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To cite this article: Fátima A Batista *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **236** 012001

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Towards improved correlations between bitumen properties and rutting resistance of bituminous mixtures – FunDBitS literature review

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Abstract. Bitumen is the most common binder used in the production of bituminous mixtures for road paving, having a fundamental influence on the performance of the pavement. However, it is not yet fully understood which bitumen properties have a significant influence on the behaviour of bituminous mixtures. In this context, the FunDBitS project was developed. Its main objective was to prepare recommendations on the properties of the bitumen to be specified in order to obtain suitable bituminous mixtures, namely in what concerns to its resistance to permanent deformation (rutting), stiffness, low temperature cracking, fatigue cracking and binder / aggregate interaction. In this framework, the research studies that have become internationally available since the BiTVal project were reviewed in order to assess performance-based bitumen characteristics, which may be introduced into bitumen specification standards. This paper specifically presents the main conclusions regarding the properties of bitumen related to the behaviour to permanent deformation of bituminous mixtures. It was concluded that the most promising test is the "non-recoverable creep compliance" (J_{nr}) from the Multiple Stress Creep and Recovery (MSCR) test method, although Zero/Low Shear Viscosity (ZSV/LSV) by creep or oscillation test method can also give good correlations with permanent deformation of bituminous mixtures.

1. Introduction

Bitumen is the most common binder used in the production of bituminous mixtures for road paving, having a fundamental influence on the performance of the pavement. However, it is not yet fully understood which bitumen properties have a significant influence on the behaviour of bituminous mixtures. In order to improve this understanding, it was recently developed the FunDBitS – "Functional Durability Related Bitumen Specification" project (funded by CEDR), that intended to forward the BiTVal – "Bitumen Test Validation" project (set up by FEHRL) carried out in the first decade of 2000 [1].

Within the scope of FunDBitS project, the data that has become internationally available since the BiTVal project was reviewed in order to assess performance-based bitumen characteristics which may be introduced into bitumen European specifications EN 12591 (paving grade bitumens), EN 14023 (polymer modified bitumens) and EN 13924 (hard paving grade bitumens). Through the literature review, possible correlations between the bitumen and asphalt properties were identified [2]. For this, the following five main asphalt properties were considered: permanent deformation (rutting); stiffness; low temperature cracking; fatigue cracking and binder/aggregate interaction.

This paper deals specifically with the properties of bitumen related to the behaviour to permanent deformation of bituminous mixtures. Therefore, it will address the main conclusions and recommendations related with that asphalt performance characteristics, resulting from FunDBitS project [3, 4].

2. Test methods to address bitumen properties and asphalt behaviour in terms of permanent deformation (rutting)

Permanent deformation or rutting is the result of visco-plastic deformations in the asphalt layer caused by the repeated passage of heavy vehicles, particularly under low speed traffic and high temperature conditions.

Due to the viscoelastic nature of bituminous bound materials, the permanent deformation mode of deterioration strongly depends on the temperature. For this reason, most test methods to assess both bitumen properties and asphalt behaviour in terms of permanent deformation are performed at elevated temperatures. At an early stage of FunDBitS project [2], the following relevant bitumen properties for elevated service temperatures were identified: viscosity; softening point; elastic and recovery properties; complex modulus and phase angle; performance grading. Furthermore, a review on the available test methods to measure the referred bitumen properties was carried out, as follows:

- Viscosity: Capillary Viscometer Test; Coaxial Cylinder Viscosity (CCV) Test; Cone and Plate Viscosity Test; Creep Zero/Low Shear Viscosity (ZSV/LSV) Test and Oscillation Zero/Low Shear Viscosity (ZSV/LSV) Test.
- Softening point: Ring and Ball (R&B) Test method
- 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 Grade (PG) classification: Superpave high temperature parameter

As regard the relevant asphalt tests on permanent deformation, they are as follows:

- in Europe: Wheel Tracking test, WTT (EN 12697-22); Cyclic compression test, CCT (EN 12697-25)
- other used tests: SUPERPAVE shear tester, SST; Simple Performance Tests, SPT (e.g. Dynamic modulus test; Flow Number; Flow Time)

In the following sections, an analysis of the possible relationship between bitumen relevant properties and the permanent behaviour of bituminous mixtures is presented.

3. Evaluation of the relationship between bitumen properties and behaviour of permanent deformation of bituminous mixtures

3.1. Bitumen viscosity

In respect to possible correlations between bitumen viscosity properties and bituminous mix permanent deformation only a limited number of relevant studies was found, particularly on Zero/Low Shear Viscosity (ZSV/LSV) either by creep and oscillation tests, according to what is synthesized in Table 1.

The data presented in Table 1. shows that in many cases the correlation between different test methods to address the resistance of mixtures to permanent deformation and viscosity tests on binder is above 0.8 and therefore good. However, in four out of 17 studied possible correlations, the coefficient of determination is below this value. These negative cases happened when the correlation analysis included samples with unmodified and polymer modified bitumen. Nevertheless, some good correlations are also obtained when testing both unmodified and modified bitumen binders.

Table 1. Correlations found between binder viscosity and bituminous mixes permanent deformation.

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	R^2	*Comment*
[8] (Robertus *et al.*, 2012)	WTT 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
[9] (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	
[10] (Gungor & Sağlik, 2012)	Axial deformation (mm) 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)
[12] (Guericke & Schlame, 2008)	HWT rut depth (mm) *vs.* ZSV (Pa*s)	Power (y= a.x^b)	25	N/A	N/A	081	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)
[16] (De Visscher & Vanelstraete, 2009)	PRD (%) *vs.* EVT1 (ºC)	Linear (y= a.x + b)	6	-0.61	42.69	0.86	U
			11	-0.60	42.12	0.83	U & PMB
	PRD (%) *vs.* EVT2 (ºC)	Linear (y= a.x + b)	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.x + b)	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.x + b)	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; UA – Unaged bitumen; A – Aged bitumen; PRD – Percentage of rut deformation in wheel tracking tests (WTT); ZSV – Zero shear viscosity; EVT1 – Equiviscous temperature 1; EVT2 – Equiviscous temperature 2; HWT –Hamburg wheel tracking test; TCCT – Triaxial cyclic compression test..

The following conclusions from the presented studies can be drawn:

- Studies on creep Zero/Low Shear Viscosity (ZSV/LSV) show that correlation between binder viscosity and wheel tracking parameter is good only when non modified binders are used. However, when the axial strain from Triaxial Cyclic Compression Tests (TCCT) is linked to ZSV/LSV, a good correlation can be achieved even when modified binders are taken into consideration:
- Studies on oscillation Low Shear Viscosity reveal that good correlations could be achieved when: the binder viscosity is linked with the rut depth (WT) and the equiviscous temperature 1 (EVT1, temperature at which the viscosity measured at very low shear rate is 2000 Pa.s) is linked to the proportional rut depth (WT) and the creep rate (TCCT).

3.2. Bitumen softening point

As regards the softening point, the Ring and Ball (R&B) test is considered as a traditional test method with a large background in data. However, it is of general understanding that this test is not suitable for modified bituminous binders. Correlation analysis between bitumen softening point and bituminous mix testing was found in seven of the reviewed papers (Table 2.), six of them correlating R&B results with wheel tracking test results and one with triaxial cyclic compression test results. It was concluded that some studies find a reasonable correlation between R&B and wheel tracking results, even when polymer modified binders are used for testing. However, these studies are generally limited to samples from the same binder source, i.e. one unique unmodified bitumen-base binder was used to produce the other polymer modified samples. In fact, poor correlations are found when a mix of unmodified and modified binders that are not from the same base bitumen is used.

Table 2. Correlations found between binder R&B and bituminous mixes permanent deformation.

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	R^2	Comment
[6] (Eckmann *et al.*, 2012)	RD (mm) *vs.* R&B (ºC)	Linear (y= a + b x)	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
[8] (Robertus *et al.*, 2012)	WTS (mm/s) *vs.* R&B (ºC)	Linear (y= a + b x)	19	N/A	N/A	0.68	U + PMB
			7	N/A	N/A	0.95	U
[12] (Guericke & Schlampe, 2008)	RD (mm) *vs.* R&B (ºC)	Linear (y= a + b x)	11	0.5893	46.523	0.84	U + PMB
[15] (Dreessen & Pascal, 2009)	R&B (ºC) *vs.* RD (mm)	Logarithmic (y= a ln x + b)	13	-22.635	91.949	0.60	U + PMB
[18] (Tusar *et al.*, 2009)	RD (mm) *vs.* R&B (ºC)	Logarithmic (y= a ln x + b)	7	-2.702	12.916	0.91	U + PMB
[20] (Renken, 2012)	RD (mm) *vs.* R&B (ºC)	No correlation found	N/A	N/A	N/A	N/A	N/A
[21] (Reyes-Lizcano *et al.*, 2009)	Accumulated axial strain (%) *vs.* R&B (ºC)	Linear (y= a + b x)	9	-0.0188	1.9494	0.54	PMB

LEGEND: U – Unmodified bitumen; PMB – Polymer modified bitumen; R&B – Ring and ball softening point; RD – Rut depth in wheel tracking tests (WTT); WTS – Wheel tracking slope in wheel tracking tests (WTT).

3.3. Bitumen elastic and recovery properties

With regard to the elastic and recovery properties, no relevant papers were found from the literature database on the Elastic Recovery test. On the other hand, a significant number of papers on Multiple Stress Creep and Recovery (MSCR) had been identified from the literature database [1], but only a limited number of them discuss correlations with asphalt permanent deformation (Table 3.). In general, these studies report quite good correlations (often at higher stress levels) for both paving grade and polymer modified binders. It is worth noticing that in the studies where negative cases occur ($R^2 < 0.7$), also quite good correlations where obtained using the same set of binders but varying the parameters that are correlated, the MSCR test conditions or the ageing of the tested binders. Most studies showed a very good correlation between non-recoverable creep compliance (J_{nr}) and bituminous mixture testing to address permanent deformation behaviour (especially for wheel tracking tests) and this for all types of binder. In fact, only one study (addressed in papers [7], [15] & [17]) obtained a lower correlation ($R^2 = 0.44$), but this was improved by using higher stress levels ($R^2 = 0.77$). The other studies found good correlations even at 'normal' stress levels (like $\tau = 3.2$ kPa, the stress level prescribed in the new EN 16659). It seems that better correlations are obtained when binders are tested after short-term ageing (e.g. after RTFOT) and for higher stress levels (≥ 3.2 MPa) used in the MSCR tests. This is thus recommended to be further investigated in the future.

Table 3. Correlations found between MSCR test results (J_{nr} or % recovery) and bituminous mixes permanent deformation.

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	R^2	*Comment*
[5] (Dueñas *et al.*,2012)	RT (WTT) *vs.* J_{nr} (T=60 ºC; τ=3,2 kPa)	Linear (y= a + b x)	4	N/A	N/A	0.87	U + PMB + Crumb Rubber Modified
	Compliance in CCT *vs.* J_{nr} (T=60 ºC; τ=3,2 kPa)	Linear (y= a + b x)	4	N/A	N/A	0.69	U + PMB + Crumb Rubber Modified
	% recovery (CCT) *vs.* %R MSCR (T=60 ºC; τ=3,2 kPa)	Linear (y= a + b x)	4	N/A	N/A	0.96	U + PMB + Crumb Rubber Modified
[7] (Dreessen & Gallet, 2012), [15] (Dreessen & Pascal, 2009) & [17] (Dreessen *et al.*, 2009)	RD (WTT – Large SD) *vs.* J_{nr} (T=60 ºC; τ=3,2 kPa)	Linear (y= a + b x)	15	N/A	N/A	0.44	7 U + 6 PMB + 2 special A (RTFOT)
	RD (WTT – Large SD) *vs.* J_{nr} (T=60 ºC; τ=25,6 kPa)		15	N/A	N/A	0.77	7 U + 6 PMB + 2 special A (RTFOT)
[8] (Robertus *et al.*, 2012)	WTS (WTT – Small SD) *vs.* J_{nr} (T=45 & 60 ºC; τ=1 kPa)	log y=a*log x	20	N/A	N/A	0.79	5 U + 11 PMB + 2 wax modified + 2 special UA
						0.90	5 U + 11 PMB + 2 wax modified + 2 special A (RTFOT)
[13] (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 + 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 + PMB
[19] (Laukkanen *et al.*, 2014)	WTT large size device *vs.* J_{nr} (τ=3,2 kPa)	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
[22] (Tabatabaee & Tabatabaee, 2010)	Unconfined cyclic creep test *vs.* J_{nr} (τ=3,2 kPa)	Not clear (Linear ?)	6	N/A	N/A	0.83	U & CMB / A
							U.D.C. at 40°C

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

3.4. Bitumen complex modulus (G) and phase angle (δ)*

Concerning bitumen binders complex shear modulus (G*) and phase angle (δ) in sinusoidal oscillatory shear mode (using a dynamic shear rheometer), only six papers from the database were found correlating bitumen rheological properties with the asphalt resistance to permanent deformation (Table 4.). The following parameters are generally used in the studies: bitumen complex shear modulus (G*), G*/sin δ characteristic and the unified evaluation index (R_J) (inversely proportional to compliance).

Table 4. Correlations found between binder complex modulus and phase angle and bituminous mixes permanent deformation.

Paper	Correlated data	Type of correlation	Data sets	Constant *a*	Constant *b*	R^2	*Comment*
[8] (Robertus *et al.*, 2012)	WT Rut Rate *vs.* G* (kPa) @ 1,59Hz & 45ºC / 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
[10] (Gungor & Sağlik, 2012)	TCCT Deformation (mm) *vs.* G*/sinδ (kPa) @ 1,59Hz & 40ºC / 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)
[11] (Beckedahl *et al.*, 2008)	WT Rut Depth (mm) *vs.* G*/sinδ (kPa) @ 1,59Hz & 60ºC *(2) (3)*	Power (y=a.x^b)	*3 (3)*	39.39	-0.29	0.93	U & PMB / UA
			3 (4)	20.53	-0.22	0.95	U & PMB / UA
[12] (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
[14] (Tan *et al.*, 2014)	WT dynamic stability (time/mm) *vs.* R_J @ 1,59Hz & 60ºC	Linear (y= a + bx)	7	788.07	323.02	0.99	U & PMB / UA
		Grey relational analysis	5	N/A	N/A	[0.89] *(4)*	U / UA
			2	N/A	N/A	[0.90] *(4)*	PMB / UA
	WT dynamic stability (time/mm) *vs.* G*/sinδ (KPa) @ 1,59Hz & 60ºC	Linear (y= a + bx)	7	-298.59	925.37	0.99	U & PMB / UA
		Grey relational analysis	5	N/A	N/A	[0.89] *(4)*	U / UA
			2	N/A	N/A	[0.59] *(4)*	PMB / UA
[15] (Dreessen & Pascal, 2009)	FWT rutting (%) *vs.* G*/sinδ (KPa) @ 1,59Hz & 60ºC	Logarithmic (y= a lnx + b)	15	-30.55	59.29	0.27	U & PMB / A

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

NOTES: (1) Paper [8] refers R^2 < 0,7 for the correlation of G* and G*/sinδ with WT Rut Rate for both unaged and aged polymer modified binders, 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) Coefficient from the Grey relational analysis.

The data presented in Table 4. shows that there are a significant number of studies were no correlation or very weak correlation (R^2 < 0.7) is obtained when relating G*/sin δ with the asphalt resistance to permanent deformation. In fact, only two papers from the six considered, found a good correlation between the referred properties. In these two cases, a limited number of binders was addressed, since in both of the studies only two modified bituminous binders were considered.

Therefore, most of the papers that determine G*/sin δ, find that it is not suitable to evaluate the asphalt resistance to permanent deformation, when analysing an ensemble of unmodified and polymer modified bituminous binders. Nevertheless, better correlations are achieved for lower frequencies.

3.5. Bitumen performance grade
No relevant papers presenting a clear relationship between the performance grade of the used/recovered binder and the permanent deformation behaviour of bituminous mixtures were found in the database. Nevertheless, it is of common understanding that the high temperature of PG grade is not suitable for ranking the bituminous mixture behaviour to permanent deformation, mainly when modified bitumen binders are used. Therefore, the present PG specification requirements based on the parameter G*/sin δ (at the high temperature grade and a frequency of 10 rad/s / 1.59 Hz) are not suitable for assessing rutting resistance. Nevertheless, new specification requirements to address rutting (e.g. MSCR test parameters) are being considered in the USA having in view to provide better parameters related to asphalt performance characteristics at elevated service temperatures.

4. Conclusions
Among the addressed bitumen properties and its relation with the permanent deformation of bituminous mixtures, the most promising tests providing better correlations are the Zero/Low Shear Viscosity (ZSV/LSV) by creep or oscillation test method [CEN/TS 15324 (Oscillation LSV); CEN/TS 15325 (Creep ZSV)] and the non-recoverable creep compliance (J_{nr}) from MSCR tests [EN 16659].

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 also run at high stress levels which are more representative for the stresses induced by rutting and it is a repeated test which better simulates the loading due to traffic. Nevertheless, the test conditions (e.g. applied stress level) need to be further investigated in the future in order to get even better results and correlations for all types of binders.

Acknowledgements
The research presented in this paper was carried out as part of the CEDR Transnational Road Research Programme Call 2013. The funding for the research was provided by the national road administrations of Denmark, Germany, Ireland, the Netherlands, the United Kingdom and Slovenia.

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