMB - Polymer Modified bitumen;
A - Aged bitumen; UA – Unaged bitumen;
CCT – Cyclic Compression Test; WTT – Wheel tracking Test;
T – test temperature; τ – stress level.

The main conclusions that can be drawn from the paper review considering relationship between the results of the MSCR test and the asphalt resistance to permanent deformation are the following:

- All papers that studied correlations between MSCR test results and asphalt permanent deformation report very good to quite good correlations.
- The MSCR test result which is directly related to permanent deformation is J_{nr}. The other parameter retrieved from the MSCR test, % recovery, is correlated in only one study and this to the % recovery in the cyclic creep test on asphalt (paper 023, Dueñas et al.). This correlation was also fairly good, although the number of binders considered was small (only 4).
- The most promising finding about the MSCR test is that all authors claim good correlations – often at higher stress levels though – for all types of binders. In most papers, paving grade binders as well as polymer modified binders are evaluated (papers 23, 185, 314, 425, 516). Specific papers deal about ‘special’ binders such as wax modified binders (paper 516); crumb rubber modified binders (papers 23, 314, 562) and binders modified with PPA (paper 456), or deal with a special technique: warm mix versus hot mix asphalt (paper 330).
- From many of the papers reviewed, it seems that for good correlations with the permanent deformation tests on the asphalt mix, higher stress levels are better. Multiple papers mention that from stress levels above 6400 Pa, better correlations are found (e.g., the papers 035, 425 and 501 by Dreessen *et al.*). In paper 516 however, an excellent correlation was obtained with results from the large size WTT even when using a stress level of only 3200 Pa.
- One study tested the binders in both the unaged and the short term (RTFOT) aged state (paper 042 by Robertus *et al.*, 2012) and obtained a better correlation in case of the short term aged binders.

2.5 *Relationship found between bitumen complex modulus and phase angle and asphalt resistance to permanent deformation*

2.5.1 Dynamic Shear Rheometer (DSR) Test

Regarding the rheological analysis of bitumen in sinusoidal oscillatory shear mode, several functions and relations can be taken into account for the viscoelastic characterization.

However, when considering relationship between the resistance to permanent deformation of asphalt and the rheological properties of bitumen, only few parameters / relations have been considered in a more general use. Procedures have been developed, using a dynamic shear rheometer (DSR), as in EN 14770, for the analysis of bitumen, grounded in the determination of complex shear modulus (G*) and phase angle.

In the literature review, only six papers (Papers 042, 047, 061, 067, 308 and 425) presented contributions to the relationship between bitumen rheological data and asphalt resistance to permanent deformation. They take into account the following parameters / relations from the rheological analysis of bitumen:

- Complex shear modulus (G*)
- G*/sin δ, developed in the Strategic Highway Research program (SHRP) as the high temperature specification parameter for evaluation of rutting resistance of asphalt pavements
- Unified evaluation index, R_J, that is inversely proportional to compliance (J), $R_J = \frac{1}{J} = \frac{G^*}{\sin\delta(1-\cos\delta)}$

In paper 042 (Robertus *et al*., 2012), G* and G*/sin δ of a total of twenty bituminous binders (five paving grade, eleven polymer modified and two “low viscosity” binders and also two special bitumens) were evaluated at 45 °C and 60 °C and at a frequency of 1,59 Hz (AASHTO T315), before and after RTFOT ageing. There is a **good correlation (power function,** with **R^2 = 0,94) between the wheel tracking (small size device) rut rate, at 45 °C and 60 °C,** of continuous graded bituminous mixtures **and G* for original (before RTFOT) unmodified binders** - see Figure 2-21. It was concluded that this trend is independent of the state of ageing or test temperature of the binders used.

However, **for most polymer modified binders** there is clearly **no correlation (R^2 < 0,70) of G* and G*/sin δ with rut rate**, independently of the state of binder ageing. The contribution of these binders to rutting resistance is generally largely underestimated in terms of G*.

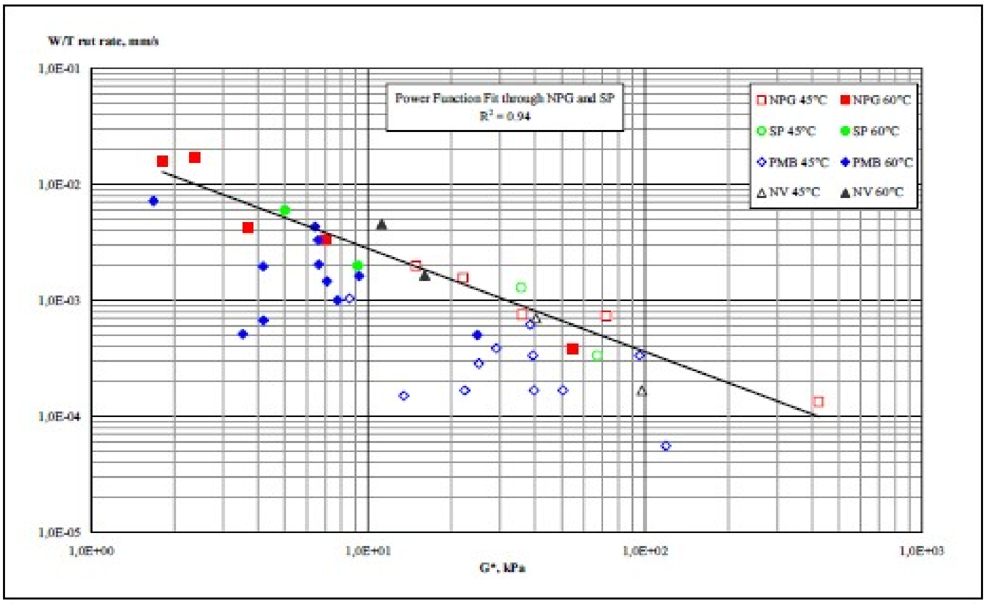


Figure 2-21: Wheel tracking rut rate *vs.* stiffness modulus (DSR @ 1,59 Hz) of unaged binders at 45 °C and 60 °C [Paper 042: Robertus *et al.*, 2012]

Paper 047 (Gungor & Sağlik, 2012) considered G*/sin δ (at 1,6 Hz; 40 °C and 50 °C) of twelve bituminous binders (four paving grade, four polymer modified with 5 % SBS and four modified with 2% of Elvaloy) after RTFOT ageing. The relationship between **G*/sin δ and** permanent deformation of asphalt concrete by **triaxial cyclic compression tests showed week power correlations: R^2 = 0,37 at 40 °C, and R^2 = 0,40 at 50 °C** (see Figure 2-22).

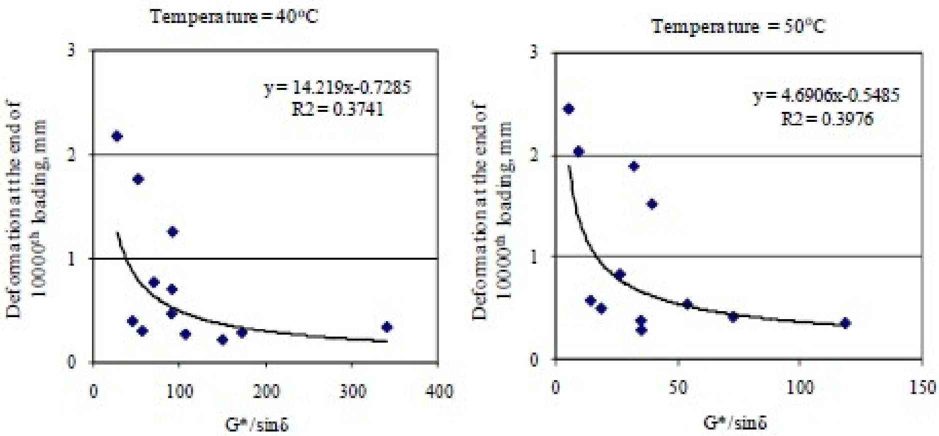


Figure 2-22: G*/sin δ *vs.* permanent deformation at 40 °C and 50 °C [Paper 047: Gungor & Sağlik, 2012]

Paper 061 (Beckedahl *et al.*, 2008) comprises only three bituminous binders: a conventional 50/70 grade, a polymer modified (PmB 45A) bitumen and a high polymer modified (PmB 25H) bitumen with higher levels of G*/sin δ. Correlations were made between **G*/sin δ** (at 1,59 Hz and 60 °C - EN14770) of these binders and the rut depth of Stone Mastic Asphalt (SMA) and Asphalt Binder mixture (ABM) tested **with wheel tracking at 60 °C** (EN 12697-22). The regression coefficients determined for each kind of mixture revealed **good correlations** (see Figure 2-23, left). Correlations are dependent on the composition of the bituminous mixture. As concluded by the authors, to make an authentic correlation, the comparison should be carried out with more than three test results.

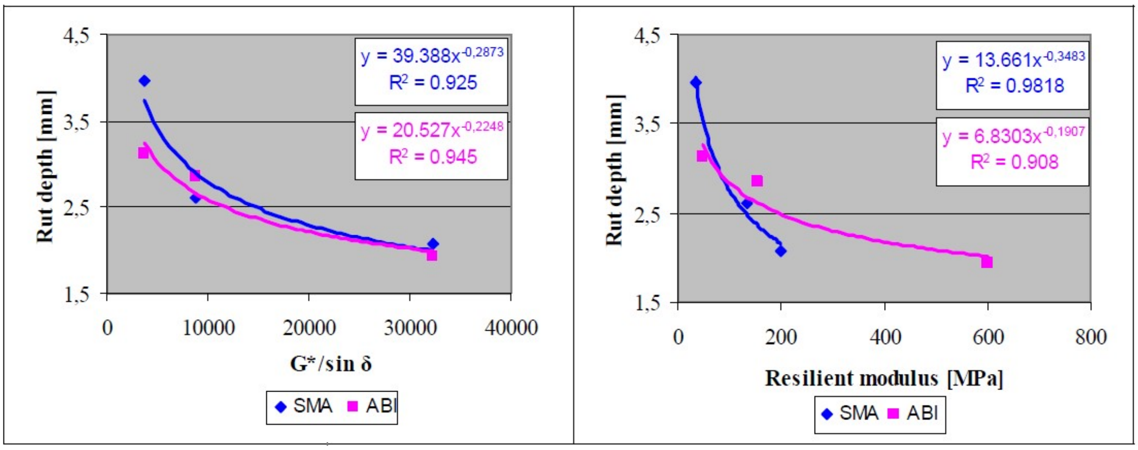


Figure 2-23: Correlation of rut depth and G*/sin φ [60 °C] (left) and correlation of rut depth and resilient modulus [50 °C] (right) [Paper 061: Beckedahl *et al.*, 2008]

Paper 067 (Guericke & Schlame, 2008) presents an approach based on the PG-binder grading system, considering the values of the temperature for which G*/sin δ of short-term aged bituminous binders (after RFT – Rotating Flask Test) equals 2,2 kPa: $T_{(G*/\sin δ=2,2kPa)}$. This study addresses to the relationship between the temperature $T_{(G*/\sin δ=2,2kPa)}$ of eleven bituminous binders, including unmodified and polymer modified bitumen, and the resistance to permanent deformation of Stone Mastic Asphalt (SMA) accessed by the Hamburg wheel tracking at 60 ºC. **The correlation between rut depth of SMA and T $_{(G^*/\sin\delta=2,2kPa)}$ showed a weak R-square value: R^2 = 0,77** (see Figure 2-24).

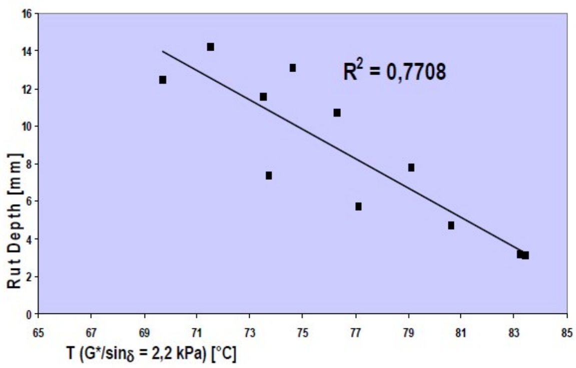


Figure 2-24: Rut depth (Hamburg Wheel tracking Test) of SMA at 60 °C *vs.* T $_{(G^*/\sin\delta=2,2\ kPa)}$ after short-term ageing (RFT) [Paper 067: Guericke & Schlame, 2008]

Paper 308 (Tan *et al.*, 2014) used the unified evaluation index (R_J) to study the high-temperature performance of seven bituminous binders (five unmodified and two modified bitumen). The R_J, obtained from rheological data at a frequency of 10 rad/s and at a temperature of 60 °C, was correlated with the dynamic stability of bituminous mixtures tested with the wheel tracking at 60 °C. The **R-square value for fitting the relationship between dynamic stability and unified R_J index is 0,99** (see Figure 2-25). It was considered by the authors that the unified R_J index could be used to evaluate the high-temperature performance of bituminous binders. With the data presented in the paper it is also possible to **correlate G*/sin δ with the dynamic stability**, as shown in Figure 2-26, **obtaining R^2 = 0,99**.

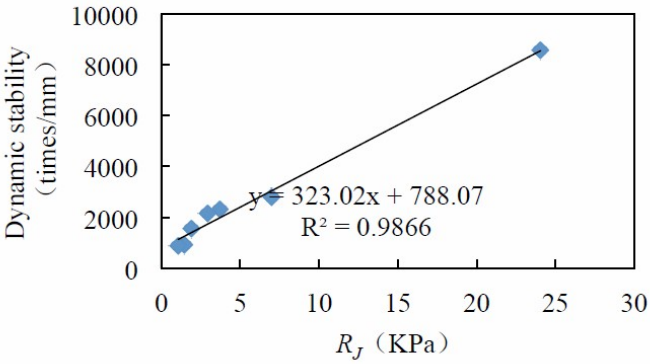


Figure 2-25: Correlation between R_J and dynamic stability (60 °C) [Paper 308: Tan *et al.*, 2014]

In the same paper a comparisons between R_J, *G**/sin *δ* and other parameters obtained from repeated creep and recovery tests (MSCRT) were done as well, i.e., Gv (non-recoverable stiffness) and accumulated strain. The rankings of the studied binders evaluated by R_J, G_V and accumulated strain are the same. This ranking is also the same as for the high-temperature performance ranking of the studied bituminous mixtures evaluated by dynamic stability. For *G**/sin *δ*, the high temperature performance ranking of the neat binders is the same as the ones for the neat mixtures, but for the modified bituminous binder, the rankings are not the same. This finding indicates that ***G*/sin δ* is not suitable for modified bituminous binders**.

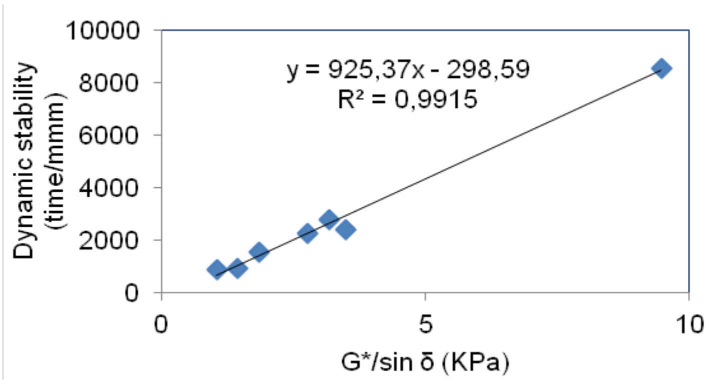


Figure 2-26: Correlation between G*/sin δ and dynamic stability (60 ºC) [Paper 308: Tan *et al.*, 2014]

Paper 308 (Tan *et al.*, 2014) presents a further analysis in order to determine which index is the best among all the indices. The Grey relational analysis (see Table 2-5) was used for the correlation of R_J, G*/sin δ, Gv and accumulated strain with dynamic stability. In this analysis, the unmodified and modified bitumen were considered separately. Looking at unmodified bitumen data, the coefficients (a measure of the strength of the relationship between variables) related to G*/sin δ and to R_J, r_1 and r_4, respectively, are of the same order of magnitude and are just below the coefficient of Gv. For modified bitumen, the correlation between R_J and dynamic stability is the highest, although the coefficient is quite similar to the one from Gv. It is noted the failure of the correlation of G*/sin δ with dynamic stability for modified bitumen.

Table 2-5: Grey relational analysis of bitumen high-temperature evaluation indices and dynamic stability of asphalt mixtures

Item	X_1	X_2	X_3	X_4
Indices	*G*/sinδ* (60 °C)	*GV* (60 °C)	Accumulated strain (60 °C)	R_J (60 °C)
Coefficient	r_1	r_2	r_3	r_4
Neat bitumen	0,8925	0,9016	0,6839	0,8935
Modified bitumen	0,5936	0,8449	0,7395	0,8990

Paper 425 (Dreessen & Pascal, 2009) presents the relationship between results from the French wheel tracking test (EN12697-22) and G*/sin δ at 60 °C (EN 14770) of several RTFOT aged bitumen (seven unmodified, six polymer modified and two special binders). Other properties of the aged bitumen were also analysed, such as R&B softening point and non-recoverable compliance (J_{nr}) coming from multiple stress creep and recovery test (MSCRT) at 60 °C. Correlations between bitumen properties and asphalt rutting are presented in Figure 2-27. The results show **no correlation between G*/sin δ and rutting as well as for the rest of assessed properties**.

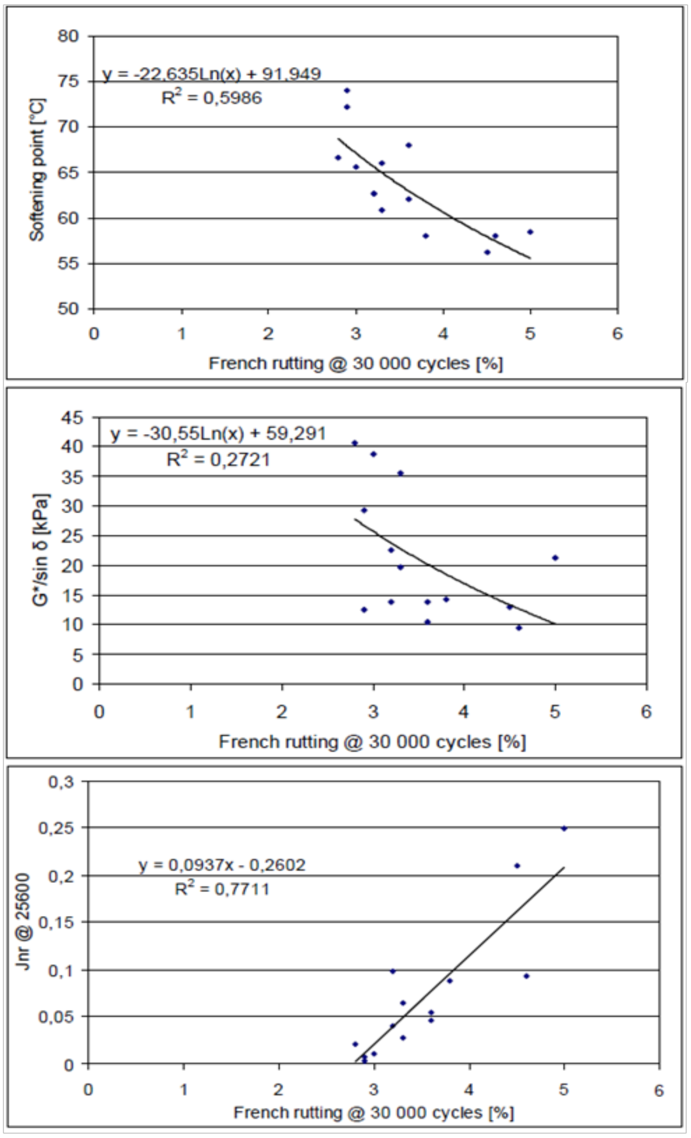


Figure 2-27: Correlation of softening point, G*/sinδ (60 °C) and J_{nr} at 25600 Pa (60 °C) with rutting [Paper 425: Dreessen & Pascal, 2009]

2.5.2 Paper analysis sum up

Table 2-6 summarizes the correlations found between binder complex modulus and phase angle and permanent deformation behaviour of bituminous mixtures.

The main conclusions that can be drawn from the paper review considering relationship between the data of rheological analysis of bitumen based on complex modulus and phase angle and the asphalt resistance to permanent deformation are the following:

Complex modulus (G*):

- Only one study (paper 042) considered G*. A good correlation was found between G* and the wheel tracking rut rate in the analysis of seven unmodified bitumen, independently of the state of ageing and test temperature. Conversely, very weak correlations were detected for most polymer modified bitumen; G* generally underestimates the contribution to rutting resistance.

- The use of G* can be questionable, not only for polymer modified bitumen, but also for unmodified binders, as it doesn't provide the individual contribution from each material function: G', the real part of complex modulus (associated with the elastic part of material behaviour), and G", the imaginary part of complex modulus (associated with the viscous part of material behaviour).

G*/sin δ characteristic:

- Most of the papers found that G*/sin δ is not suitable to evaluate the asphalt resistance to permanent deformation, whether studying aged (paper 042) or unaged (papers 042 and 308) polymer modified bituminous binders or when analyzing an ensemble of unmodified and polymer modified aged bituminous binders (papers 047, 067 and 425).
- Only two papers detected high levels of correlation between G*/sin δ and asphalt resistance to permanent deformation, i.e. wheel tracking rut depth (paper 061) and dynamic stability (paper 308). One of them (paper 61) analyzed only three unaged binders (1 unmodified and 2 polymer modified bitumen). In the other one (paper 308), it was considered an ensemble of unmodified and polymer modified bitumen and a group of unmodified binders (in this last case it was applied the grey relational analysis considering a package with only two binders).

Unified evaluation index (R_J)

- According to paper 308, R_J is considered suitable for the evaluation of the high-temperature performance of asphalt. This conclusion is based on the analysis of a set of unmodified and PMB binders and also based on Grey relational analysis considering separately the group of neat bituminous binders and the group of modified binders. The coefficients of correlation were of the same order of magnitude as the ones obtained from creep stiffness (Gv).

Table 2-6: Correlations found between binder complex modulus and phase angle and permanent deformation behavior of bituminous mixtures

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	*R^2*	*Comment*
Paper 042 (Robertus *et al.*, 2012)	WT Rut Rate *vs.* G* (kPa) @ 45ºC and 60ºC	Power (y= a.x^b)	14	N/A	N/A	0,94	U / UA
			30	N/A	N/A	<0,70 (1)	U & PMB / UA
Paper 047 (Gungor & Sağlik, 2012)	TCCT Deformation (mm) *vs.* G*/sinδ (kPa) @40ºC and 50ºC	Power (y= a.x^b)	12	14,22	-0,73	0,37	U & PMB / A (TCCT@40ºC)
			12	4,69	-0,55	0,40	U & PMB / A (TCCT@50ºC)
Paper 061. (Beckedahl *et al.*, 2008)	WT Rut Depth (mm) *vs.* G*/sinδ (kPa) @ 60ºC (2) (3)	Power (y=a.x^b)	3 (2)	39,39	-0,29	0,93	U & PMB / UA
			3 (3)	20,53	-0,22	0,95	U & PMB / UA
Paper 067 (Guericke & Schlame, 2008)	HWT Rut Depth (mm) *vs.* $T_{(G*/\sin\delta=2.2kPa)}$ (ºC) @ 60ºC	Linear	11	N/A	N/A	0,77	U & PMB / A
Paper 308. (Tan *et al.*, 2014)	WT dynamic stability (time/mm) *vs.* R_J (4) @ 60ºC	Linear (y= a + bx)	7	788,07	323,02	0,99	U & PMB / UA
		Grey relational analysis	2	N/A	N/A	0,89 (5)	U / UA
			5	N/A	N/A	0,90 (5))	PMB / UA
	WT dynamic stability (time/mm) *vs.* G*/sinδ (KPa) @ 60ºC	Linear (y= a + bx)	7	-298,59	925,37	0,99	U & PMB / UA
		Grey relational analysis	2	N/A	N/A	0,89 (5)	U / UA
			5	N/A	N/A	0,59 (5)	PMB / UA
Paper 425 (Dreessen & Pascal, 2009)	FWT rutting (%) *vs.* G*/sinδ (KPa) @ 60ºC	Logarithmic (y= a lnx + b)	15	-30,55	59,29	0,27	U & PMB / A

LEGEND: U - Unmodified bitumen; PMB - Polymer Modified bitumen;
A - Aged bitumen; UA – Unaged bitumen;
FWT – French Wheel Tracking Test; HWT - Hamburg Wheel tracking Test; TCCT – Triaxial Cyclic Compression Test; WT – Wheel tracking Test.

NOTES:

(1) Paper 042 refers $R^2 < 0.7$ for the correlation of G* and G*/sinδ with WT Rut Rate for both unaged and aged polymer modified bitumen, but the type of correlation is not clearly identified. However, the paper refers that for rheological complex binders (i.e. most PMBs) there is clearly no correlation between rut rate and G*.

(2) Rut depth of Stone Mastic Asphalt (SMA).

(3) Ruth depth of Asphalt Binder mixture (ABM).

(4) $R_J = \frac{1}{J} = \frac{G^*}{\sin\delta(1-\cos\delta)}$

(5) Coefficient from the Grey relational analysis.

2.6 Relationship found between bitumen Performance Grading and asphalt resistance to permanent deformation

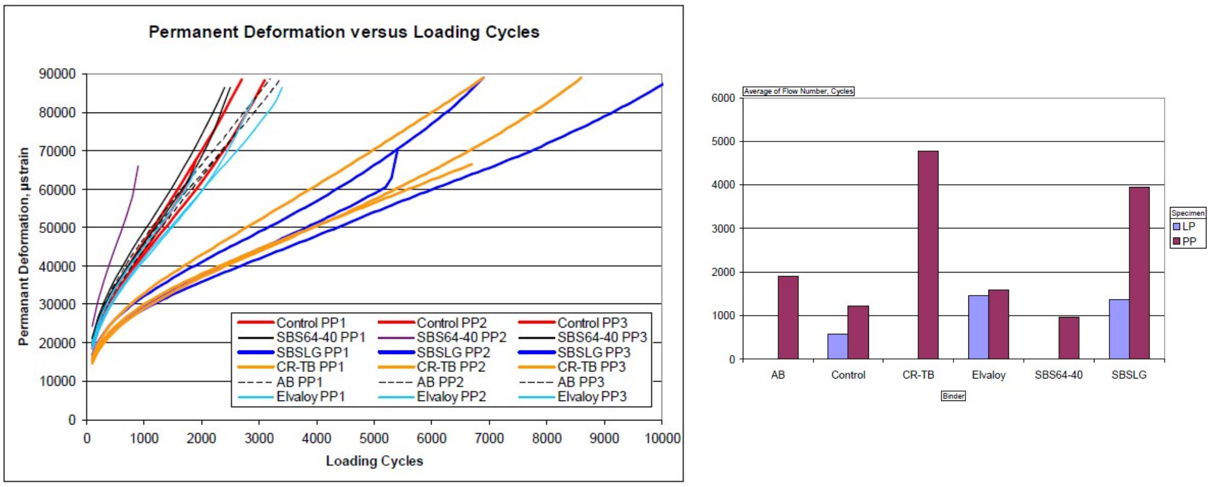
2.6.1 Performance Grade (PG)

No papers were found addressing correlations between performance grade of the bitumen and the correspondent bituminous mixture resistance to permanent deformation.

However, some studies have data on the permanent deformation performance of mixtures produced with the same or different bitumen performance grading classification, as it is described in following paragraphs.

Paper 153 (Willis *et al.*, 2012) states that the current test method using Dynamic Shear Rheometer (DSR) specified in AASHTO M320 **may not be suitable for determining the high temperature performance characteristics of highly polymer-modified**. While the highly polymer-modified (7,5 % of SBS) binder had a high temperature performance grade of 88 ºC and rotational viscosity of 3.6 Pa.s, its workability and compactability were similar to those of a PG 76-22 binder both in the laboratory and in the field.

Paper 235 (Azari *et al.*, 2008) addresses the rutting of HMA produced with six different bituminous binder types (one PG 70-22 unmodified bitumen; four PG 70-xx modified bitumens; one PG 76-28 bitumen-rubber), both in the laboratory and in plant. Flow number tests were performed on three Plant-Produced & Lab-compacted (PP) replicate samples for each one of the six binder type considered and on three Lab-Produced & Compacted (LP) replicate samples for three binders. Figure 2-28 (a) shows permanent deformation versus loading cycles for PP HMA specimens. The results clearly show that SBSLG samples, produced with a PG 70-28 binder (and CR-TB samples, produced with a PG 76-28 binder), performed better than other mixtures also produced with PG 70-xx binders (Control, AB, SBS64 and Elvaloy). Thus, it may be concluded that **bituminous mixtures with the same high temperature performance grade showed different permanent deformation behaviours.**



(a) (b)

Figure 2-28: Flow Number test results: (a) Permanent deformation versus loading cycles for plant-produced HMA using six different binders; (b) Average FN [Paper 235: Azari *et al.*, 2008]

Paper 314 (Willis *et al.*, 2014) presents a research project which designs and compares the performance of seven open-graded friction course (OGFC) mixtures which contained six different ground tire rubber (GTR) modified binders and a styrene-butadiene-styrene (SBS) modified binder. These mixtures were compared namely for rutting susceptibility. The six rubber products modified a standard PG 67-22 binder, achieving the performance grades shown in Table 2-7. OGFC specimens were subjected to Asphalt Pavement Analyzer testing (GDT115; testing @ 64 °C for 4 h) and to Hamburg testing (AASHTO T324; testing @ 50 °C for 20 000 passes), whose results are presented in Figure 2-29. **The results obtained for bituminous mixes** produced with different modified binders but **presenting similar high temperature performance grade showed different permanent deformation behaviours**.

Table 2-7: Modified binders properties

OGFC mix ID	Modified binder ID	% modified binder on the mix	m-Value (-12 ºC)	PG	True Grade	Softening Point % Diff	Jnr % Diff
Control	SBS with fibers(1)	5,75	-	-	-	-	-
20 Mesh	-20 Ambient	6,33 (10% of rubber by weight of binder)	0,315	82-22	83,1-24,6	16,4	85,8%
Crackermill	-30 Crackermill		0,306	82-22	82,8-23,1	12,4	50,9%
Cryohammer	-30 Cryohammer		0,307	82-22	82,2-23,2	15,9	34,2%
MD-105-TR	MD-105-TR		0,317	76-22	77,9-25,6	0,8	26,1%
MD-400-TR	MD-400-TR		0,316	76-22	80,4-24,2	17,2	19,2
MD-400-AM	MD-400-AM		0,294	82-16	82,1-20,8	13,8	30,5%

(1) Cellulose fibers necessary for the control design were added at a rate of 0,3 %by weight of the mix.

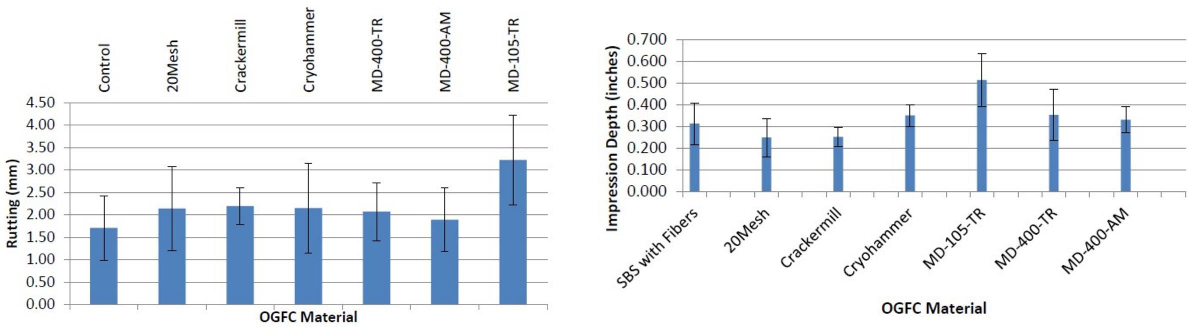


Figure 2-29: (a) Average Rut Depth from APA Testing; (b) Average Hamburg Impression Depths [Paper 314: Willis *et al.*, 2014]

2.6.2 Papers analysis sum up

There are no relevant papers presenting a clear relationship between the performance grade of the used/recovered binder and the permanent deformation behaviour of the bituminous mixture. Nevertheless, it is of common understanding that the high temperature of PG is not suitable for ranking the bituminous mixture behaviour to permanent deformation, mainly when modified bitumens are used.

2.7 Binder ageing effect on permanent deformation

As referred in 2.1, asphalt mixtures permanent deformation develops in three stages: the primary stage, that occurs after construction of the asphalt layers, thus corresponding to a short-term ageing of the bituminous material; the secondary stage, that develops through most of the pavement life, thus corresponding from a short-term to long-term ageing of asphalt layers; and finally the tertiary stage, which is expected not be observed in the asphalt pavement life.

It is well known that the resistance to permanent deformation of asphalt layers increases with time, due to the hardening of the bitumen with ageing.

Therefore, when evaluating this performance requirement of asphalt mixtures, there is a major concern in assessing the properties of bitumen binders in their fresh unaged stage. The most appropriate choice is to test the binders after short-term ageing (for example, after RTFOT), because this binder state corresponds more closely to the state of the binder just after construction and before the start of the long term ageing. Besides, the study presented in paper 042 (Robertus *et al*., 2012) concluded that a better correlation between the asphalt wheel tracking rut rate and the bitumen non-recoverable creep compliance (J_{nr}) from the MSCR test was obtained for short-term aged binders rather than for unaged binders.

Taking into account the above, it is recommended that in the future, the bituminous binder be tested after short-term ageing, i.e. after RTFOT.

2.8 Conclusions on relationships between bitumen properties and the resistance to permanent deformation of bituminous mixtures

The analysis of the possible relationships between bitumen properties and the mixture permanent deformation behaviour, showed the following potential relations between further summarized bitumen properties and asphalt mix behaviour in terms of rutting resistance:

Viscosity properties

- Although ZSV shows good potential to link binder to mix properties, more studies are needed to be able to draw stronger conclusions.
- Test conditions for ZSV vary strongly from one paper to the next. A more detailed standardization of the test conditions would be beneficial for the next series of European standards.
- ZSV measurements in creep mode on polymer-modified binders take a long time (up to 10 hours) to reach a steady state. Therefore, it seems that oscillation ZSV can be run more efficiently than creep ZSV.
- A major concern with ZSV measurements is that they are performed at very low shear stress and therefore, the behaviour of the binder at high shear stress is not captured. This is problematic in case of stress sensitive binders.

Softening point by R&B test method

The R&B test is a method with long tradition and large data background. However, it does not give good correlation between bitumen and asphalt mix level when polymer-modified binders are used.

Elastic and recovery properties by MSCR test

- Although MSCR test is a relatively new method, existing data shows that fairly good correlations can be obtained between the “non-recoverable compliance” (J_{nr}) of the bituminous binder and the permanent deformation on the bituminous mixtures.
- Among the range of stress levels that can be/are applied on the binder during MSCR tests (e.g. from 100 Pa up to 25 600 Pa), it seems that generally better correlations are achieved when higher stresses (above 6400 Pa) are applied.

Complex modulus and phase angle by tests on DSR

- It is confirmed by several studies that there is a poor correlation between $G^*/\sin\delta$ and asphalt resistance to permanent deformation, particularly in the case of polymer modified bitumens.

- The unified evaluation index, Rj (inversely proportional to compliance), was considered in one study as a possible alternative of correlation between binder and mix properties.

Bitumen Performance Grading is not suitable for assessing rutting resistance.

Among the addressed bitumen properties and its relation with the permanent deformation of bituminous mixtures, the most promising tests are the Zero/Low Shear Viscosity (ZSV/LSV) by creep or oscillation test method and the non-recoverable compliance (J_{nr}) from the MSCR test method.

Comparing both type of tests (Creep or oscillation Zero/Low Shear Viscosity and MSCR tests), it seems that the MSCR test method is more promising in a near future, given that, at the present, it seems to be an easier test method for the laboratories to implement, there is a European standard specifying the test and it is a method preferred in other countries as well, such as USA. From a technical point of view, it is believed that the MSCR test is better than the LSV/ZSV tests, because the MSCR test is also run at high stress levels which are more representative for the stresses induced by rutting.

Table 2-8 shows synthesis of an overall evaluation of applicable tests for bitumen properties related with permanent deformation behaviour of bituminous mixtures.

Table 2-8: Overall evaluation of applicable tests for bitumen properties related with permanent deformation behaviour of bituminous mixtures

Bitumen test	Pros	Cons	Availability in Europe(1)	Standardized in Europe	Limitations
Capillary Viscometer Test (kinematic and dynamic viscosity)	Usually used to determine the viscosity of unmodified bitumen at 135 °C. Results can be used to calculate dynamic viscosity when the density of the test material is known or can be determined.		Usually	EN 12595 (kinematic viscosity)	These test methods are not suitable for testing PMB
	Usually used to determine viscosity of unmodified bitumen at 60 °C	Preparation of samples and cleaning the tubes takes a lot of effort	Often	EN 12596 (dynamic viscosity)	
Coaxial Cylinder Viscosity Test	Developed for modified binders, but it is suitable for all types of bituminous binders		Occasionally	EN 13702-2	Specific test methods, which are often not available in laboratories.
Cone and Plate Viscosity Test	Developed for modified binders, but it is suitable for all types of bituminous binders		Rarely	EN 13702-1	
Creep Zero/Low Shear Viscosity (ZSV/LSV) Test	Some studies show a good correlations between ZSV/LSV and tests on asphalt mixture level (WTT, TCCT)	Measurements on PMB take a long time (up to 10h) to reach a steady state	Occasionally	CEN/TS 15324 (LSV) prEN 15325 (ZSV)	
Oscillation Zero/Low Shear Viscosity (ZSV/LSV) Test	Some studies show a good correlations between ZSV/LSV and tests on asphalt mixture level (WTT, TCCT)		Occasionally	CEN/TS 15324	
Ring and Ball (R&B) Test	Test method available in most of the labs. Large data background. Easy to use.	No correlation between R&B and modified bitumens	Usually	EN 1427	Only suitable for non-modified bitumen
Multiple Stress Creep and Recovery (MSCR) Test	Suitable for both unmodified and modified bituminous binders.		Occasionally	EN 16659	
Elastic Recovery Test			Usually	EN 13398	There were not found relevant studies correlating the Elastic Recovery Test with asphalt mixes' permanent deformation.
Dynamic Shear Rheometer (DSR) Test (Complex shear modulus and phase angle)	From the test, not only the norm of the complex shear modulus, IG*I, and its phase angle, δ, at a given temperature and frequency can be calculated, as well as the components G', G'', J' and J'' of the complex shear modulus and of the complex compliance	The precision of the test method has not yet been established	Often	EN 14770	

(1) Considered ranking scale: Usually - often - occasionally - rarely

2.9 References for permanent deformation

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