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Functional Durability-related Bitumen Specification (FunDBitS)

Correlations between bitumen and asphalt properties

Stiffness

Deliverable D.2a
August 2016

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FunDBitS
Functional Durability-related Bitumen Specification

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Stiffness

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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 summarized in the interim project report D.1. Possible correlations between the bitumen and asphalt properties related not only to stiffness were identified. Based on the findings five key asphalt performance-based and durability oriented characteristics were considered: permanent deformation (rutting); stiffness; low temperature cracking; fatigue cracking and binder/aggregate interaction.

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. Particular reports to Deliverable D.2 of the FunDBitS project presents the review of the correlations between the referred five asphalt characteristics and bitumen tests/properties.

The presented report is a part of deliverable D.2 and deals specifically with the correlations between the asphalt stiffness (which can be determined by several methods) and bitumen tests/properties related to stiffness/elasticity behavior and performance-based characteristics like complex shear modulus. Recommendation are given by the conclusions with respect to future steps and most suitable tests available so far.

It should be noted that the technical question of asphalt stiffness is a complex issue that is still not given enough attention especially in the case of relation to used bituminous binders. Simultaneously, it seems appropriate to always recommend monitoring and assessment of this characteristic in close correlation with resistance to permanent deformation. The first of these two asphalt aspects is focused on behavior at intermediate temperatures and the second area assesses performance in the range of high temperatures. For this reason, the search results and related analysis devoted to MSCR test are not included in this report. Although in recent years MSCR test has been intensively discussed in order to better characterize the bituminous binders.

In the case of characteristics that would appear to be appropriate for suitable correlations between bitumen and asphalt, i.e. bitumen complex shear modulus determined at temperatures <50 ° C, there are still only limited data sets that are presented in scientific articles and reports. This is further multiplied, if the aim is to find a suitable tool to compare bitumen and asphalt master curves, which are within the search from available and proven experience more frequently used in bituminous binders and conversely more fully missed in assessing the behavior of asphalt mixtures.

By far the biggest weakness can be seen in the approach to the phenomenon of thermo-oxidative ageing. In this case, relatively good ageing procedures exist for the essential characterization of binders and this mainly for the short-term ageing (RTFOT, TFOT). It is obvious especially in Europe that long-term bitumen ageing is strictly required to a lesser extent and there is only limited focus on rigorous requiring assessment of the bitumen behavior for this type of ageing. This requirement is then missed completely for asphalt mixtures with the exception of some research works presented scientific papers. However the definition of an index of ageing applicable to characteristics like stiffness modulus could be a relatively simple indicator for the quality determination of an asphalt mixture. Nevertheless in this area, it was basically impossible to identify any appropriate correlation.

Generally, the approach to search correlations between stiffness behavior of bituminous binders and asphalt mixtures focused on several areas and bitumen properties. Still as the most logical is to assume that there is a sufficiently strong correlation between the stiffness modulus of asphalt mixture and complex shear modulus of the used bitumen. Problems that result from the aforementioned analyses and statistical assessments can be summarized as follows:

- Measurements are often performed for bituminous binders and asphalt mixtures at different temperatures and thanks to it, eventually found correlations are more difficult defendable. It is for example questionable, in case that bitumen complex shear modulus is tested e.g. at 60 °C but the corresponding asphalt stiffness at 15 °C, if finally stiffness of the same material is correlated.
- While the test method used for determination of the complex shear modulus for bituminous binders is only one (EN 14770), the stiffness of an asphalt mixture can be obtained by several test methods EN 12697-26 (at least three are regularly used and results can be found in research or practice papers and reports). Although a clear relationships between the different asphalt stiffness test methods has not yet been proven. Therefore, data obtained in different countries are problematically comparable between themselves.
- It is shown by many examples, that the determinations of stiffness of asphalt mixtures (and that applies even for different variants or combinations with used bituminous binders) are more conducted and disseminated than those for binders. The data published in the available papers or reports usually lacks corresponding values for binders. These values are either missing or they are not published.
- With regard to the fact that there are no uniform harmonized requirements in Europe for neither asphalt mixtures nor binders in terms of determination of stiffness modulus of asphalt mixtures or complex shear modulus, there is no common data collection, which could help with better adjustment of limit values. On the other hand, stiffness modules represent in many countries very important parameter in point of view of pavement design calculation guide used for asphalt pavement dimensioning.
- There is absence of test and corresponding data performed on specimens exposed to artificial laboratory ageing.

The next assessed area was the determination of correlations between softening point, penetration or penetration index of bitumen and stiffness modulus of asphalt mixtures. The penetration index was essentially excluded with regard to the conclusions published in the project BitVal, which proved that penetration index is insignificant in terms of assessing the asphalt stiffness. On the other hand, it is evident that it is possible to find data from many conference or journal papers and/or reports of bitumen penetration and softening point, which were afterwards used in asphalt mixtures, which had the stiffness modulus measured. In this regard the attention was focused on assessing the correlations and comparing them with the previous findings and conclusions made by project BitVal.

The third area are potential correlations and relations between asphalt stiffness modulus and low temperature behavior of binders assessed by using BBR or DT. It was unfortunately shown that there is only a very limited research works, which are focused on this problematic in a sufficient way. This conclusion is made at least based on the analyses done within FunDBitS project. It is practically shown that professional community apparently does not believe that there is any direct relation between these characteristics. Similarly, there was no identified suitable data or data sources, which would be more intensely focused (from point of view of asphalt stiffness) on area of PG bitumen grading system and usage of this classification for determination of asphalt stiffness. Even in analyzed papers originating in the U.S. such direct comparison was not sufficiently found.

Last but not least on the basis of knowledge from FunDBitS interim report D.1 there was an assessment of detailed research in the area of prediction models, which would allow calculations or forecast of stiffness modulus behavior based on data collected for binders or vice versa. It should be point out that there are some models, which are being long-term developed or further improved, but their practical use is still sporadic. It might be therefore advisable to motivate and run calculations for a broader set of different asphalt mixtures from different regions to get clear confirmation if some of the models are practically applicable.

1. Introduction

The stiffness of asphalt is a structural property that can be used in the design of pavements but which varies with temperature and frequency, as with many asphalt properties. The relevant European asphalt test is EN 12697-26:2012, Stiffness, containing several options (two-, three and four-point bending, indirect tension, direct tension-compression and direct tension) that give mutually consistent resultants. The scope states that the test method is used to rank asphalt mixtures on the basis of stiffness, as a guide to relative performance in the pavement, to obtain data for estimating the structural behavior in the road and to judge test data according to specifications for asphalt. Additionally in some countries stiffness characteristics are one of the crucial parameters which is used for asphalt pavement design. Therefore relevant data are needed and at the same time it should be forced that values gained for stiffness on laboratory test specimens are correlated or normalized with values which would be determined on specimens cored or cut from the existing pavement. This is highly important to compare whether stiffness values of laboratory test specimens correspond to stiffness values of particular compacted asphalt layers.

2. Relationship found between bitumen properties and asphalt stiffness

2.1 General

Iwanski and Mazurek (2012, Paper 037) studied the effect of bitumen properties on the resilient modulus of elasticity and air voids content of asphalt. The significances found at a compaction temperature of 125 °C with a significance level of α = 0,1 are given in Table 0-1.

Table 0-1: Significance of bitumen properties on asphalt

	Resilient modulus of elasticity	Air voids content
Penetration index	Non-significant	Significant
Complex modulus	Significant	Non-significant
Phase angle	Significant	Non-significant
Low shear viscosity (LSV)	Significant	Non-significant

These results indicate that the binder's visco-elastic properties of complex modulus, phase angle and LSV play a major role in the value of the resilient modulus of elasticity at 20 °C but not on the air voids content while the reverse is the case for penetration index.

2.2 Dynamic Shear Rheometer (DSR)

The dynamic stiffness modulus, |G*|, as measured by the Dynamic Shear Rheometer (DSR) is the obvious predictor of the binder effect on the stiffness modulus of asphalt, and this relationship was found in the BiTVal project (Nicholls, 2007). This relationship has been found by several teams.

Mangiafico *et al*. (2012, Paper 025) examined mixtures with different grades of bitumen (15/25, 35/50 and 70/100) and different RA contents (0, 20 %, 40 % and 60 %) for which they measured the complex moduli at 15 °C and 10 Hz. These results are strongly correlated, as shown in Figure 0-1.

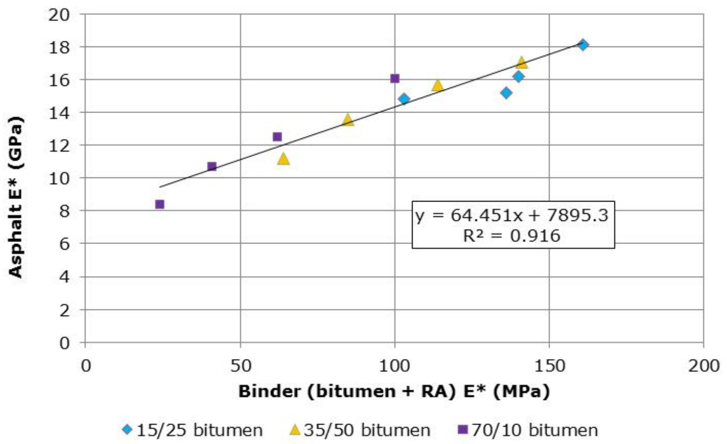


Figure 0-1: Comparative stiffness values from Mangiafico *et al*.

Similarly, Eckmann *et al*. (2012, Paper 026) examined AC10 mixtures with 20/30 base bitumen and different proportions of an unnamed cross-linked elastomer polymer. Again, a good correlation was observed between the stiffness moduli measured on the asphalt at 15 °C and 0.02 s and the |G*| value measured on the corresponding binders at 15 °C and 10 Hz as shown in Figure 0-2.

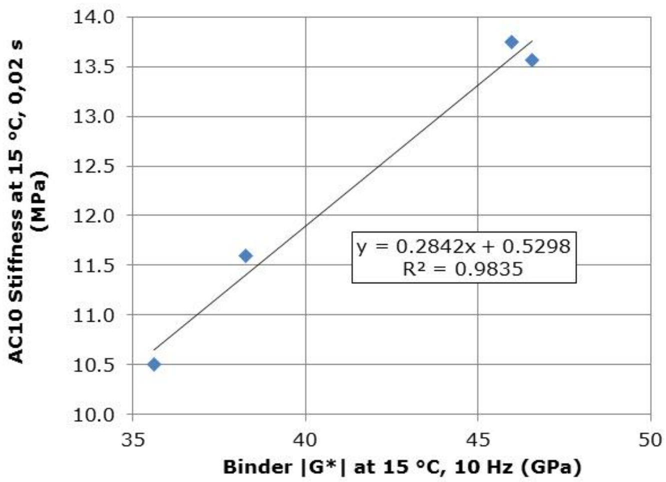


Figure 0-2: Comparative stiffness values from Eckmann *et al*.

Yang *et al*. (2014, Paper 347) measured the resilient modulus at different ages (0, 2, 4, 8, 24, 36 and 52 weeks) of four asphalt specimens cored from the recovered slab. After the test, the top 25 mm of the specimens were sawed cut and the binders were extracted from the top 25 mm portion of the mixtures to measure the dynamic shear modulus (G*) and phase angle (δ) of the recovered binder at 64 °C. The stiffness of the binder had a good correlation with that of the asphalt, as shown in Figure 0-3.

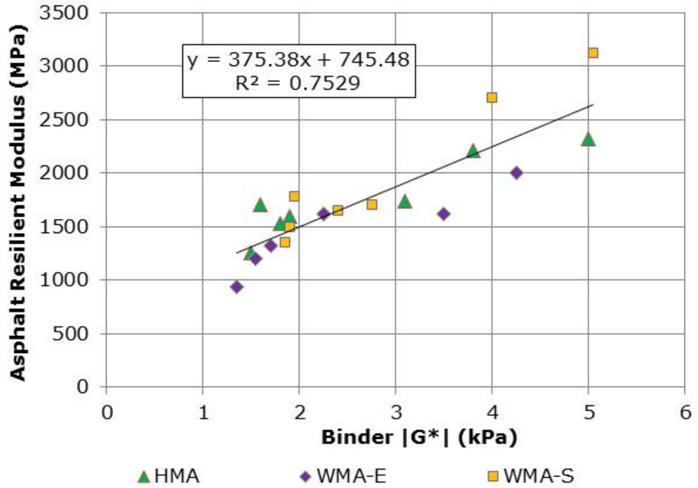


Figure 0-3: Comparative stiffness values from Yang *et al*.

Hase (2011, Paper 510) reported on measurements of the stiffness of high modulus asphalt mixtures (EME) with different bitumen grades (10/20, 20/30, 35/50, 50/70 x 2, 70/100 and 160/220) both with and without 30 % RA. The bitumen stiffness was also measured, but not after mixing with the binder from the RA. The correlation between the stiffness of the asphalt, both with and without RA, and that of the fresh binders are shown in Figure 0-4.

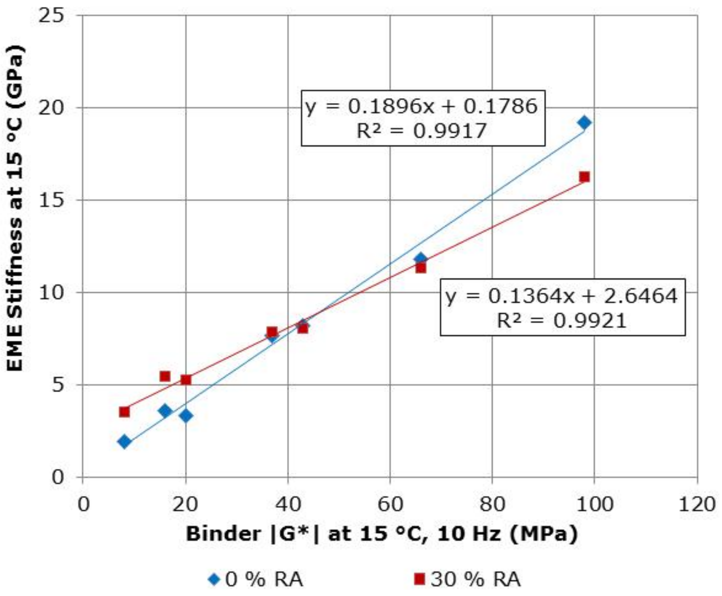


Figure 0-4: Comparative stiffness values from Hase

Tabatabaee and Tabatabaee (2010 Paper 563) studied five bituminous binders (PG70-22, air-blown, SBS LG, CR-TR, terpolymer modified bitumen) with asphalt mixtures at constant binder contents of 5,3 %. The complex shear modulus of the tested binders and the dynamic modulus of asphalt are given in Table 0-2 and shown in Figure 0-5.

Table 0-2: Complex shear modulus of tested binders

Binder	Complex shear modulus of binder, G* (MPa)	Dynamic modulus of asphalt, E* (MPa)
70-22	28,42	7847
Air Blown	16,23	6561
CR TB	9,165	4536
Terpolymer	7,179	3726
SBS LG	10,33	4467

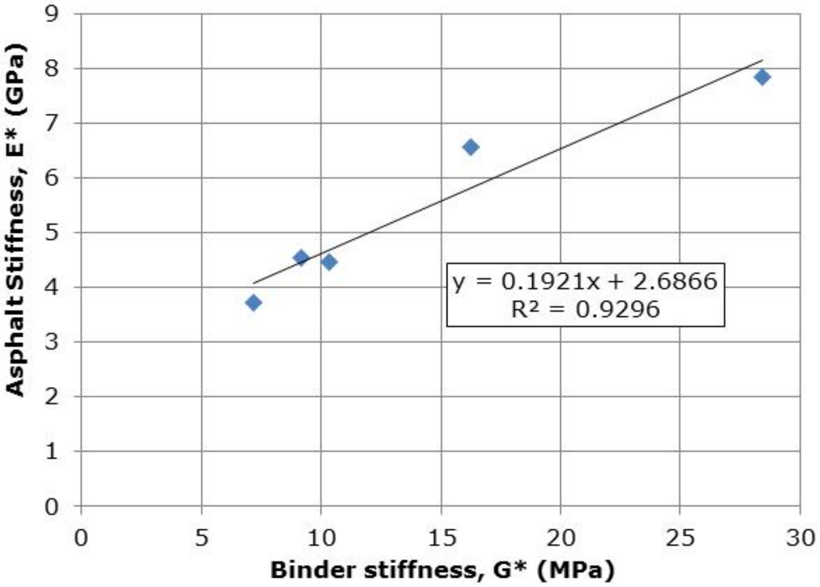


Figure 0-5: Relationship between G* and E* of asphalt mix

The correlation equations from these five studies are combined in Table 0-3.

Table 0-3: Correlations found between binder and asphalt stiffness values

Paper		Test temp.	Data sets	Coefficient	Constant	R^2
Mangiafico *et al.*		15 °C	12	64,451	7895,3	0,916
Eckmann *et al.*		15 °C	4	0,2842	0,5298	0,984
Yang *et al.*		64 °C (bit)	21	375,38	745,48	0,753
Hase	No RA		7	0,1896	0,1786	0,992
	30 % RA		7	0,1364	2,6464	0,992
Tabatabaee and Tabatabaee			5	0,1921	2,6866	0,930

The weighted mean correlation coefficient, R^2, from these studies is 0,88.

Wen et al. (2010, Paper 563) presented in his paper five types of bituminous binders used at federal highway administration (FHWA) accelerated loading facility (ALF) were tested in this study, including paving grade bitumen and different modifications. One binder content of 5,3 M% and one coarse graded diabase mixture with a nominal maximum aggregate size of 12,5 mm were used. The laboratory tests of bituminous binders were conducted using a TA Dynamic Shear Rheometer Instrument (AR2000) that allows isothermal loading of the bitumen. The binders were aged using the rolling thin film oven (RTFO) prior to the testing. Constant strain shear-rate was applied to the binder specimen until the peak stress was reached. Three shear rates were used: 0,005/s, 0,0075/s, and 0,01/s. The tests were conducted at 19 °C. Dynamic modulus |E*| master curves of the asphalt mixtures were constructed according to the AASHTO TP-62 protocol. Different testing temperatures and frequencies were used, reported are 19 °C and 10 Hz. The tests were conducted using the Asphalt Mixture Performance Tester (AMPT).

Two binders might have the same shear strength, but their complex shear moduli are significantly different from each other. This indicates that a high modulus binder might not be resistant to fatigue.

It was found by this paper that the bitumen modification methods reduced the complex shear modules of binders. In addition, except for air blown method, other methods increased the critical strain density of binders and improved the fatigue resistance of binders.

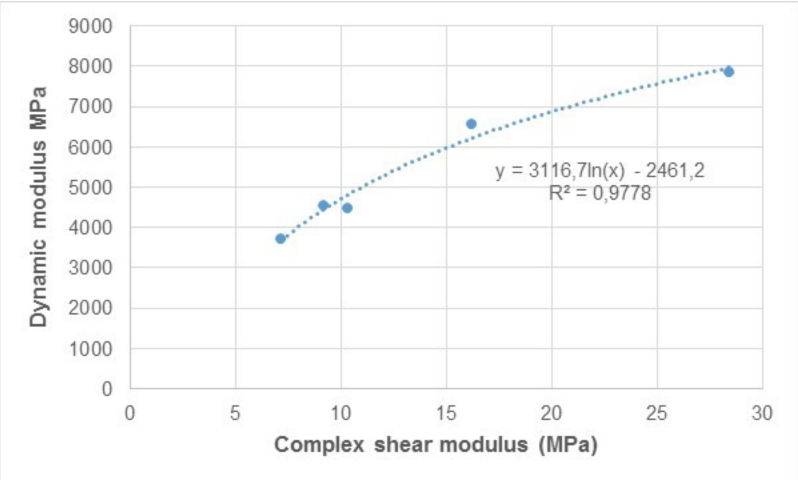


Figure 0-6: Relationship between complex shear modulus and asphalt dynamic modulus

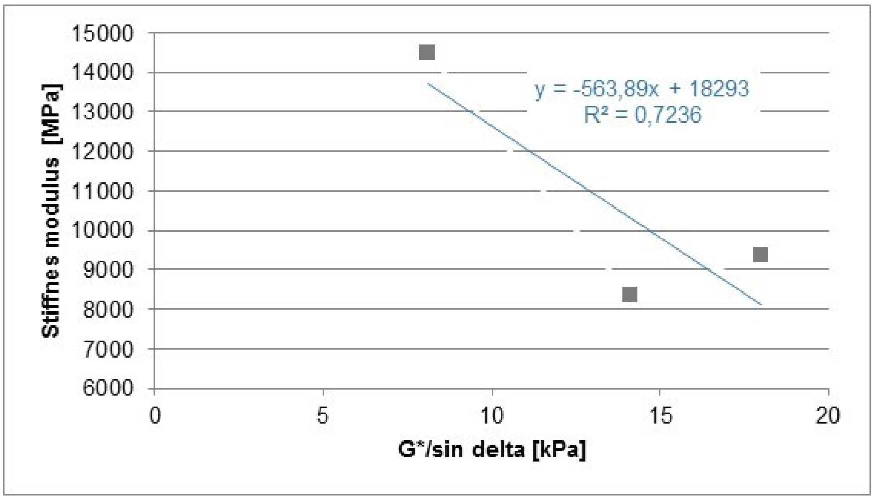


Figure 0-7: Relationship between G*/(sin δ) and asphalt stiffness

Bureš et al. (2009, Paper 405) tested new type of PMB binder which was compared with regular paving grade 30/45 and PMB 25/55-60. Binder as well as asphalt assessments have been done for a high stiffness modulus asphalt concrete (HMAC 16). It is possible to provide a correlation between asphalt stiffness and bitumen properties. Such correlations are however influenced by limited set of tested mixtures and therefore statistically the found results have to be considered with precaution. The Figure 0-5 and Figure 0-5 show correlations of stiffness and bitumen complex shear modulus or penetration and softening point. It was found, that G* (more precisely the SHRP parameter G*/sin(δ) correlates well. On the other hand the correlations found for penetration and softening point were moderate or lower and match only partly with findings from different research works as presented later in this report.

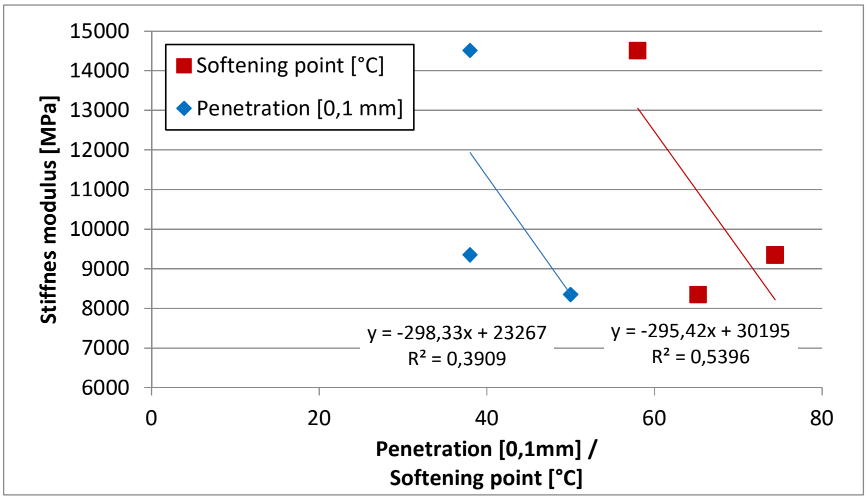
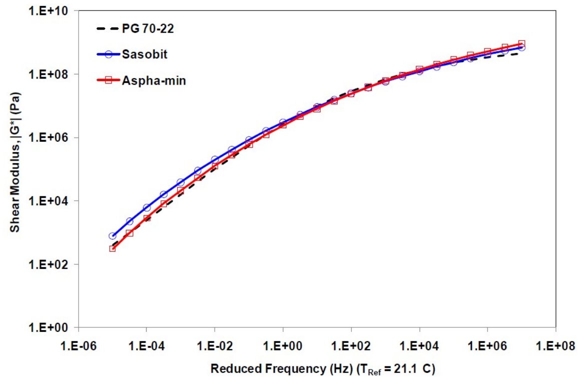


Figure 0-8: Relationship between penetration and softening point and asphalt stiffness

Other teams found the relationship was less clear. Zelelew *et al*. (2012, Paper 128) reported on measurements of the shear modulus |G*| master curves for a series of binders and the |E*| master curves for the associated asphalt mixtures for a control hot mix asphalt and a series of WMA technologies (Sasobit®, Accu-Shear®, Rediset®, Advera®, Aspha-min® and Evotherm®). The plots are shown in Figure 0-9 for the binders and Figure 0-10 for the asphalts with the associated plots alongside each other. These plots show different shaped master curves for the binder and associated asphalt mixture, casting doubt on the correlation between these properties.



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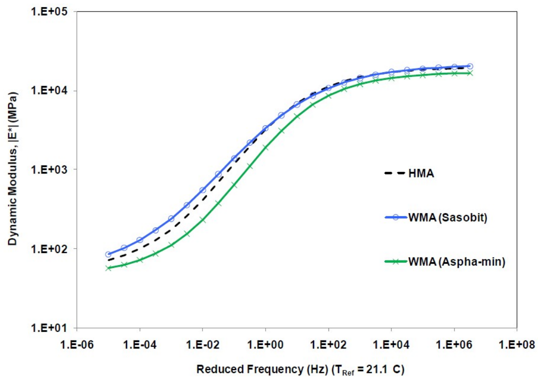

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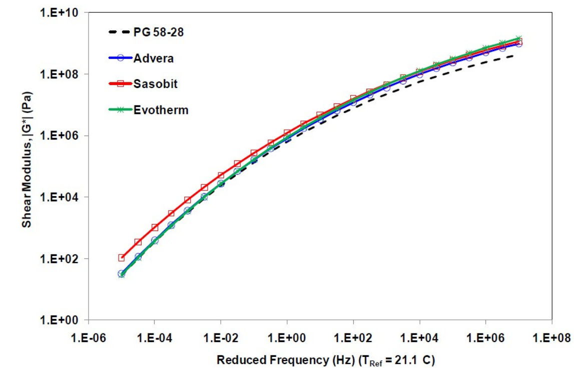

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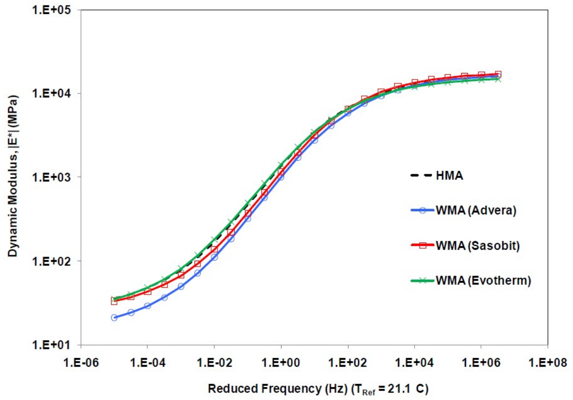

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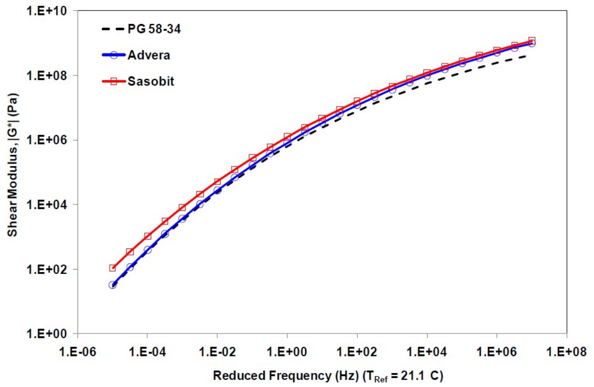

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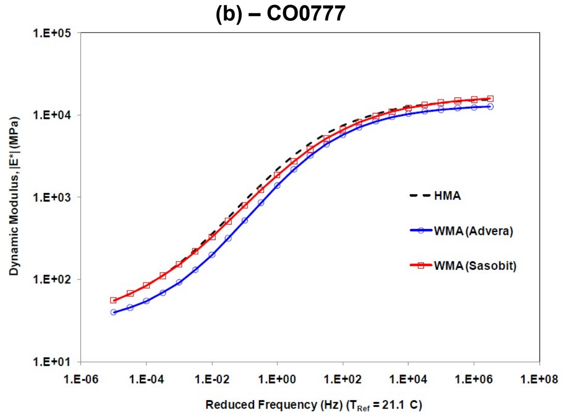

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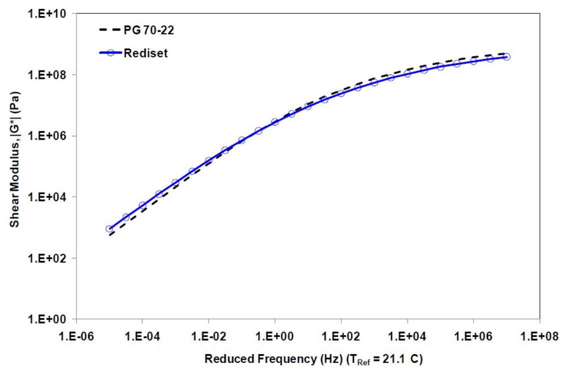

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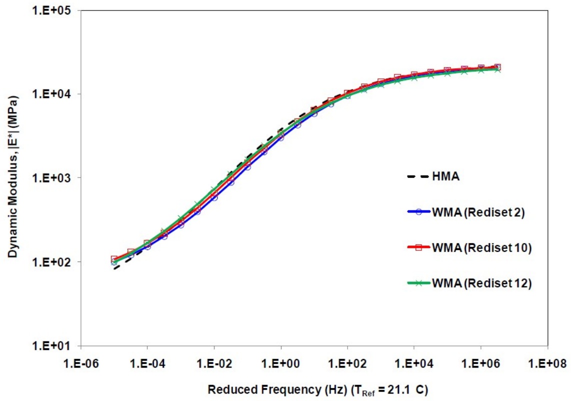

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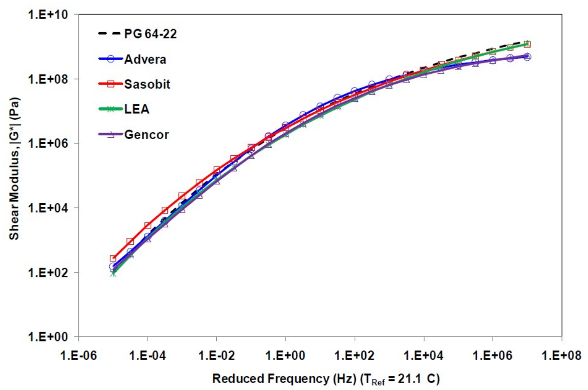

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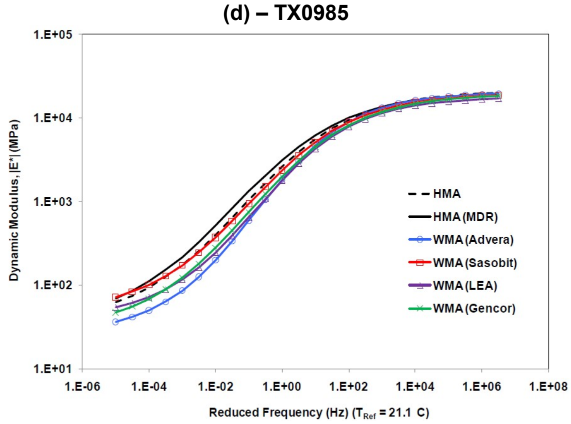

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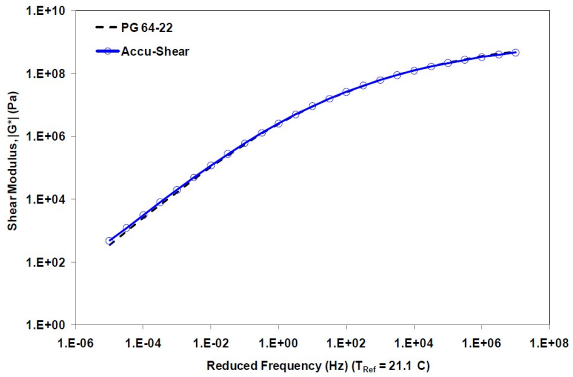

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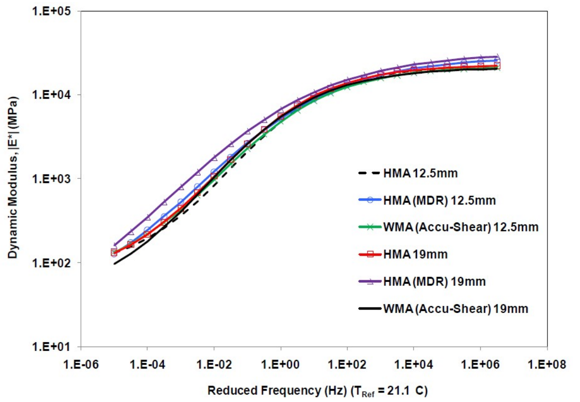

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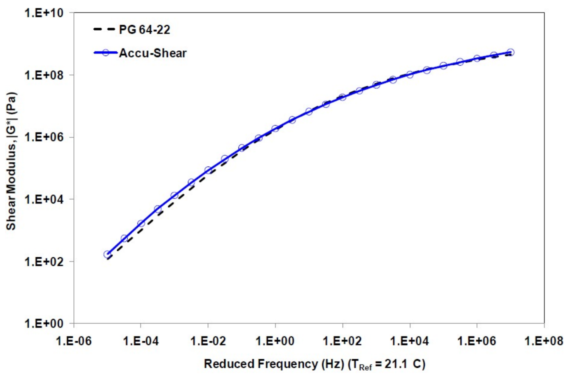
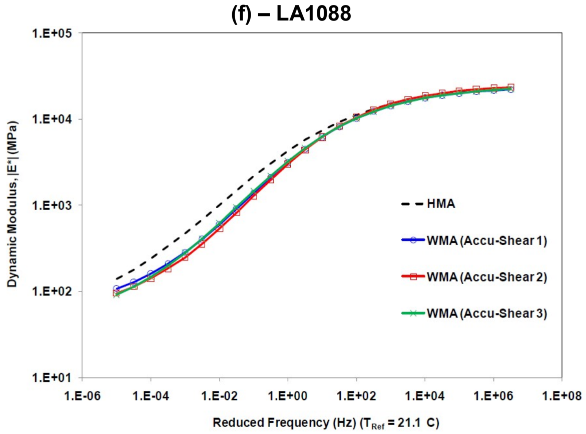


(g) – IN1099



(g) – IN1090

Figure 0-9: Shear modulus master curves of binders

Figure 0-10: Dynamic modulus master curves of asphalts

Ballié *et al*. (2008, Paper 071) analyzed more than 160 mechanical physical characteristics of ten typical French binders (pure, polymer-modified and special bituminous binders). Laboratory tests were conducted on binders before ageing, after RTFOT artificial ageing and after extraction from asphalt. Only the asphalt complex modulus, an intrinsic property of the asphalt, seemed to be related to other measures of performance.

Both Figure 0-11 and Figure 0-12 present the master curves of the modules and phase angles of binder A and its asphalt mixture after vertical and horizontal shift.

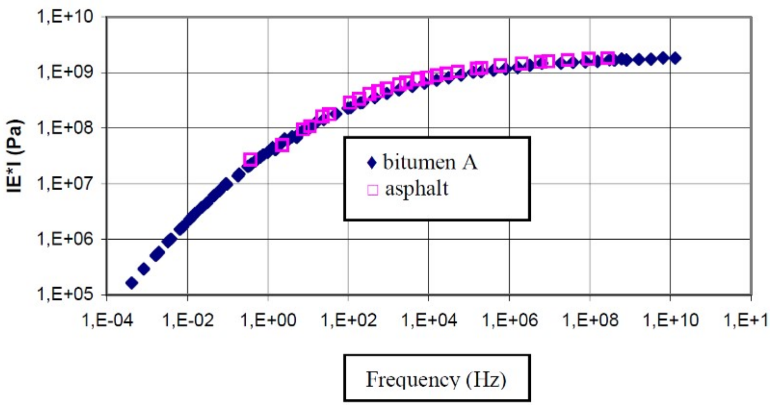


Figure 0-11: Modulus master curves, at 20°C, of extracted binder A and its asphalt after translations

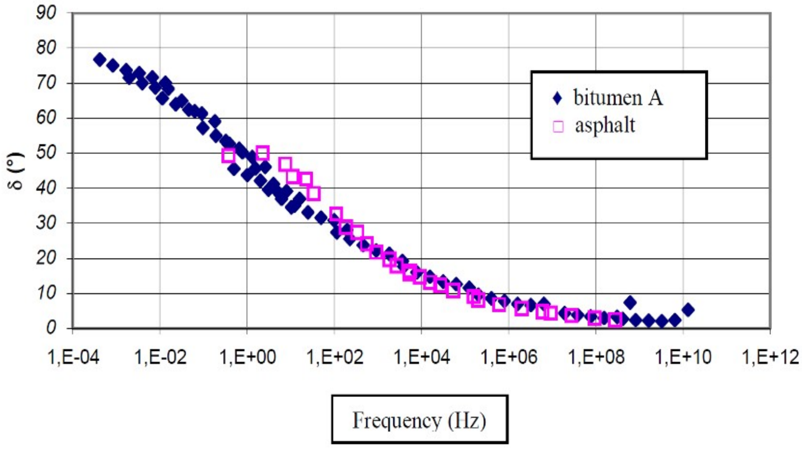
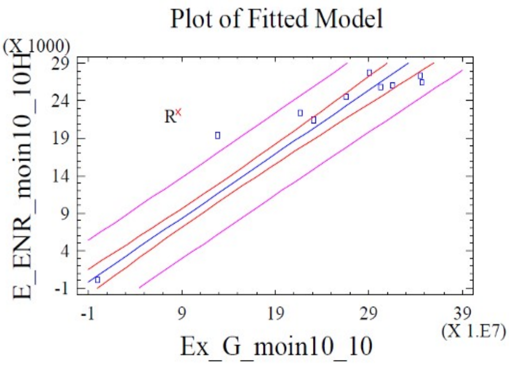


Figure 0-12: Phase angle master curves at 20°C (extracted binder A and asphalt after horizontal translation)

Ballié *et al*. found that the complex modulus of the asphalt can be determined directly, to a certain extent, for a given asphalt mix design. Multivariate statistical analysis clearly highlighted the correlation between the modulus values of the binder and asphalt at a given frequency and temperature, as illustrated by Figure 0-13 at -10°C and 10 Hz, 30°C and 10 Hz, and at 15°C and 10 Hz for the measured modulus or phase angle points.



Asphalt Modulus E* *vs* Binder modulus G* at -10°C 10 Hz

```
Correlation Coefficient = 0.981536
R-squared = 96.3412 percent
Standard Error of Est. = 2509.46
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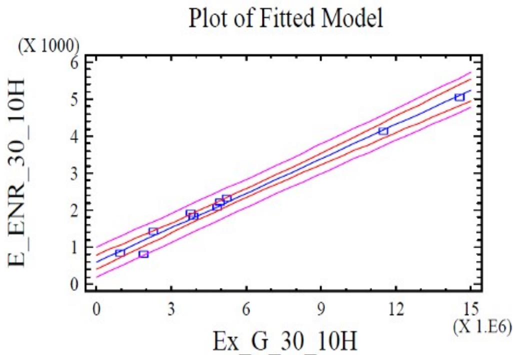

Asphalt Modulus E* *vs* Binder Modulus G* at 30°C 10 Hz

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Correlation Coefficient = 0.993815
R-squared = 98.7668 percent
Standard Error of Est. = 158.732
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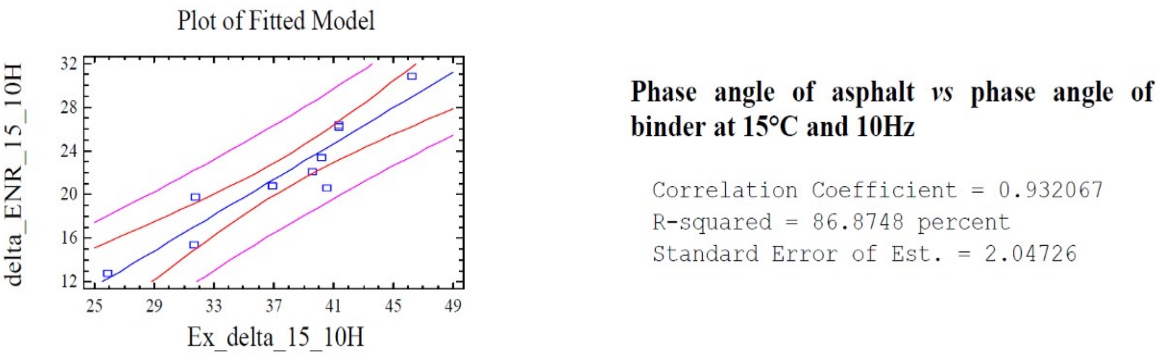


Figure 0-13: Examples of correlation obtained between the asphalt modulus and binder modulus

Not all these correlations are surprising. In a relatively narrow temperature and frequency area, the asphalt modulus |E*ENR| can be derived from the binder modulus |E*bit|, either using models (Huet model modified by adding a viscous element) or by relations such the following one given by Olard in 2003:

$$\frac{\left|E^{*}_{ENR}\right|}{\left(E^{\infty}_{ENR}-E^{0}_{ENR}\right)} = \frac{E^{0}_{ENR}}{\left(E^{\infty}_{ENR}-E^{0}_{ENR}\right)} + b * \frac{\left|E^{*}_{bit}\right|}{E^{\infty}_{bit}} \qquad (1)$$

Valentin *et al*. (2012, Paper 038) measured the stiffness results for binders at 60 °C and 1,59 Hz in control-stress mode together with stiffness moduli of the associated asphalt using both the indirect tensile method on cylindrical specimens (IT-CY) and the two-point bending method on trapezoidal specimens (2PB-TR), the former at two sample preparation temperatures. The data was collected on three binders, 50/70+3 % FTP, 50/70+3 % FAA and 50/70+0,5 % PPA. The correlations between asphalt stiffness modulus and binder stiffness are shown in Figure 0-14 with the correlation equations in Table 0-4.

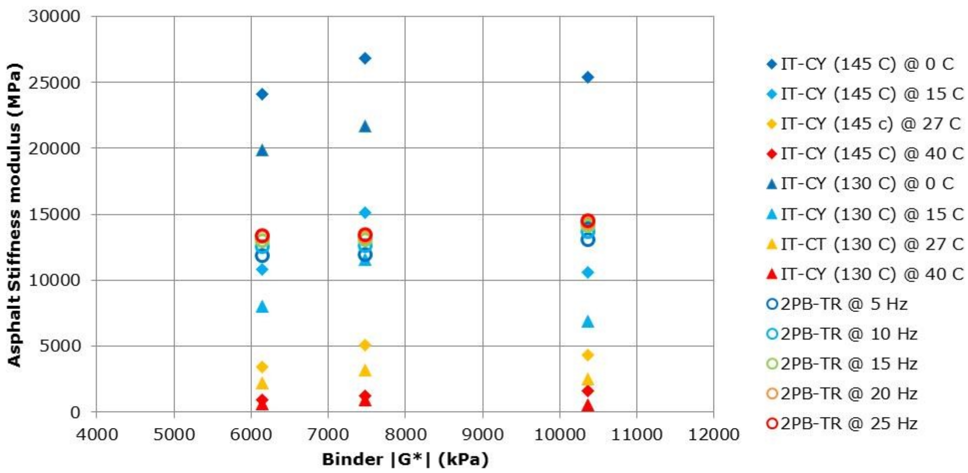


Figure 0-14: Comparative stiffness values from Valentin *et al.*

Table 0-4: Correlation equations for comparative stiffness values from Valentin *et al*.

Stiffness method	Preparation temperature	Test temp. / frequency	Coefficient	Constant	R^2
IT-CY	145 °C	0 °C	0,1804	23991	0,003
		15 °C	0,2918	14499	0,061
		27 °C	0,1344	3192,5	0,116
		40 °C	0,1617	-59,69	0,986
	130 °C	0 °C	-0,14781	30516	0,722
		15 °C	-0,4821	12688	0,178
		27 °C	0,0205	2,469,3	0,007
		40 °C	-0,0423	1004,9	0,192
	Mean		0.01	12262	0,280
	Standard deviation		0.24	11809	0,370
2PB-TR	5 Hz		0.3024	9885,8	0,944
	10 Hz		0.278	10738	0,949
	15 Hz		0.2854	11112	0,919
	20 Hz		0.2861	11514	0,938
	25 Hz		0.2823	11395	0,899
	Mean		0.29	10929	0,930
	Standard deviation		0.01	655	0,020
All	Mean		0.12	11706	0,530
	Standard deviation		0.23	8758	0,430

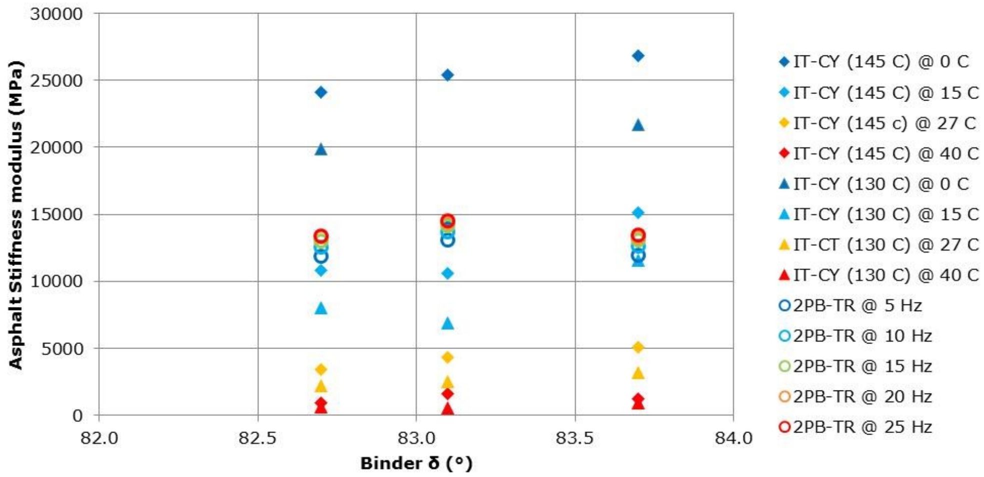


Figure 0-15: Asphalt stiffness compared with binder phase angle from Valentin *et al*.

The correlation was variable with the IT-CY method for asphalt stiffness despite there being just three points for each trend line. There are even some trend lines with negative coefficients, indicating that higher binder stiffness values give lower asphalt stiffness value.

However, there is good correlation with the 2PB-TR method. The difference between the two methods is surprising because the methods are generally considered as equivalent and are treated as providing comparable result in the European standard EN 12697-26.

Overall, there is a positive correlation between the binder stiffness and the asphalt stiffness, but that relationship is not always as robust as might be expected, particularly when measuring the asphalt stiffness with the IT-CY method.

Valentin *et al*. (2012, Paper 038) also measured the binder phase angle. Repeating the comparison of the asphalt stiffness with the binder phase angle gives Figure 0-15 and Table 0-5.

Table 0-5: Asphalt stiffness compared with binder phase angle from Valentin *et al*.

Stiffness method	Preparation temperature	Test temp. / frequency	Coefficient	Constant	R^2
IT-CY	145 °C	0 °C	2671,1	-196709	0,991
		15 °C	4552,6	-366461	0,812
		27 °C	1671,1	-134709	0,978
		40 °C	223,68	-17370	0,103
	130 °C	0 °C	2605,3	-197971	0,123
		15 °C	3934,2	-318362	0,649
		27 °C	1013,2	-81628	0,988
		40 °C	328,95	-26691	0,633
	Mean		2125.02	-167488	0,660
	Standard deviation		1602.60	128142	0,370
2PB-TR	5 Hz		-55.658	16932	0,002
	10 Hz		-35.921	15947	0,001
	15 Hz		-114.47	22914	0,008
	20 Hz		-158.95	26871	0,016
	25 Hz		-66.711	19349	0,003
	Mean		-86.34	20403	0,010
	Standard deviation		49.83	4504	0,010
All	Mean		1274.49	-95222	0,410
	Standard deviation		1659.18	136518	0,430

These correlations are poor, but there is no inherent reason for the asphalt stiffness to be related to the binder phase angle.

Cope *et al*. (2007, Paper 022) performed DSR tests on bitumen/vegetable oil blends under controlled strain mode of loading using test temperatures between 0 °C and 80 °C and test frequencies between 0,01 Hz and 10 Hz. The complex shear modulus G* of the blends at a reference temperature of 25 °C are given in Figure 0-16. Dense bitumen macadam mixtures were then manufactured with the blends and either compacted immediately or kept in a loose state in an oven for a period of 4 h prior to compaction in order to simulate short term mix ageing. Indirect tensile stiffness moduli at 20°C were measured initially and following immersion in water at 20 °C for periods of two and four weeks. The results are shown in Figure 0-17.

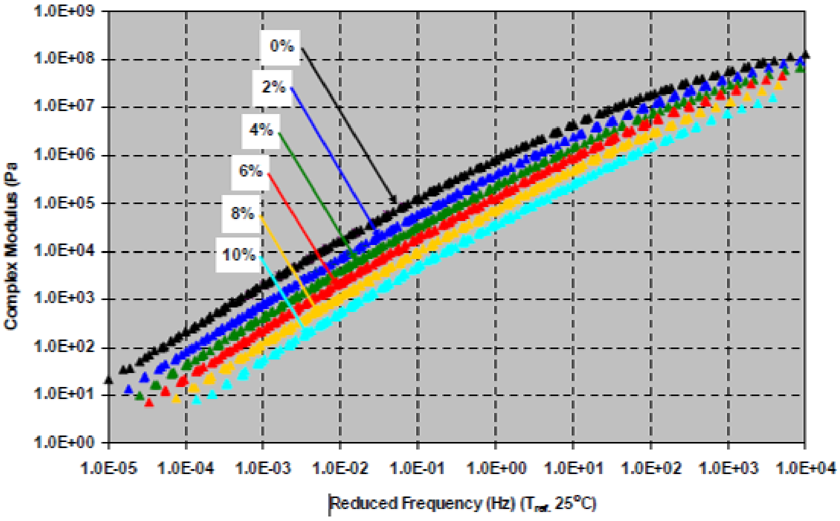


Figure 0-16: Complex modulus G* master curves at 25°C reference temperature for all bitumen/oil blends investigated

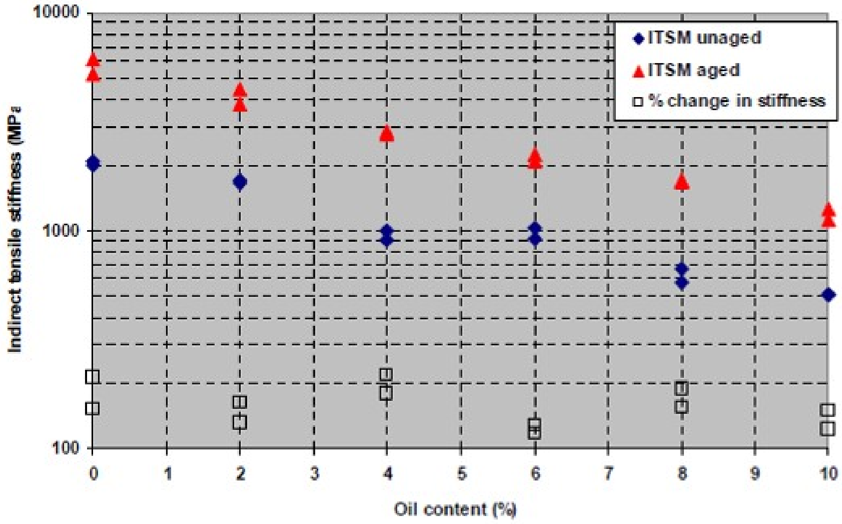


Figure 0-17: IT-CY values of asphalt mixes at different oil contents

Both G* and IT-CY values are reduced with oil content.

Similarly to the previous paper, Peréz-Jimenéz et al. (2012, Paper 0134) focused in their research on the comparison of the behavior of two bituminous binder (B13/22 and B60/70) and corresponding asphalt mixtures of AC16S type. The research is addressing alternative fatigue tests, nevertheless within these tests also initial complex modules have been gained.

Primarily failure criteria currently used in fatigue testing of asphalt mixtures and binders have been analyzed focusing on the characteristics like complex modulus G*, and phase angle, δ, with the parameter (G*sin(δ)). For asphalt mixtures s cyclic uniaxial tension-compression test under strain controlled conditions – EBADE test – was performed. When testing binders 20 mm diameter samples have been used with a height of 39,5 mm. Because of the ductility of binders the testing temperature was 10°C (with 10 Hz frequency) to allow successful mounting of the specimens. Test temperature for asphalt mixtures was 20 °C with the test frequency of 10 Hz.

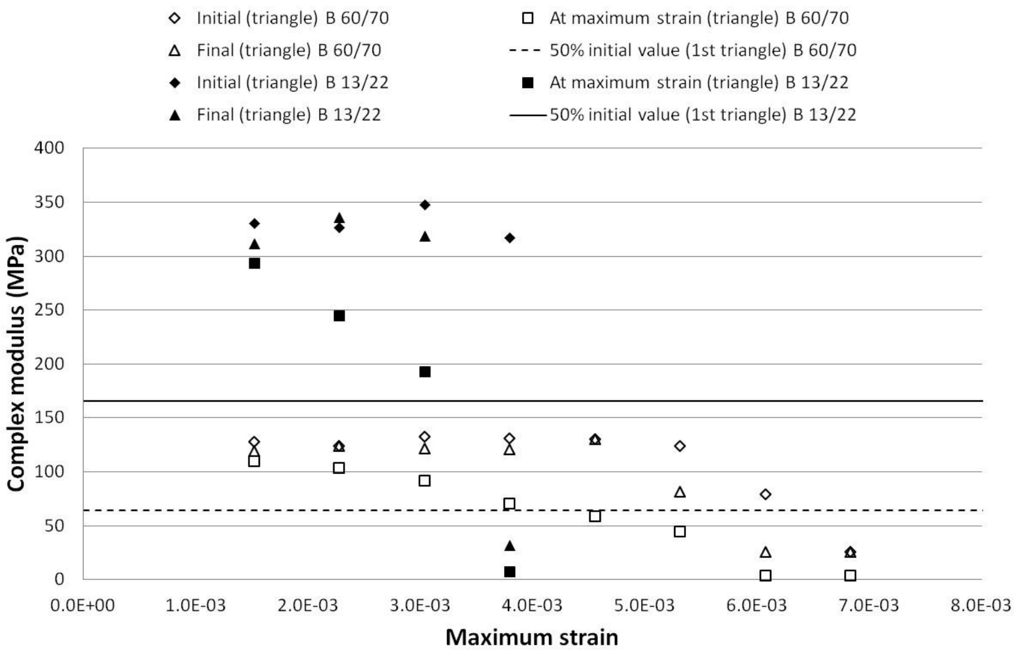


Figure 0-18: Bitumen complex modulus values at different stages of the up&down strain sweep tests

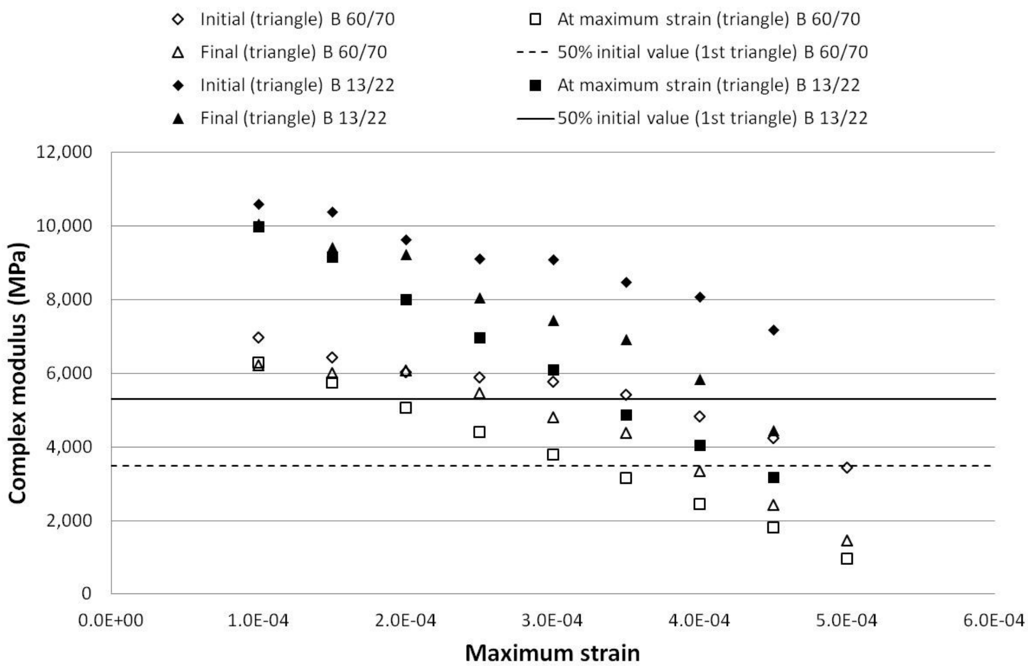


Figure 0-19: Asphalt mix complex modulus values at different stages of the up&down strain sweep tests

If focusing in Figure 0-17 and Figure 0-17 only on initial complex modules it can be stated that there is not an unambiguously strong correlation between the bitumen and mix data. For both binders it is evident, that the stiffness starts to degrease for strain values between $4x10^{-3}$ and $5x10^{-3}$. The decreased complex modulus has then not a linear relation to the maximum applied strain. On the other hand for asphalt mixture containing these two binders the complex decreases from the first applied maximum strain and the functionality might be linear. It can be summarized, that from the perspective of stiffness bitumen 13/22 shows almost constant initial complex modules in the first three triangles and fails in the fourth. Bitumen 60/70 exhibits constant initial complex modules and fails in the seventh triangle. The behavior of the mixtures was slightly different. From the beginning the initial complex modulus of each triangle decreased with increasing the maximum strain.

Similarly tested Peréz-Jimenéz et al. (2012, Paper 0272) three bituminous binders, related mastics and AC 16 S mixture by the same approach. In this case the bitumen and mastic were always tested and 10 Hz frequency for three temperatures: 10 °C; 3 °C and -5 °C using different strains starting at 760 microstrains. Bituminous binders were additionally short-term aged and the results for the aged binders compared to mastic or asphalt mixture. In both cases there is a functionality between the stiffness values whereas for bitumen-mastic correlation it clearly follows the expected behavior, i.e. harder bitumen or PMB are demonstrating always higher mastic stiffness values and in limited extent higher bitumen values. For bitumen-mixture comparison the material elasticity seem to play important role.

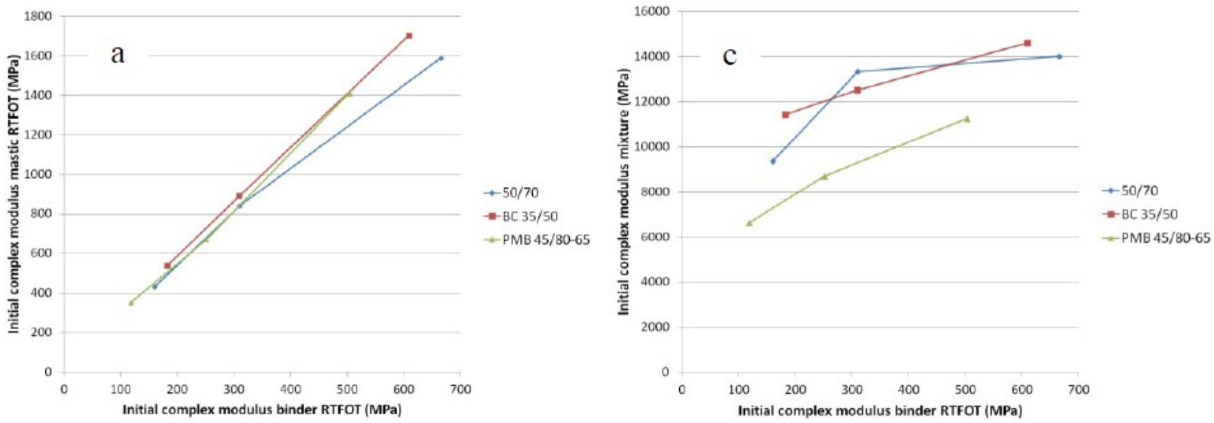


Figure 0-20: Relation between the parameters of binder and mastic (a) and binder and asphalt mixture (c)

Sheng Zhao et al. (2014, Paper 305) evaluated the laboratory performance of a hot mix asphalt (AC type mixture) produced with binders modified by selected bio-char. This is hardly comparable to previous findings but can provide a different view on the possible relations between asphalt and bitumen stiffness properties. For comparison purpose samples of carbon black and carbon fibers were included in the study as a kind of reference additives to the used bio-char modification. The bio-char used in the research was according to previous findings of the authors the most effective one. Bituminous binders and aggregates were heated for 2 hours in an oven to 165°C prior to mixing. Meanwhile, the carbon-based additives were dried at 120°C for 2 hours and then blended with heated bitumen at target concentrations using a mixing device designed for mastic research in the laboratory. From the results presented by the authors some basic correlations can be made, nevertheless should be considered with precaution since the complex shear modulus (G*) was tested for virgin binders at 64°C, whereas the asphalt resilient modulus was determined at 20°C. The resulting correlations for two levels of additive content in the bitumen/asphalt mixture are given in Figure 0-17. The found correlations are not very strong and as most appropriate exponential functions have been found to provide the best coefficients of determination.

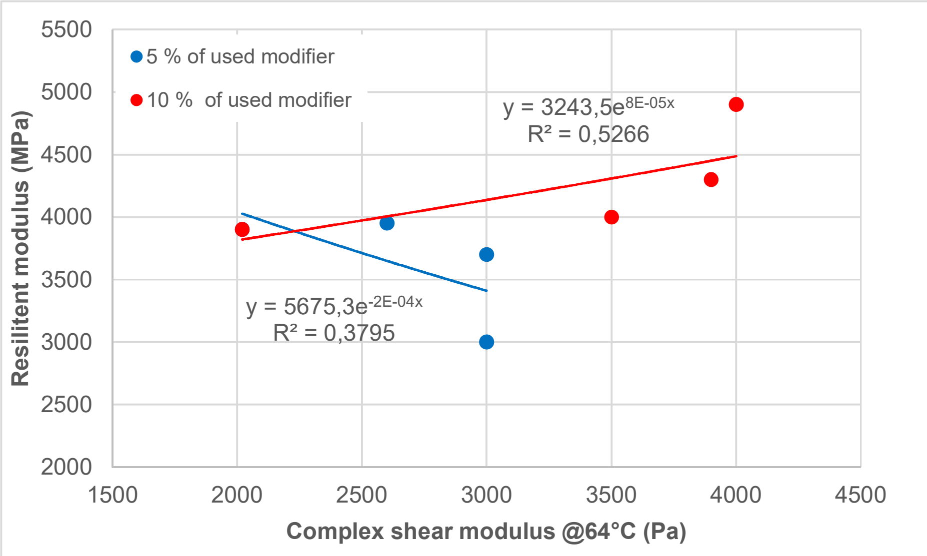


Figure 0-21: Relation between the bitumen complex shear modulus and asphalt resilient modulus

Other data can be found in the literature, where several correlations can be studied, however are usually limited only to sufficient data for asphalt mixtures and do lack of data related to used binders. An example can be found if using data from Valentin et al. (2013, Paper 361) and data from Dašek et al. (2009, Paper 402). Both papers focuses on new developments and assessments of asphalt mixtures for acoustic surface courses (SMA LA, BBTM, PA). Research presented in both papers provides a lot of data about mix performance nevertheless has only limited data of functional testing done for used binders. The correlations which can be done based on 17 different asphalt mixtures containing not only different binder contents but also types of bituminous binders can be limited only to asphalt stiffness vs. voids content (see Figure 0-17). There is however no direct link to the bitumen and in what extent the binder influences mainly the stiffness. Important is the result for quite large set of similar mixtures (differ slightly in mix design, mainly in used aggregates). It could be shown, that the most suitable functionality explaining the relationship between both characteristics is an exponential function. Nevertheless even in this case the found correlation is weak providing R^2 with a value of only 0,37.

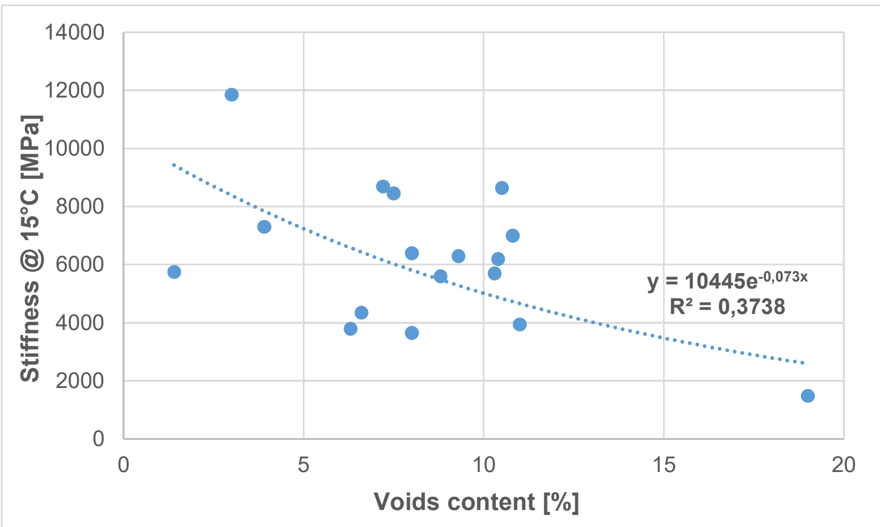


Figure 0-22: Relation between asphalt stiffness and voids content (asphalt mixtures for pavements with reduced noise levels)

That a clear relationship between asphalt stiffness and voids content can be more than questionable is shown by another comparison based on data from the WMA research provided by Valentin et al. (2009, Paper 392). In this case three different additives used in 50/70 paving grade bitumen were added and used in an asphalt concrete mix. Found correlation is presented in Figure 0-17.

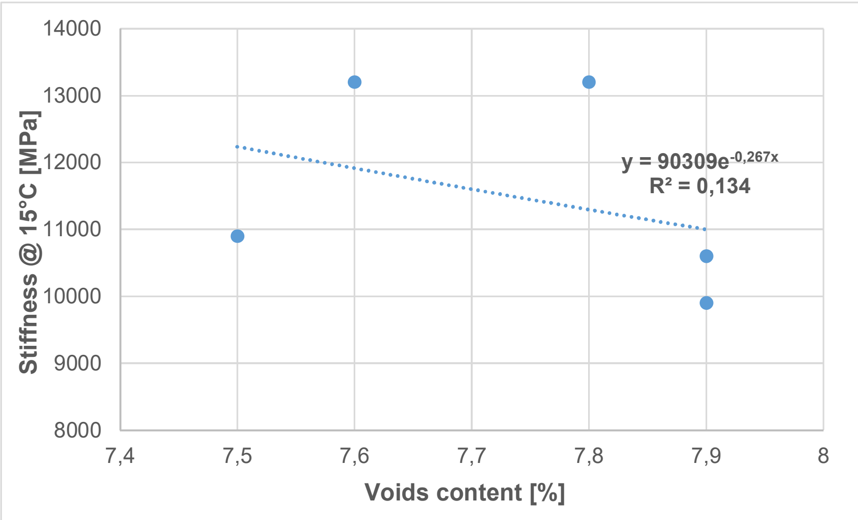


Figure 0-23: Relation between asphalt stiffness and voids content (WMA)

2.3 Bending Beam Rheometer (BBR)

No additional papers on binder BBR and asphalt stiffness properties to those reviewed in BitVal have been found. The only existing findings are related to comparability studies between binder BBR and binder stiffness defined by G*.

2.4 Direct Tensile Test (DTT)

No additional papers on binder DTT and asphalt stiffness properties to those reviewed in BitVal have been found.

2.5 Needle penetration and Ring & ball Softening point

The traditional properties of penetration and softening point are taken together because most researchers report both properties together.

Nordgren and Olsson (2012, Paper 031) examined mixtures with seven different paving grade bituminous binders that were cored after one year in service. The stiffness modulus at 10 °C was determined for each mixture both directly and after ITSR conditioning for 7 days. The results relative to the traditional binder properties are shown in Figure 0-24 and Figure 0-25, with the conditioning producing only a marginal decrease in stiffness modulus for all mixtures.

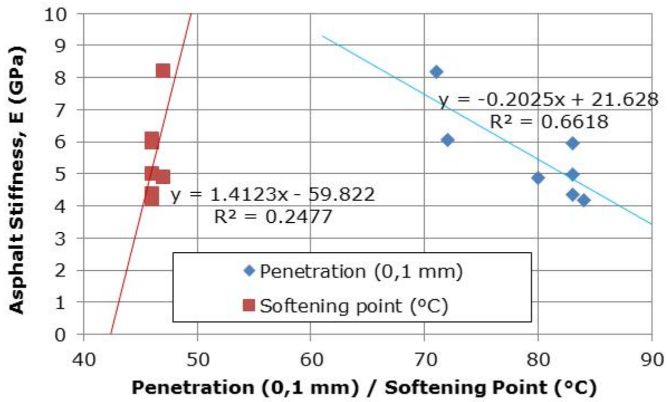


Figure 0-24: Stiffness moduli relative to traditional binder properties for cores after one year in the road from Nordgren and Olsson

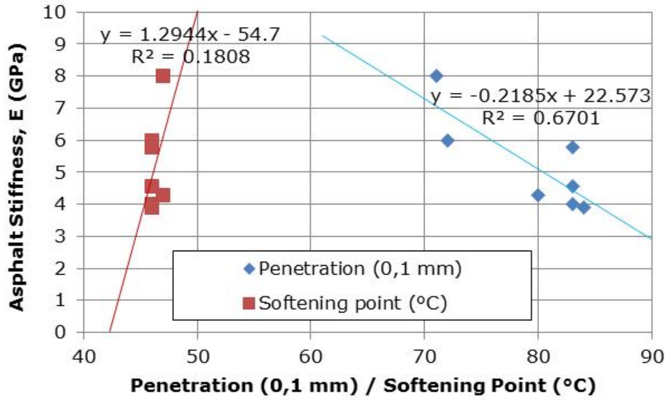


Figure 0-25: Stiffness moduli relative to traditional binder properties for cores after one year in the road and seven day conditioning from Nordgren and Olsson

Olard *et al*. (2012 Paper 024) compared a mixture with two paving grade bituminous binders and two polymer-modified bituminous binders. The stiffness moduli at 15 °C and 10 Hz relative to the traditional binder properties are shown in Figure 0-26.

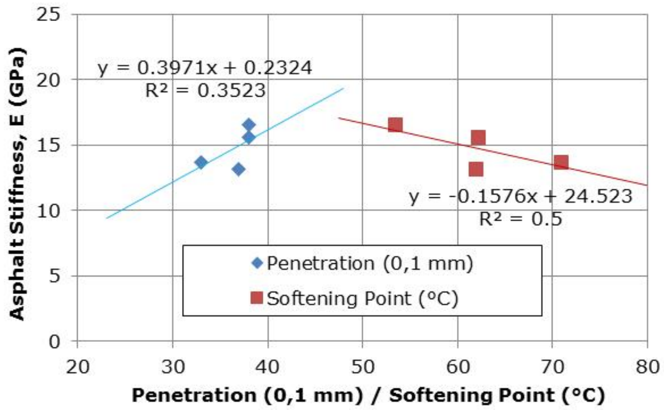


Figure 0-26: Stiffness moduli relative to traditional binder properties from Olard *et al.*

Pap (2010, Paper 544) studied an AC 11 mixture with four binders, two paving grade bitumen and two polymer-modified bituminous binders. The stiffness modules at 20 °C and 1,28 Hz relative to the traditional binder properties are shown in Figure 0-27.

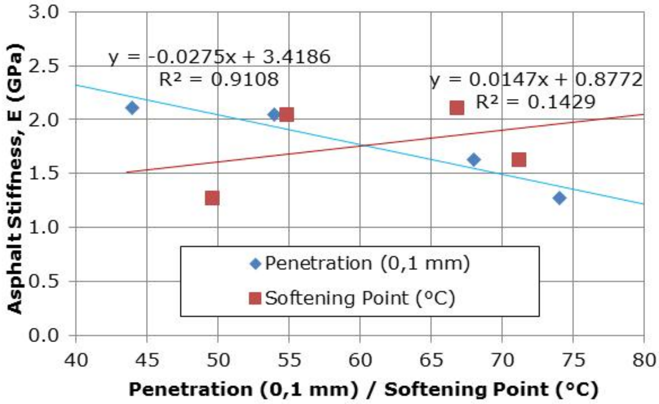
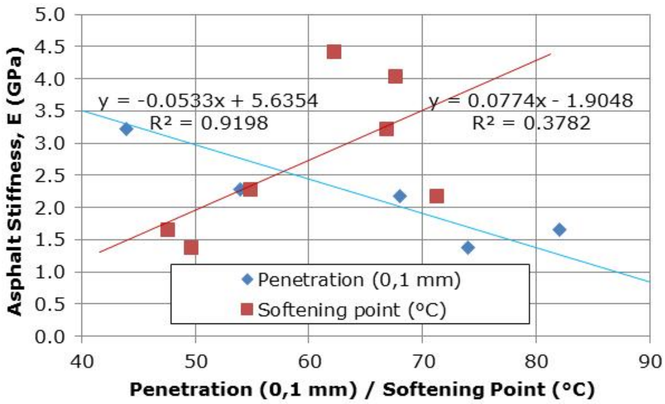
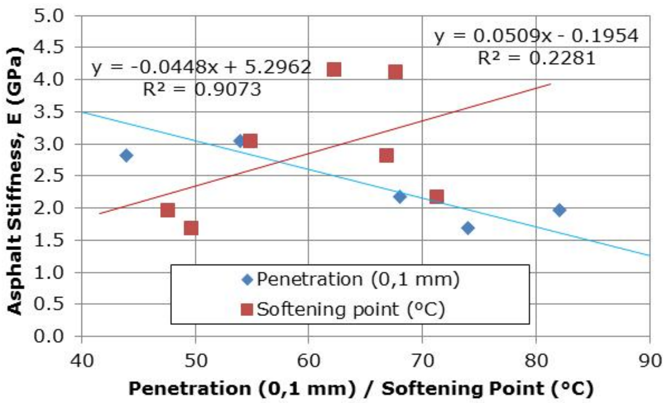


Figure 0-27: Stiffness moduli relative to traditional binder properties from Pap

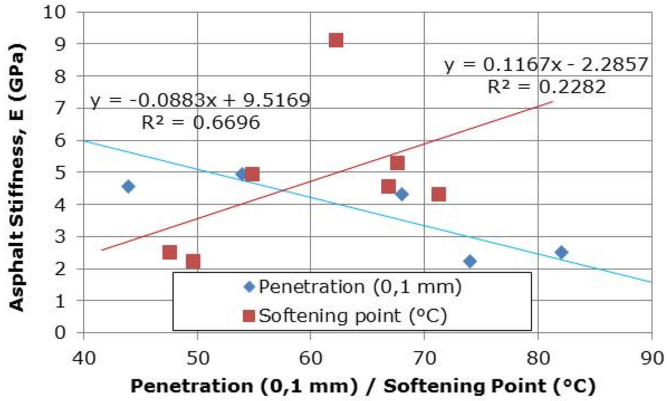
Sybilski *et al*. (2009, Paper 504) studied seven binders (three paving grade and four polymer-modified bituminous binders) in four mixtures. The stiffness moduli gained by IT-CY method at 15 °C relative to the traditional binder properties are shown in Figure 0-28(a) to (d) for the four mixtures.



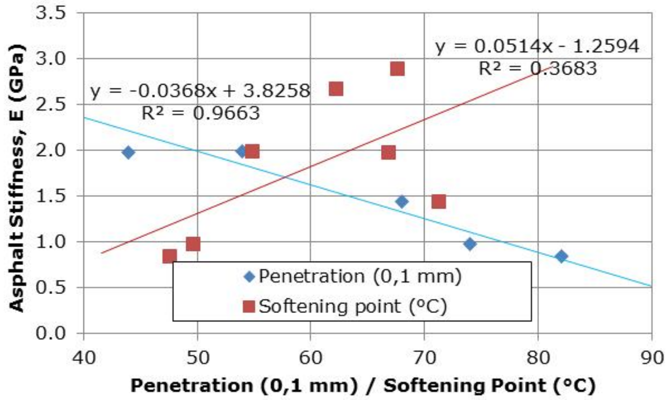
(a) Stone mastic asphalt with basalt aggregate



(b) Asphalt concrete with basalt aggregate



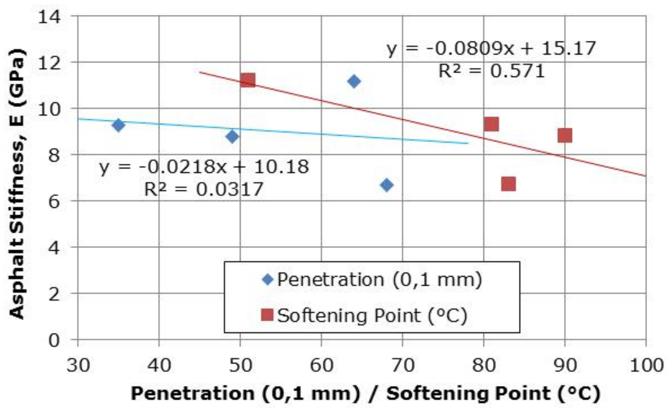
(c) Asphalt concrete with limestone aggregate



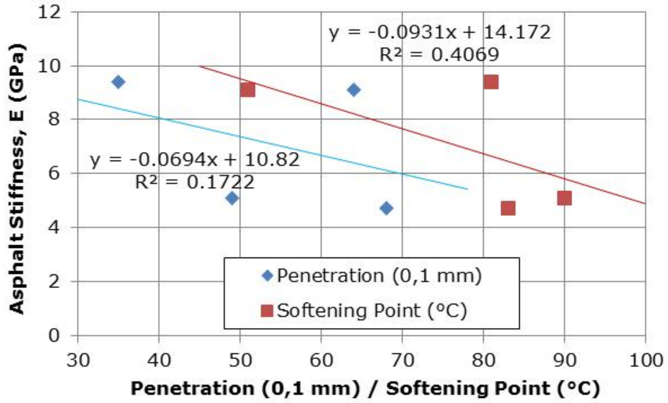
(d) Porous asphalt with basalt aggregate

Figure 0-28: Stiffness modules relative to traditional binder properties from Sybilski *et al.*

Sybilki *et al*. considered that the stiffness modulus correlated fairly well with the penetration test, but that the coefficients were different for different mixtures, whereas the biggest difference was shown for AC mixture with basalt or limestone aggregate. In general the “a” parameter of the linear regression is between -0,037 (PA mixture) and -0,88 (AC mixture, limestone). In all mixtures the same types of selected bituminous binders were used.



(a) HMAC 16 mixture

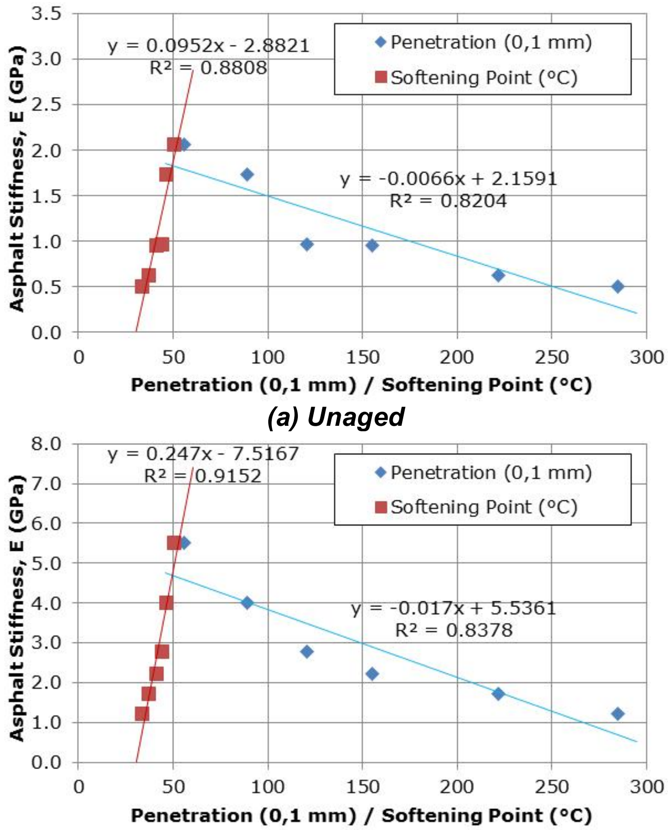


(b) SMA 16 mixture

Figure 0-29: Stiffness moduli relative to traditional binder properties from Racantel *et al*.

Racanel *et al*. (2010, Paper 479) studied four binders (one paving grade and three polymer-modified bituminous binders) in two mixtures of AC16 and SMA16. The stiffness moduli relative to the traditional binder properties are shown in Figure 0-29(a) and (b).

The negative slope for softening point trend line is unexpected, but the trend line for the two traditional binder properties has a correlation coefficient, R^2, of only 0,16 so that opposite signed trend lines against other properties is not certain.

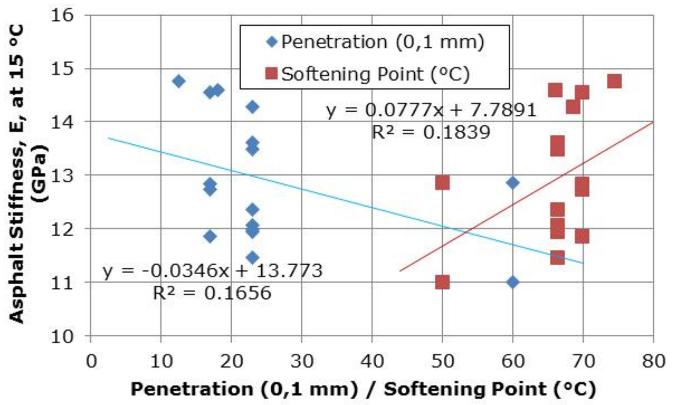


(b) Aged

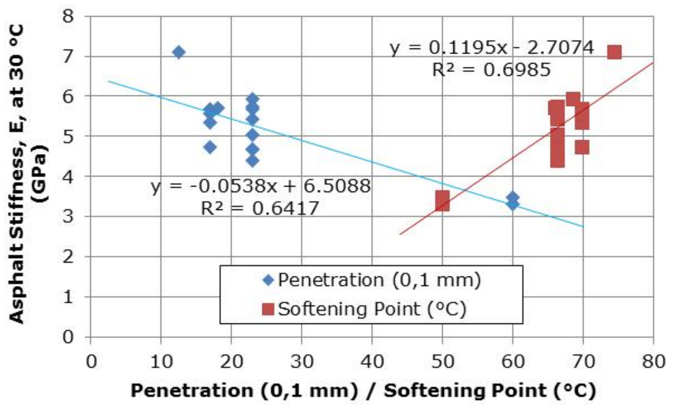
Figure 0-30: Stiffness modules relative to traditional binder properties from Cope *et al*.

Cope *et al.* (2007, Paper 022) studied a mixture with 40/60 paving grade bitumen modified by groundnut cooking oil in 2 % increments from 0 % to 10 % by mass. The stiffness moduli relative to the traditional binder properties are shown in Figure 0-29(a) and (b) for the aged and unaged samples.

de Visscher *et al*. (2008, Paper 074) measured the stiffness of a series of mixtures at both temperatures 15 °C and 30 °C and a frequency of 10 Hz. The traditional properties of the four polymer-modified bituminous binders were reported but not those of the two (hard) paving grade bituminous binders, for which mid-range values had to be assumed. The stiffness moduli relative to the traditional binder properties are shown in Figure 0-31, although the correlations are weaker than would otherwise be the case because there is not a consistent mixture design with different binder properties.



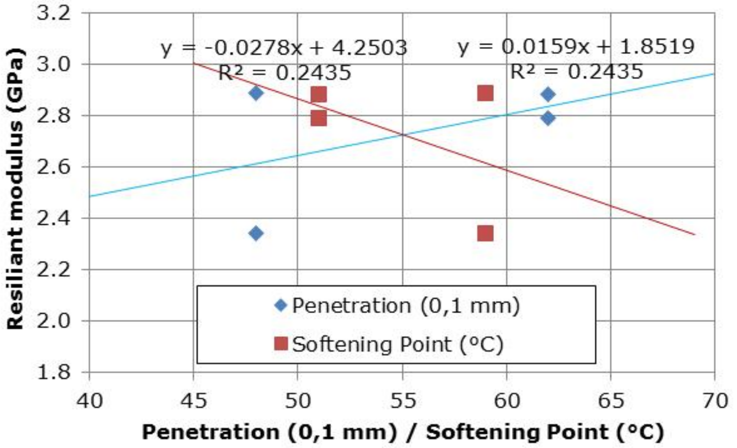
(a) 15 °C temperature



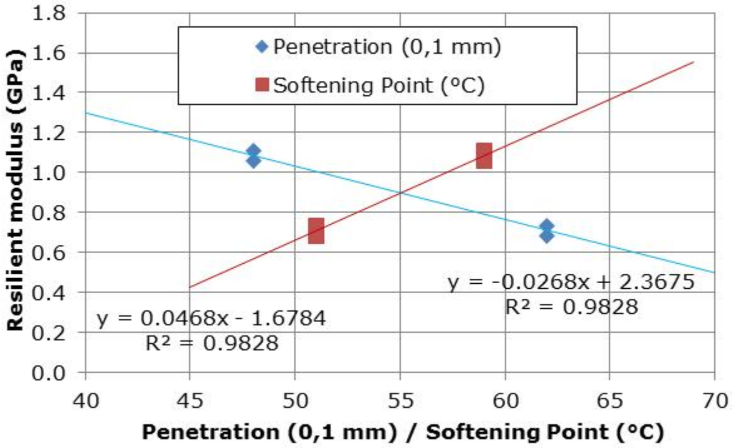
(b) 30 °C temperature

Figure 0-31: Stiffness moduli relative to traditional binder properties from de Visscher *et al.*

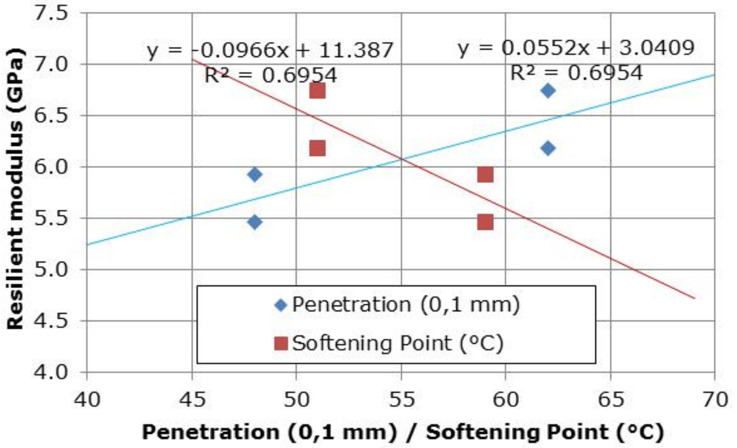
Kamal *et al*. (2010, Paper 049) studied one paving and one polymer-modified bitumen in two mixtures, but measured the resilient modulus at a range of temperatures and stresses. The resilient moduli relative to the traditional binder properties are shown in Figure 0-28(a) to (d) for four different combinations of temperature and stress.



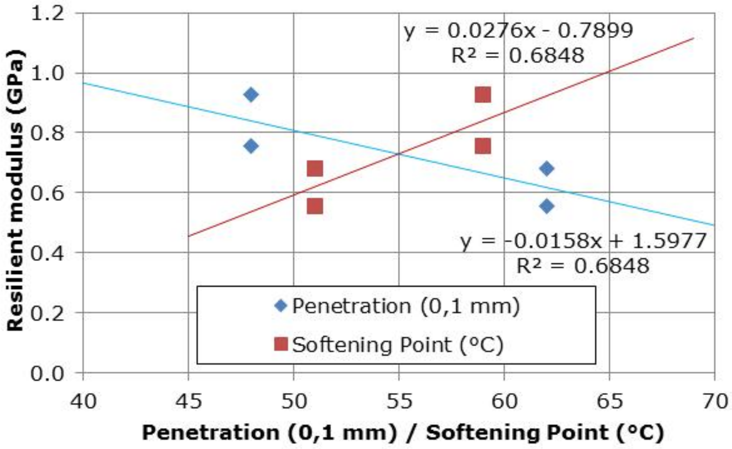
(a) 25 °C temperature and 100 kPa stress level



(b) 55 °C temperature and 100 kPa stress level



(c) 25 °C temperature and 500 kPa stress level



(d) 55 °C temperature and 500 kPa stress level

Figure 0-32: Stiffness modules relative to traditional binder properties from Kamal *et al.*

Similarly an example can be given base on the research WMA study of Valentin et al. (2009, Paper 392) for 3 types of used additives which were premixed to the 50/70 paving grade and used in the same type of asphalt concrete.

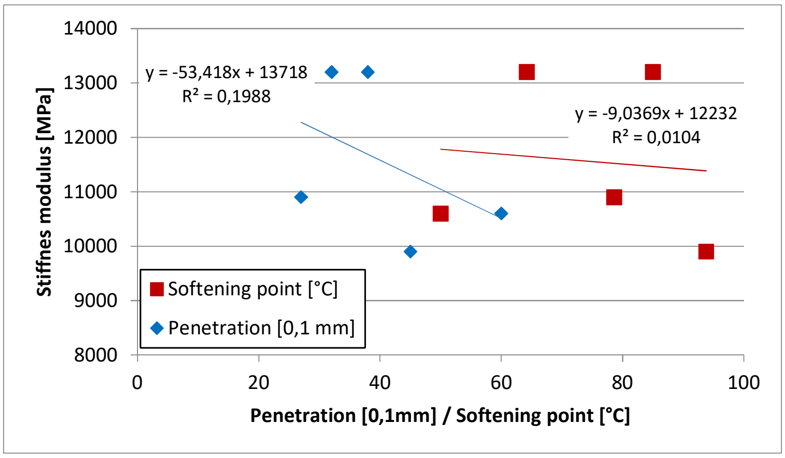


Figure 0-33: Stiffness modules relative to traditional binder properties in a WMA from Valentin *et al.*

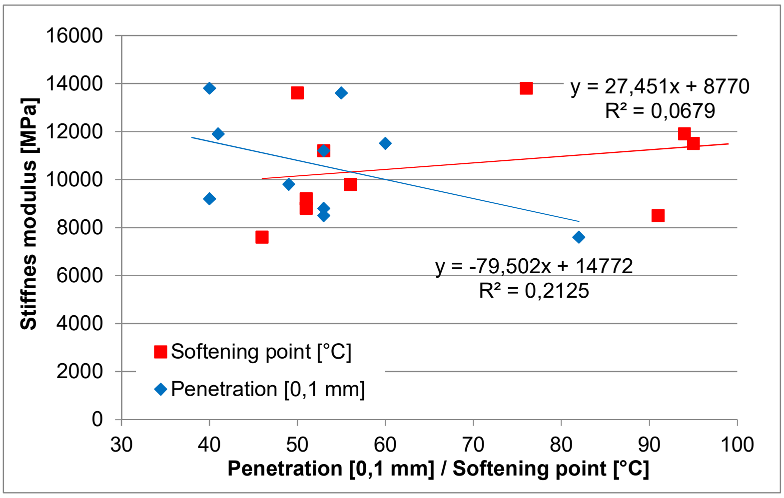


Figure 0-34: Stiffness modules relative to traditional binder properties

Valentin et al. (2011, Paper 382) focused in their paper on research results done in the field of warm mix asphalts. Two different asphalt concrete mixtures were used together with ten bituminous binders doped by selected warm mix additives. Basis were 50/70 and 70/100 binders. From these results for softening point and penetration the correlation with asphalt stiffness (IT-CY) does not work well. Nevertheless penetration provides again better correlation coefficient than the softening point.

Radenberg et al. from the University in Bochum published measurements on a series of ten bituminous binders (Radenberg, 2012). In the tested set of bituminous binders traditional paving grade bitumen as well as PMBs and binders with wax based additives were represented. The basic correlation focused on comparison of complex shear modulus and the S-value gained from the low-temperature range test on bending beam rheometer (see Figure 0-28). Besides this it was looked for a possible correlation between complex shear modulus and the penetration of bitumen. The found results are for the tested set presented in the Figure 0-28 and the results show a good agreement of exponential functionality between |G*| tested at 20 °C and traditional penetration test at 25 °C. There were no additional comparability studies between bitumen and asphalt mixture.

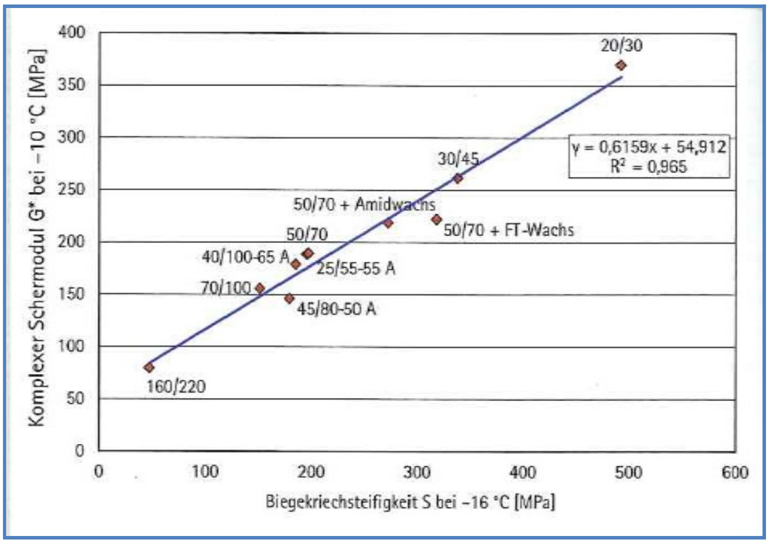


Figure 0-35: Correlation between complex shear modulus G* at -10 °C (y-axis) and bending stiffness S at -16 °C (x-axis) from Radenberg *et al.*

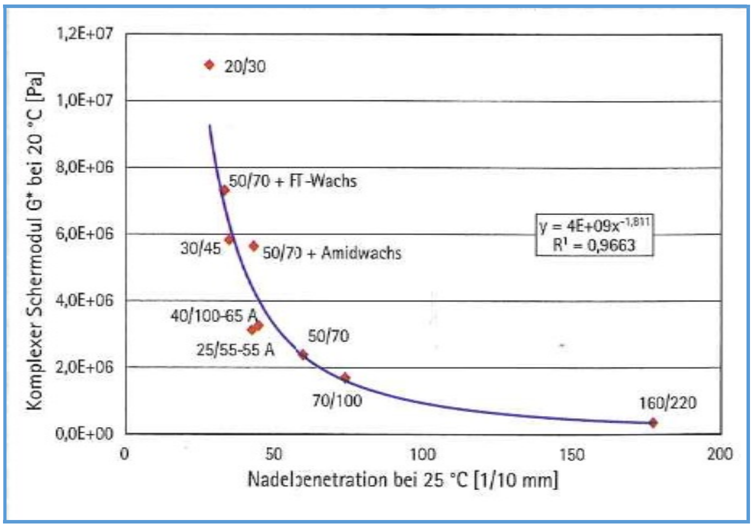


Figure 0-36: Correlation between bitumen complex shear modulus G* at 20 °C (y-axis) and the value of penetration at 25 °C (x-axis) from Radenberg *et al.*

Ádorjanyi et al. focused on their paper (Ádorjanyi, 2012) on correlations between penetration index and rheological characteristics which can be obtained on DSR for regular testing of complex shear modulus G*. The found correlations between particular characteristics are given in Table 0-3. They can be further compare with similar research which was reporter in 2005 by Soenen et al. and is presented either for paving grade binders or for PMBs in Table 0-3 and Table 0-3.

Table 0-6: Group correlations between penetration index and particular rheological characteristics obtained by DSR testing (20 °C, 20 Hz) paving grade binders, (Ádorjanyi, 2012)

Rheological characteristic	Correlation equation	R^2
Complex viscosity [Pa·s]	|η*| = 175441*(*PI*)+280694	0,8810
Imaginary part of complex viscosity [Pa·s]	η" = 161447*(*PI*)+223310	0,9029
Real part of complex viscosity [Pa·s]	η' = 77538*(*PI*)+164623	0,7931
|G*|/sinδ	*G**/(sin *δ)* = 23,63*(*PI*)+31,13	0,9091
Elastic (storage) modulus [MPa]	*G*' = 10,13*(*PI*)+14,03	0,9026
Viscous (lost) modulus [MPa]	*G*" = 4,871*(*PI*)+10.345	0,7935
Complex shear modulus [MPa]	|*G**|=11,019*(*PI*)+17,643	0,8804
Phase angle [°]	δ = 43,575-9,5459*(PI)	0,7812

Table 0-7: Mutual group correlations of the penetration index and particular rheological characteristics obtained by DSR testing, paving grade binders, (Soenen et al., 2005)

Coefficient R^2	Logarithmic functionality						Temperature	
	ZSV 0,001 Hz	G*/sin(δ) 0,001 Hz	G*/sin(δ) 1,59 Hz	RCT 25 Pa J_{nr}	RCT 300 Pa J_{nr}	Static Creep J	PG Grade	KK
	(Pa.s)	(Pa)	(Pa)	(Pa^{-1})	(Pa^{-1})	(Pa^{-1})	(°C)	(°C)
Log (PEN@25 °C)	0,94	0,94	0,96	0,94	0,95	0,94	0,94	0,96
R&B (°C)	0,98	0,98	0,98	0,98	0,98	0,98	0,95	1,00
PG Grade (°C)	0,97	0,97	0,99	0,98	1,00	1,00	1,00	0,95

Table 0-8: Mutual group correlations of the penetration index and particular rheological characteristics obtained by DSR testing, paving grade binders, (Soenen et al., 2005)

Coefficient R^2	Logarithmic functionality					
	ZSV 0,001 Hz	G*/sin(δ) 0,001 Hz	G*/sin(δ) 1,59 Hz	RCT 25 Pa J_{nr}	RCT 300 Pa J_{nr}	Static Creep J
	(Pa.s)	(Pa)	(Pa)	(Pa^{-1})	(Pa^{-1})	(Pa^{-1})
LSV osc. @ 0,001 Hz	1,0	0,94	0,02	0,99	0,77	0,94
G*/sin(δ) @ 0,001 Hz	-	1,00	0,03	0,94	0,75	0,92
G*/sin(δ) @ 1,59 Hz			1,00	0,02	0,00	0,01
RCT @ 25 Pa				1,00	0,75	0,96
RCT @ 300 Pa					1,00	0,80
Static creep						1,00
Upper PG temperature	0,46	0,49	0,21	0,50	0,09	0,31
Log (PEN@25 °C)	0,00	0,00	0,85	0,00	0,00	0,10
Softening point (°C)	0,53	0,51	0,25	0,59	0,19	0,47

Further, it is possible to report on papers where the coherence and correlations between complex shear modulus of DSR test and bitumen stiffness modulus derived according to van der Poel nomogram have been evaluated. Calculation of bitumen stiffness modulus $S_{bitpen\text{-}R\&B}$ according to Van der Poel is a very old and well known method (Van der Poel, 1954). It is based on empirical nomographs which are derived from input values of bitumen penetration and softening point. Van Poel worked for Shell company, which used his approach and transformed it to a more sophisticated form of a computer-aided tool called „Shell-Band“, (Shell, 2000). After setting input data it is possible to calculate stiffness modulus of a bituminous binder, which is defined as $S_{bitpen\text{-}R\&B}$. Complex modulus E^*_{bit} which is determined by DSR for an incompressible fluid (Poisson value = 0,5) has a simple relationship with complex shear modulus according to the following equation (2):

$$|E^*_{bit}| = 3 \cdot |G^*| \quad (2)$$

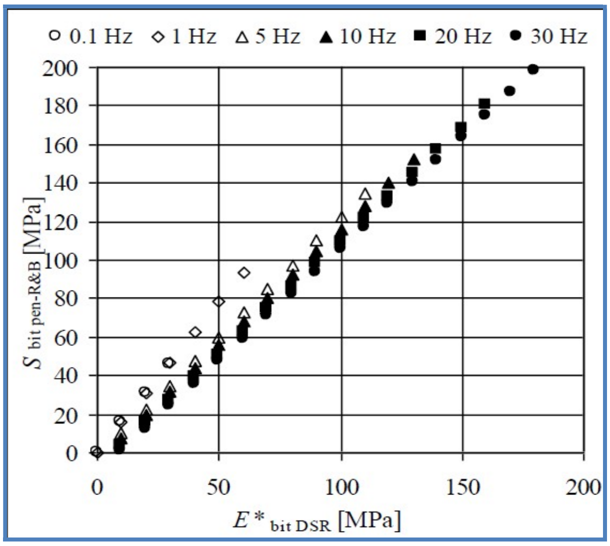


Figure 0-37: Stiffness modulus according to Van der Poel nomogram vs. complex modulus E^*_{bit} (20 °C, f = 0,1-30 Hz), PMBs

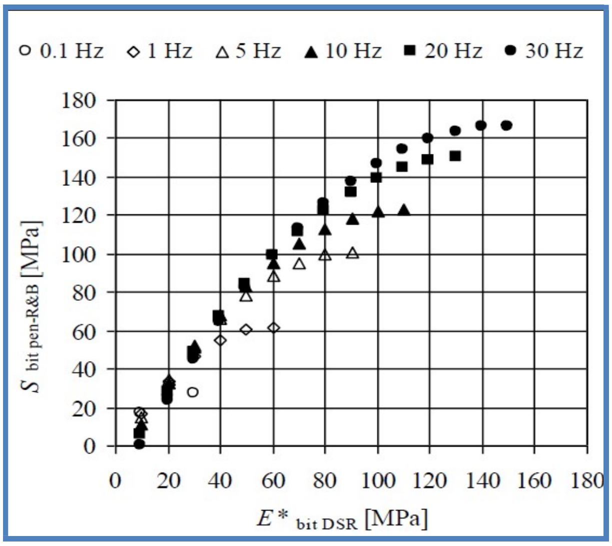


Figure 0-38: Stiffness modulus according to Van der Poel nomogram vs. complex modulus E^*_{bit} (20 °C, f = 0,1-30 Hz), paving grades

The correlation between $S_{bitpen-R\&B}$ and E^*_{bit} (T = 20°C, f = 0,1-30 Hz) is a polynomic function in case of paving grade bituminous binders following the equation (3). The interval of correlation coefficient value is R^2 = 0,9284-0,9701.

$$Y = a + b \cdot X + c \cdot X^2 \qquad (3)$$

Overall, the correlations found from all these studies are combined into Table 0-3 for penetration and Table 0-10 for softening point.

Table 0-9: Correlations found between binder penetration and asphalt stiffness

Paper		Data sets	Coefficient	Constant	R^2
Single aggregate grading, paving grade binders					
Nordgren and Olsson	1 year	7	-0,2025	21,6280	0,662
	plus cond.	7	-0,2185	22,5730	0,670
Single aggregate grading, polymer-modified and paving grade bituminous binders					
Olard *et al.*		4	0,3971	0,2324	0,352
Pap		4	-0,0275	3,4186	0,911
Sybilski *et al.*	SMA basalt	7	-0,0533	5,6354	0,920
	AC basalt	7	-0,0448	5,2962	0,907
	AC limestone	7	-0,0883	9,5169	0,670
	PA basalt	7	-0,0368	3.8258	0,966
Thives *et al.*	AC 16	4	-0,0218	10,180	0,032
	SMA 16	4	-0,0694	10,820	0,172
Cope *et al.*	Unaged	6	-0,0066	2.1591	0,820
	Aged	6	-0,0170	5,5361	0,838
Multiple aggregate gradings					
de Visscher *et al.*	15 °C	16	-0,0346	13,773	0,166
	30 °C	16	-0,0538	6,5088	0,642
Kamal *et al.*	25 °C, 100 kPa	4	0,0278	4,2503	0,244
	55 °C, 100 kPa	4	-0,0268	2,3675	0,983
	25 °C, 500 kPa	4	0,0552	3,0409	0,695
	55 °C, 500 kPa	4	-0,0158	1,5977	0,685

Table 0-10: Correlations found between binder softening point and asphalt stiffness

Paper		Data sets	Coefficient	Constant	R^2
Single aggregate grading, paving grade binders					
Nordgren and Olsson	1 year	7	1,4123	-59,8220	0,248
	plus cond.	7	1,2944	-54,7000	0,181
Single aggregate grading, polymer-modified and paving grade bituminous binders					
Olard *et al.*		4	-0,1576	24,5230	0,500
Pap		4	0,0147	0,8772	0,143
Sybilski *et al.*	SMA basalt	7	0,0774	-1,9048	0,378
	AC basalt	7	0,0509	-0,1954	0,228
	AC limestone	7	0,1167	-2,2857	0,228
	PA basalt	7	0,0514	-1,2594	0,368
Thives *et al.*	AC 16	4	-0,0809	15,1700	0,571
	SMA 16	4	-0,0931	14,1720	0,407
Cope *et al.*	Unaged	6	0,0952	-2,8821	0,881
	Aged	6	0,2470	-7,5167	0,915
Multiple aggregate gradings					
de Visscher *et al.*	15 °C	16	0,0777	7,7891	0,184
	30 °C	16	0,1195	-2,7074	0,699
Kamal *et al.*	25 °C, 100 kPa	4	-0,0278	4,2503	0,244
	55 °C, 100 kPa	4	0,0468	-1,6784	0,983
	25 °C, 500 kPa	4	-0,0966	11,3870	0,695
	55 °C, 500 kPa	4	0,0276	-0,7899	0,685

The weighted mean correlation coefficient, R^2, (excluding the multiple aggregate gradings, for which additional factors are influencing the resulting relationships) from the analyzed studies is 0,71 for penetration and 0,41 for softening point. It is interesting to note that when the Nordgren and Olsson data with additional parameter of ageing are excluded as well, these values increase marginally to 0,72 for penetration and 0,46 for softening point. Therefore, it would appear that there is a good correlation with penetration and a less good one with softening point. However, these correlations are not that good because Oland *et al.* found a positive slope for penetration and a negative one for softening point, implying that the stiffness of the asphalt increases as the binder gets less viscous, which is counter intuitive. However, that this relationship is supported by Kamal *et al.*, who found the trend lines for the asphalt resilient modulus had a positive slope for penetration and a negative one for softening point when tested at 25 °C but the reverse at 55 °C.

2.6 PG grading

No additional papers specific for PG grading and comparison of asphalt stiffness and PG grades have been found additionally to the information provided within the data reviewed in BitVal project.

2.7 *Predictive models of asphalt stiffness*

The concept of models to predict the asphalt mix behavior makes use of multiple parameters but are more general in that the estimates are not restricted to a single mixture with different binders. The most commonly used predictive models are shown in Table 0-11 (Pellinen *et al.*, 2007, Paper 188).

Table 0-11: Most used stiffness predictive models

Model	Predicted	Predictor variables	Sample preparation	Temperature range (°C)
Shell Model	S_m [1]	S_b [2], Vol.[3]	Lab-no ageing; slab compactor	(-15) – 30
Asphalt Institute	$\|E^*\|_{mix}$	λ [4], Vol.	Lab-no ageing; kneading	5 – 40
Witczak (1996)	$\|E^*\|_{mix}$	η [4], Vol. Grad.[5]	Lab-no ageing; kneading	5 – 40
Witczak (1999)	$\|E^*\|_{mix}$	η Vol. Grad.	Lab-no ageing; kneading & gyratory	(-15) – 54
Witczak (2006)	$\|E^*\|_{mix}$	$\|G^*\|_{binder}$, Vol. Grad.	Lab–STOA[7]; Plant, mostly gyratory	(-15) – 54
Hirsch (2003)	$\|E^*\|_{mix}$ $\|G^*\|_{mix}$	$\|G^*\|_{binder}$, Vol.	Lab-STOA; mostly gyratory	(-10) – 54
2S2P1D	$\|E^*\|_{mix}$ $\|E^*\|_{binder}$	τ [6]	Lab-no ageing; slab compactor	(-30) – 45
Global-DB	$E^*\|_{mix}$	E_{0_mix}, E_{inf_mix}	Lab-no ageing; slab compactor	(-30) – 45

NOTE: [1] S_m is $|E^*|_{mix}$, [2] S_b is $|E^*|_{binder}$, [3] Vol. stays for Volumetrics, [4] binder viscosity, [5] gradation, [6] characteristic time, [7] short-term ageing

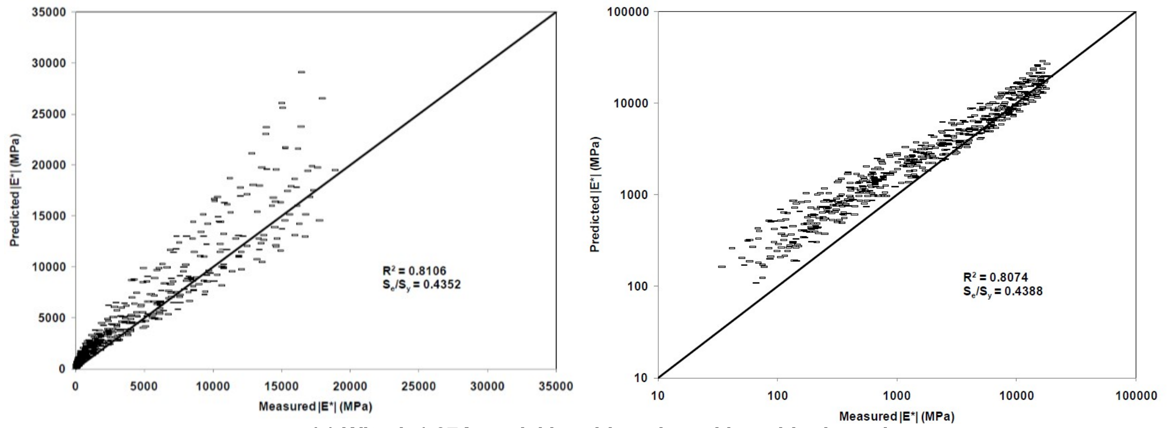
Zelelew *et al.*, (2012, Paper 128) used three of these models (Witczak 1-37A, Witczak 1-40D and Hirsch) that were developed for HMA mixtures to estimate the stiffness of WMA mixtures. The inputs for the models include:

- Witczak 1-37A model – Mixture volumetrics (air voids content and effective binder content), four aggregate gradations (0,075 mm, 4,76 mm, 9,5 mm and 19 mm sieves), binder viscosity and loading frequency.
- Witczak 1-40D model – Similar to the Witczak 1-9 37A model except the binder viscosity and loading frequency parameters are replaced by the binder shear modulus |G*| and the binder phase angle.
- Hirsch model – The binder |G*|, voids in mineral aggregates, and voids filled with asphalt. The loading frequency of the binder is the same as that for the mixture.

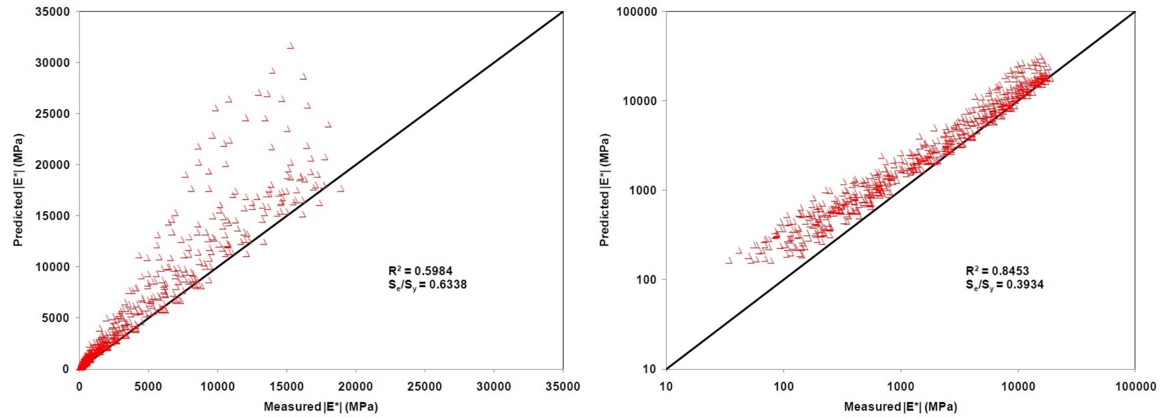
Figure 0-39 presents a comparison of laboratory measured and predicted |E*| using the three models in arithmetic and logarithmic scales. A total of 570 data points were used for mixtures tested at four temperatures and six loading frequencies. Over-prediction of |E*| was observed for the Witczak 1-37A and 1-40D models, with the over-prediction being pronounced with higher modulus values that correspond to the asphalt being tested at high loading frequencies and low test temperatures. In the logarithmic scale, the correlations for the predicted |E*| were:

- Hirsch model R^2 = 0,9005 S_e/S_y (error) = 0,3154;
- Witczak 1-40D model R^2 = 0,8453 S_e/S_y (error) = 0,3934;
- Witczak 1-37A model R^2 = 0,8074 S_e/S_y (error) = 0,4388.

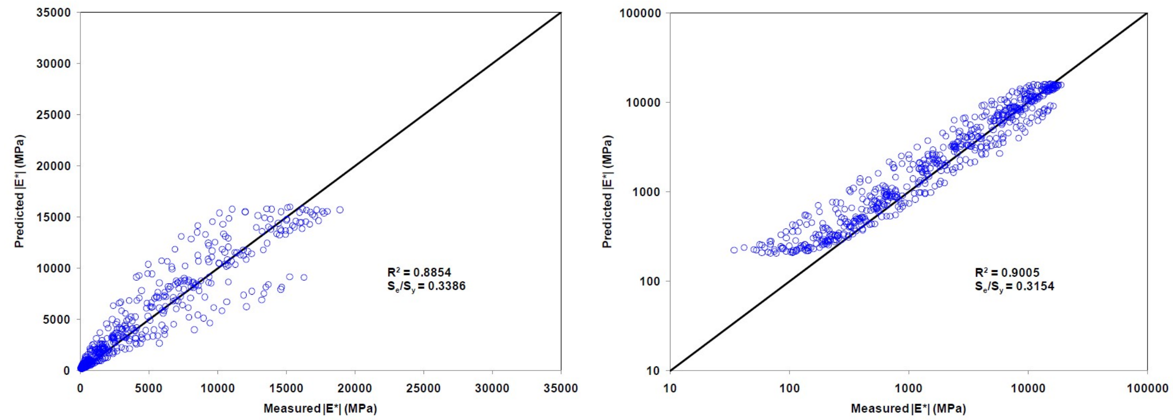
Better predictions were obtained using the Witczak 1-37A model following the Hirsch model when the arithmetic scale is considered. These findings are consistent with the model developers with high correlation coefficient and low error in logarithmic scale for the Witczak 1-40D and Hirsch models.



(a) Witzak 1-37A model in arithmetic and logarithmic scales



(b) Witzak 1-40D model in arithmetic and logarithmic scales



(c) Hirsch model in arithmetic and logarithmic scales

Figure 0-39: Comparison of measured and predicted |E*|; (Zelelew *et al.*, 2012, Paper 128)

A study (Pellinen *et al*., 2007, Paper 188) compared the models by Di Benedetto *et al*. (DB), Witczak and Hirsch using two sets of asphalt dynamic modulus |E*| and binder complex shear modulus |G*| test data from FHWA-ALF and MnROAD studies. Predictions were made using Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) aged binder data. Binder modulus was converted to viscosity using existing empirical conversion equations. The results indicated that all three models can be used to estimate the mixture stiffness when certain conditions are met.

Figure 0-40 summarizes the predictions for all mixtures and models studied. Overall, the most accurate and least variable predictions are produced by the Hirsch model, which is logical because ALF mixtures were included into the calibration dataset of the Hirsch model. However, Hirsch model seems to over-predict at high temperatures where the prediction seems to be confined by the static modulus of the model. Global DB model rotates round the equality line and over- and under-predicts the mixture stiffness.

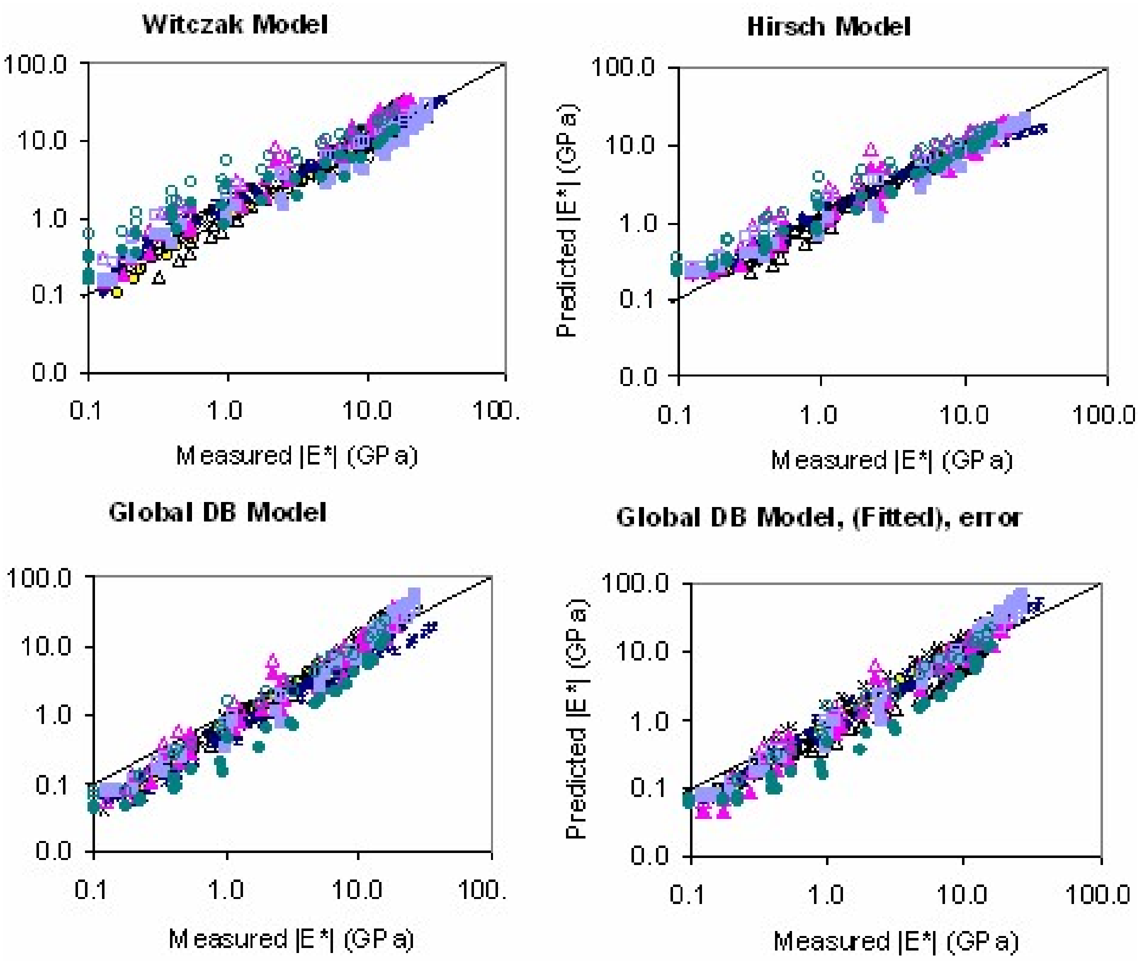
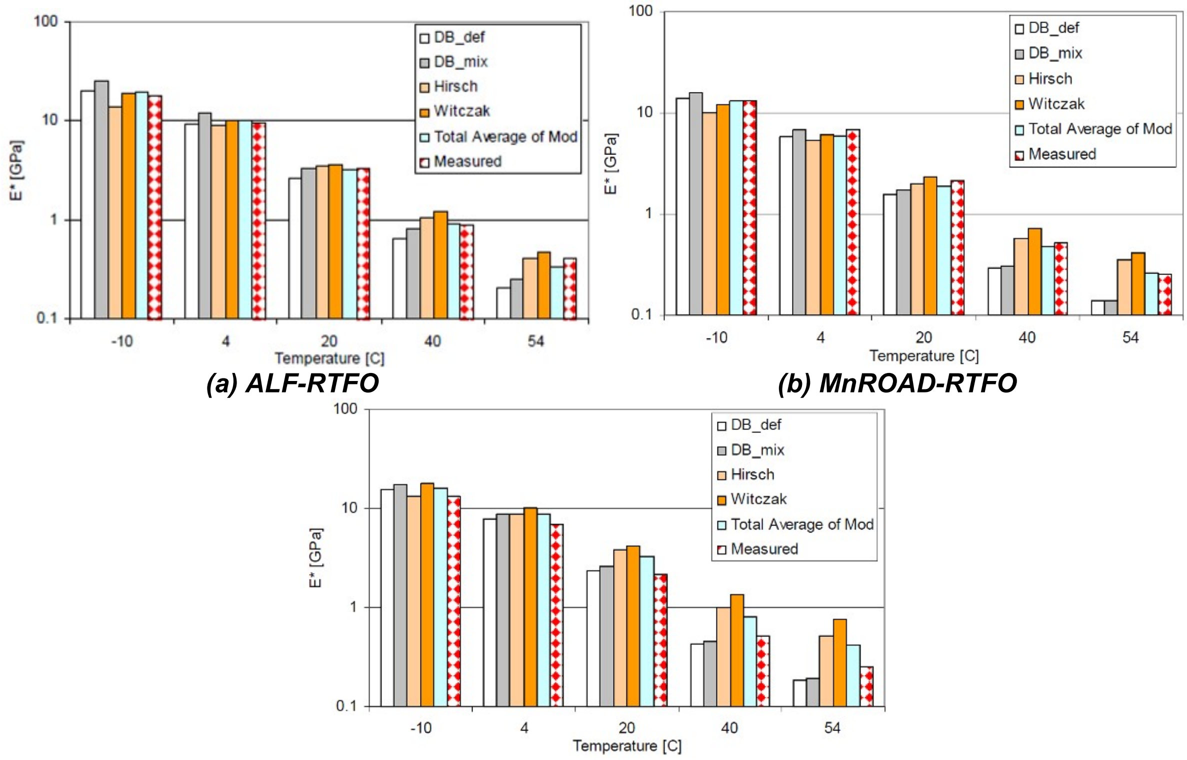


Figure 0-40: Stiffness predictions from Pellinen *et al.*

Figure 0-41 compares the predicted modulus values to the measured values for all the models at all temperatures. All the models gave comparable predictions overall as far as magnitude, but at higher temperatures, the DB model deviated substantially from the Hirsch and Witczak models. For the RTFO-MNROAD and PAV-MNROAD data, the DB model starts to underpredict at 20 °C. Generally, the DB underpredicted, and the Hirsch and the Witczak models overpredicted the stiffness. The DB model had lower variation in the predictions at high temperatures, and the predictions are somewhat lower than the measured values in contrast to the Witczak and Hirsch models which are overpredicting the stiffness.



(a) ALF-RTFO

(b) MnROAD-RTFO

(c) MnROAD-PAV

Figure 0-41: Comparison of predicted to measured values from Pellinen *et al*.

One aspect not covered by the models is sample preparation. Laboratory-fabricated and aged mixtures were found (Pellinen *et al*., 2007, Paper 188), on average, to be 30 % stiffer than plant produced asphalt mixtures compacted in the laboratory and up to 65 % stiffer than asphalt pavement cores. However, the variation between mixtures was large and mixture-type dependent (Table 0-12).

Table 0-12: Average adjustment factors for mixture stiffness

Mix Type	Raw – Plant	Plant – 1st coring	Raw – 1st coring	2nd forint – 1st coring
AC	1,36	1,25	1,77	1,68
SMA	1,14	1,38	1,51	1,31
All	1,26	1,31	1,65	1,52

The complex modulus of an asphalt mixture can be calculated using a function that includes the ratio of the volume of dry aggregates to the volume of binder, air voids content, and the complex modulus of the bituminous binder (Francken and Vanelstraete, 1996). Vervaecke *et al*. (2008, Paper 497) reported that the stiffness of bitumen can be determined with DSR measurements or can be estimated from its conventional properties by means of Van der Poel's nomogram (VDP). The stiffness of an asphalt mixture can be estimated with a series of empirical relations in which mix composition and the complex modulus of the bituminous binder is considered (Francken and Vanelstraete, 1996):

$$\left|E^*\right|(T,f) = E_\infty \cdot R^*(T,f) \tag{4}$$

The stiffness, G*, of the binder was measured (Vervaecke *et al*., 2008, Paper 497) by DSR and the pure elastic modulus of the bitumen $E^*_{\infty,bit}$ was determined as the asymptotic value of E^*_{bit} towards low X values (low temperatures, high frequencies) together with the Arrhenius relation to determine a master curve from DSR measurements performed on the bituminous binder. The stiffness modulus E* of the asphalt mixtures was measured with the two-point bending test at various temperatures between -20°C and 30°C applying different loading frequencies between 1 Hz and 30 Hz. The results showed that the various methods are capable to predict the stiffness of a HMA mixture with an accuracy of 15-20 %, except the Van der Poel-Francken method with $E^*_{\infty,bit}$ = 3 000 MPa.

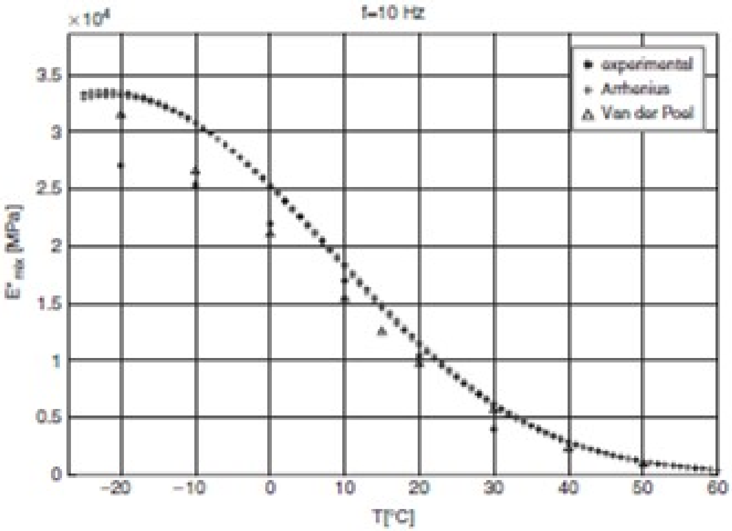


Figure 0-42: Change in bitumen stiffness with temperature

The influence of the skeleton of the asphalt mixture on the accuracy of the stiffness estimation was investigated. No correlation between the skeleton and the accuracy of the stiffness estimation was found (BRRC, 2006).

As interesting might be evaluated data presented by Ali H. (2011, paper 0147). In this case comparison between complex shear modulus of the bitumen and dynamic modulus of the asphalt mixtures were summarized, whereas thy dynamic modulus were

The asphalt material as well as cores were obtained from a hot in-place recycling project. Bitumen was extracted and tested according to the PG-grade specifications, further some modifications have been done to rejuvenate the binder. From the perspective of stiffness correlation recovered blended bitumen was tested at two temperatures in a frequency range of 0,10-100 rad/s. At the same time dynamic modulus was tested on cores according to AASHTO TP61 at 4°C, 20°C and 40°C and frequencies of 0,1; 1 and 10 Hz for each temperature. Based on the testing data, dynamic modulus for laboratory mixtures with blended bitumen was estimated applying Hirsch model. The correlation which can be drawn from the binder complex modulus and estimated mix modulus are given in Figure 0-40 and shows very good functionality of the data (R^2 = 0,9888). Because the authors compared estimated mix modules and measured modules from the cores and found a very good agreement between the data, the correlation can be used to define a possible relation between extracted bitumen and the cores. From the data presented in Figure 0-40 it is possible to summarize that the Hirsch model seems slightly to overestimate the modulus at lower temperatures and underestimate the modulus at the higher temperatures.

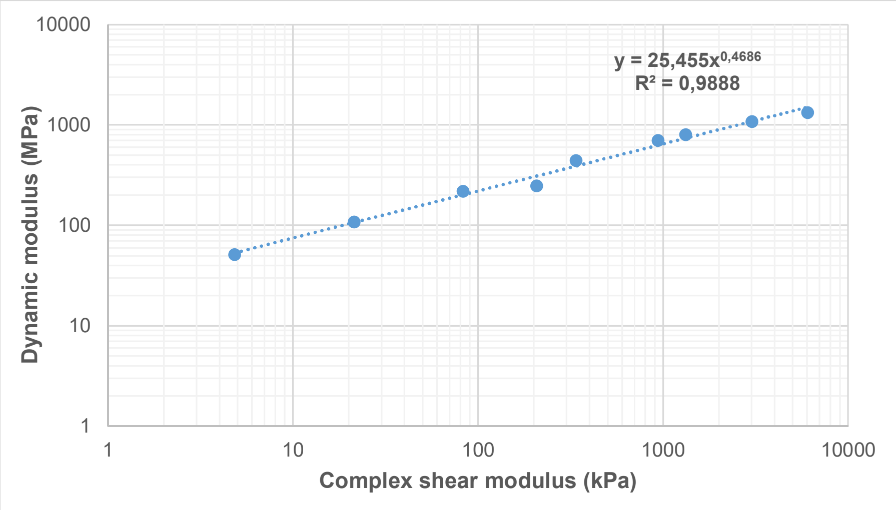


Figure 0-43: Correlation between bitumen complex shear modulus and estimated recycled asphalt mixture dynamic modulus

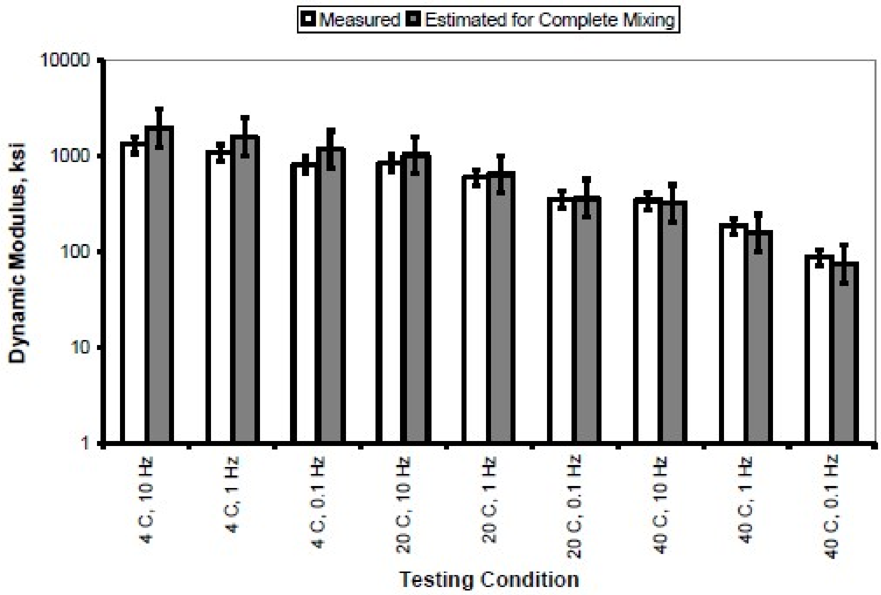


Figure 0-44: Comparison of dynamic modulus of field mixtures (cores) and estimated fully blended laboratory mixtures

Different approach with some correlations between tested and calculated (predicted) values of complex modules can be found in the research done by Pouget et al. (2012, paper 029). The authors investigated forward and inverse problems related to stiffness assessment (Figure 0-40) for materials obtained from paving grade bitumen and polymer modified bitumen. Experimental measurements of bitumen complex shear modulus are performed with a Dynamic Shear Rheometer (DSR), while asphalt mixture complex modulus is measured using the three-dimensional complex modulus test developed at ENTPE.

Prediction of asphalt three-dimensional linear viscoelastic properties from bitumen one-dimensional linear viscoelastic properties is based on the ENTPE SHStS transformation (forward problem). This transformation allows to predict asphalt behavior efficiently from bitumen complex modulus on large frequency and temperature ranges. The same transformation can be applied to obtain bitumen properties from asphalt properties, e.g. if RAP is used and the intention is to predict the properties of bitumen (inverse problem). The prediction tool seems to have a good potential for practical design of bituminous asphalts.

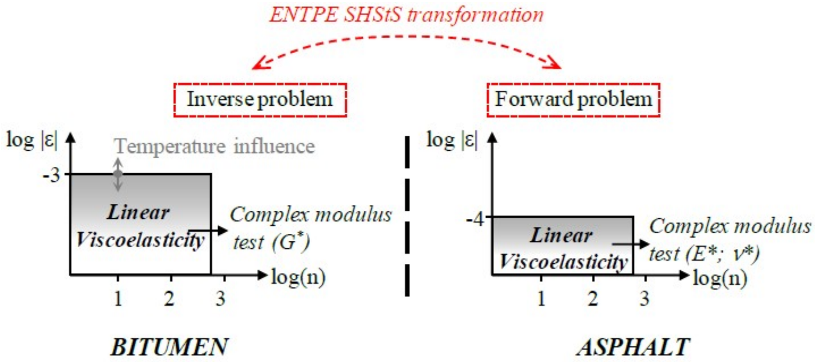


Figure 0-45: Linear viscoelastic domains for bitumen and asphalts in the axes log(strain amplitude)-log(number of cycles)

The transformation is based on the following equation defining the relation between bitumen and asphalt complex modulus.

$$E^*_{asphalt}(\omega,T) = E_{00\_asphalt} + \left[E^*_{bitumen}(10^{\alpha}\omega,T)\text{-}E_{00\_bitumen}\right]\frac{E_{0\_asphalt} - E_{00\_asphalt}}{E_{0\_bitumen} - E_{00\_bitumen}} \quad (5)$$

As was confirmed by the authors, ENTPE SHStS transformation simulates very good complex modulus of asphalt mixture with paving grade bitumen 50/70 from experimental data issued from the bitumen on a large range of frequencies and temperatures (Figure 0-40). For PMBs and asphalt mixtures with this type of binders it can be observed (Figure 0-40) that there is not very well conformity to time-temperature superposition principle at high temperatures. This is an expected result, due to the higher content of polymer. In order not to overload the formalism, the simplification of considering time-temperature superposition principle (TTSP) respected is introduced in the modelling tool. Nevertheless, predicted curves correctly describe the evolution of complex modulus. This observation is particularly valid for low temperatures, where TTSP is well respected.

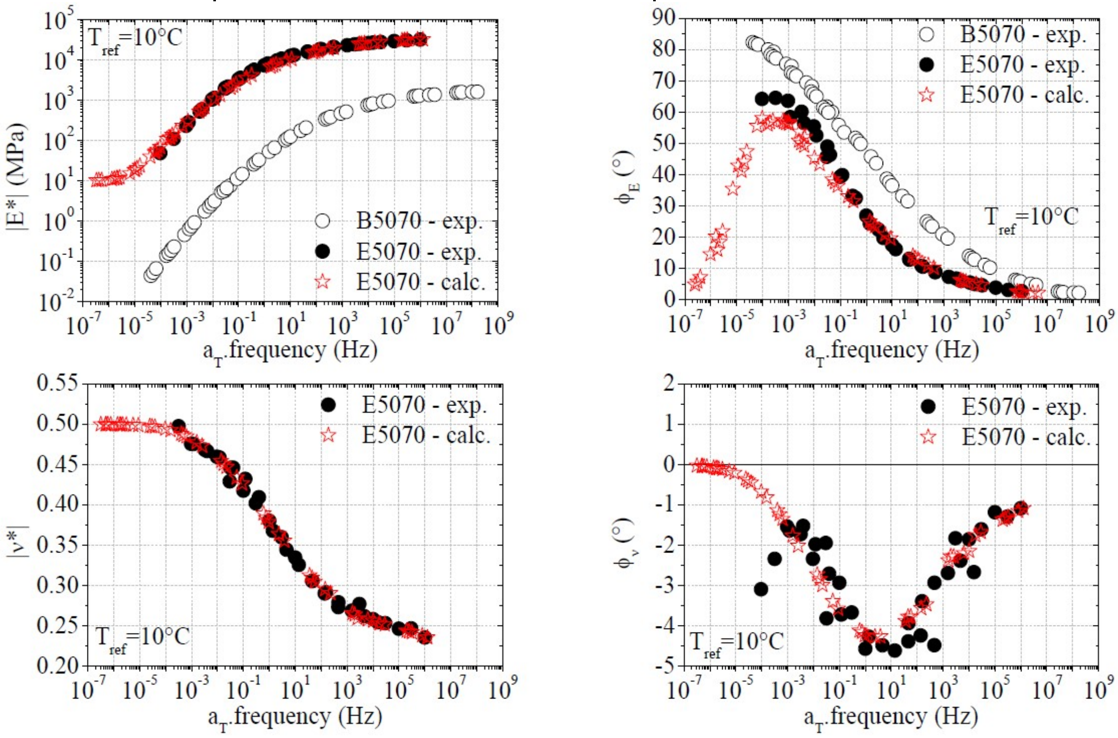


Figure 0-46: Experimental data of complex modulus of asphalt mixture with 50/70 bitumen and prediction of the modulus using equation (5) and data of bitumen complex modulus

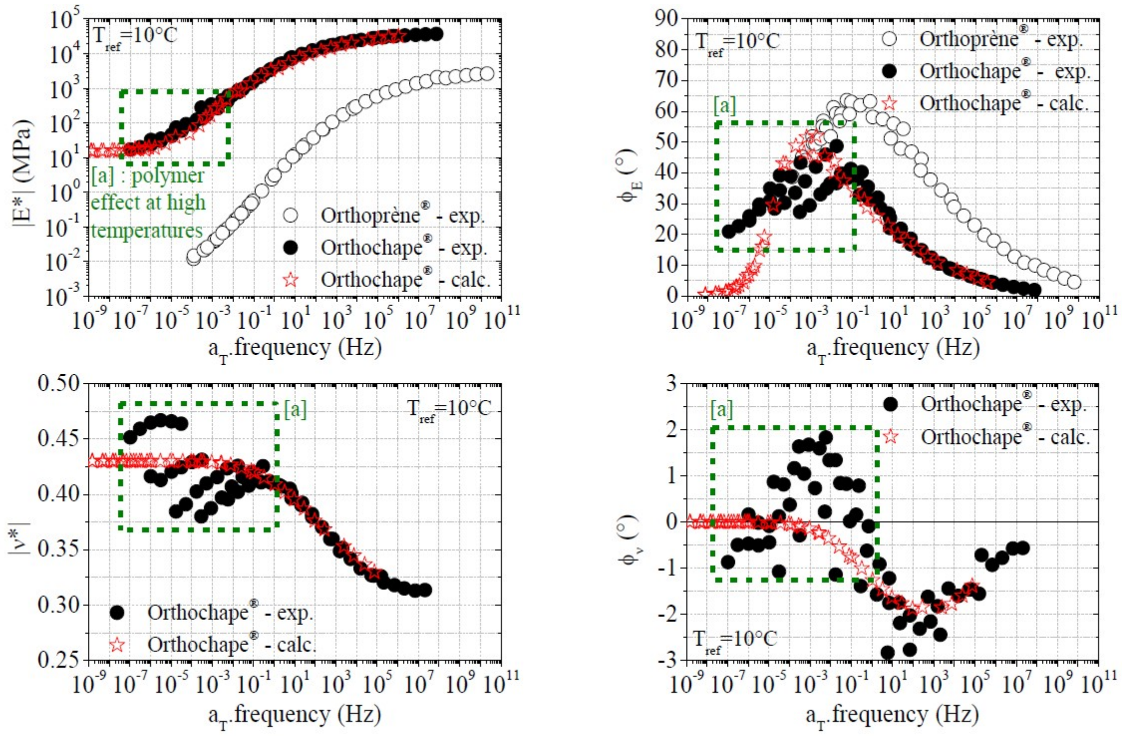


Figure 0-47: Experimental data of complex modulus of asphalt mixture with PMB and prediction of the modulus using equation (5) and data of PMB binder complex modulus

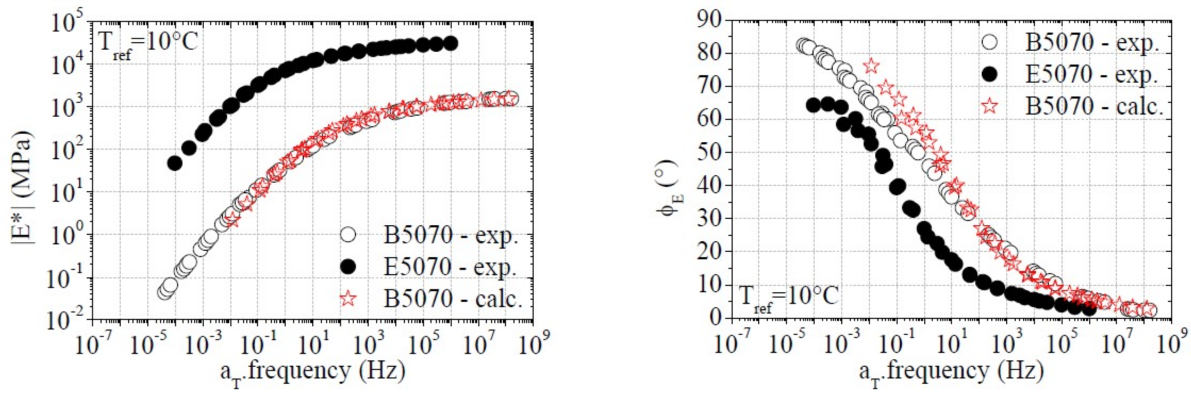


Figure 0-48: Experimental data of complex modulus of bitumen 50/70 and prediction of the modulus using equation (5) based on data of measured complex modulus of asphalt mixture with this bitumen

Similarly findings related to research done in the field of relation between bitumen and asphalt mixture modules for a given design can be found e.g. in work of Franken et al. (1995, 1996), Lytton et al (1993), Olard et al. (2003) or Zeng et al. (2001).

3. Conclusions for stiffness

The analysis of the possible relationships between asphalt stiffness and bitumen characteristics which are related to stiffness showed the following potential relations which are further summarized below according to the bitumen characteristics and/or test protocols which are used for their determination. It is however necessary to accentuate, that asphalt stiffness can be presently determined according to EN 12697-26 by several test methods for which so far not a satisfying relationship was found. Separately the asphalt dynamic modulus test according to AASHTO TP62 has to be mentioned. Also here it is not possible to set equal sing between the dynamic modulus form this test and the stiffness (resilient) modulus gained by the test protocols stipulated in the European standard. Additionally it is clearly demonstrated by many papers that stiffness test is not always run at same temperatures and frequencies, therefore good results and promising proof of a correlation given for test conditions in by one author in one paper for a custom practice in some region of Europe or the U.S. does not necessarily mean that the correlation will stay valid if test conditions are changed or modified. Additionally it has to be accentuated as well, that not always the bitumen complex shear modulus values are determined for similar temperatures. In this case the situation can be even broader (wide interval of temperatures) than in case of asphalt mix stiffness testing (usually the determining testing is done in a temperature range between 10 °C and 20 °C).

Usability of advanced tools for describing the bitumen or asphalt behavior in wide temperature and frequency range – the master curves – are due to a very low tradition in European testing difficult for a proof since there is a critical lack of sufficient data and consistent research done by more countries. This might be in general one topic to be recommended for further practical use, since providing master curves on bituminous binders need small amount of samples. The resulting information cover wide range of temperatures and frequencies simulating various traffic and climatic conditions. Bitumen thermal susceptibility can be studied. For asphalt mixtures the testing might require slightly increased number of test specimens and running the tests at different temperatures might be more time consuming. But the resulting information again does better explain the behavior of the asphalt mixture and of the asphalt layer. Additionally for both levels of testing (binder and asphalt) it might be important to use the original samples or test specimens for ageing and then perform the tests again. Results for unaged and aged binders and asphalt mixtures can be later compared in a simple ageing index providing a fast indication about the effects of bitumen ageing.

If comparing the FunDBitS results with the findings of BitVal project, the key conclusions already stated in interim report D.1 can be amended as follows:

1. BBR test
   ***BitVal**: This test can be discounted at that time because there were only two papers with diametrically opposing conclusions with regard to the ability of that test to reflect potential asphalt stiffness, if only because the testing was carried out under different conditions. However, because this divergence neither proved nor disproved any relationship, further work could make it relevant.*
   FunDBitS: There were not any new findings and conclusions with respect to creep stiffness and its correlation to asphalt stiffness. No relevant paper has been found dealing with sufficient data covering both characteristics with similar or same binders. Since BBR testing becomes more regular in Europe in might be advisable to focus on data collection and o recommendation to national road administration look on potential correlations between creep stiffness of bituminous binders and stiffness of corresponding asphalt mixtures. Such data collection and assessments can be run within suitable research tasks. At the same time it is nevertheless important to raise the

question if there could be a theoretically relevant relation between both characteristics and how to interpret such relation.

2. DSR related bitumen characteristics.
   ***BitVal**: The DSR is covered by many papers which, in general, supported there being a relationship between the binder stiffness and asphalt stiffness. The relationship is particularly strong when using the same temperature and frequency conditions for both the binder and the mixture. However, the relationship is also dependent on the aggregate skeleton of the mixture.*
   FunDBitS: Similarly to BitVal project findings, it was confirmed that most papers related to potential asphalt stiffness correlations are in the field of DSR bitumen testing. Generally if focusing on relation functionality between IG*I and asphalt stiffness most paper show a linear regression with a verified mean correlation coefficient R^2=0,88. This is mainly valid if the stiffness is determined by 2PB, 4PB or IT-CY test. In one paper correlation was possible for dynamic modulus according to AASHTO TP62 and IG*I for aged binders using logarithmic function. Even in this case a very good correlation was found (R^2=0,978). On the other hand interesting could be to assess correlation between the SHRP parameter IG*I/sin(δ) and asphalt stiffness. In this case compared to purely IG*I characteristics the correlation coefficient was lower. If assuming only narrow temperature range and the transformation from IG*I to E_{bit}, then the relation between the bitumen stiffness can be very well modelled to calculated E_{asf} as can be found in the literature e.g. by using Huet model.
   The last aspect is focused on the possible correlation between IG*I bitumen master curve and E_{asf} asphalt master curve. Only limited number of papers have been found which focused on this topic. In some of these papers it was repeatedly shown that the shape of master curves for bitumen and asphalt is different. On the other hand e.g. Ballié showed in his research that for binders after RTFOT there was a very good fit of master curves for bitumen and asphalt. Nevertheless this was done for only limited number of asphalt mixtures and related binders used in these mixtures.

3. Bitumen breaking point according to Fraass
   ***BitVal**: The data on the Fraass test was limited to data from a single paper and, therefore, insufficient to draw conclusions at that time. However, the Fraass brittle temperature would not be expected theoretically to be related to mixture stiffness.*
   FunDBitS: Based on the conclusions and findings from the BitVal project this characteristic and its relevance for stiffness correlations was in the conference paper/ journal article/ research report review checked. The results of the review process showed about 9 papers where Fraass breaking point was part of the complex bitumen testing. Nevertheless in these paper no adequate set of asphalt mixtures and their stiffness data was shown. Based on these findings and due to the stated doubt about the relevance of possible relations between bitumen Fraas breaking point and asphalt stiffness it is recommended to not follow such relationship.

4. Penetration was found to correlate well with mixture stiffness, especially at the same temperature and loading time, although generally not as well as the DSR binder stiffness which is able to evaluate binder stiffness over a large range of temperatures and frequencies. The relationship was less good for PMBs than for paving grade bitumen. Nevertheless, it had potential for initial assessments because the test is simpler to perform than the DSR.
   ***BitVal**: Penetration was found to correlate well with mixture stiffness, especially at the same temperature and loading time, although generally not as well as the DSR binder stiffness which is able to evaluate binder stiffness over a large range of temperatures and frequencies. The relationship was less good for PMBs than for paving grade*

bitumen. Nevertheless, it had potential for initial assessments because the test is simpler to perform than the DSR.
FunDBitS: The conclusions formulated by BitVal project were confirmed by FunDBitS review and assessments. There are several papers from which it is possible to set down relation between the bitumen penetration and the asphalt stiffness. However, in general neither the research paper nor the practical reports focus on extensive study of such relation. Therefore, compared to BitVal project, there were less paper in which it would be possible to differentiate between PMBs and paving grade binders. Two reviewed suitable papers focused on warm mix asphalts and binders which are modified or doped by suitable low-viscosity or surface activating additives. The correlations found for these binders are, however much lower. On the other hand one of the positive aspects is the possibility to run both tests at similar temperatures and to avoid any impacts of too different test temperatures since in such case the binders are influenced due to their viscoelastic behavior. Last important aspect is the test method used for determining asphalt stiffness. There is no relevant knowledge about the difference in correlated data if different test method according to EN 12697-26 is used.

5. Penetration index
   ***BitVal**: The penetration index generally had a marginally worse correlation with the mixture stiffness than the penetration whilst being a more complicated measure, so there appeared no justification to use it as the binder measure for asphalt stiffness.*
   FunDBitS: Following the conclusions made by BitVal project it was decided within FunDBitS project not to seek for relations between penetration index and asphalt stiffness.

6. Bitumen softening point (R&B)
   ***BitVal**: The R&B softening point generally has a significantly worse correlation with the mixture stiffness than the penetration, so there appears no justification to use it as the binder measure for asphalt stiffness.*
   FunDBitS: Findings which have been made during the BitVal project were confirmed in FunDBitS review and analysis of possible correlations. Generally there is usually a low correlation coefficient between the softening point and the asphalt stiffness. This was proven not only for paving grades, but also for various PMBs and additionally even for binders applicable to warm mix asphalts. Even in cases where the tested binders and asphalt mixtures showed low correlation between penetration and stiffness, the relation to softening point was even worse. It is therefore recommended to use softening point for the first (fundamental) bitumen classification, nevertheless to characterize the performance behavior of a binder and to get a sound correlations with asphalt properties related to asphalt layer performance it is necessary to target the integration of relevant bitumen tests to the European standardization.

In Table 0-12 a synthesis is provided of the overall evaluation of applicable tests for deriving asphalt stiffness behavior based on the relevant properties of bituminous binders in a broader range of temperatures (penetration, softening point complex shear modulus, non-recoverable creep compliance, low temperature stiffness according to BBR/DT test).

Table 0-13: 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
Creep Zero/Low Shear Viscosity (ZSV/LSV) Test	If some result found in the past, then the studies focused mainly on correlation between ZSV/LSV and permanent deformation	Measurements on PMB take a long time (up to 10h) to reach a steady state	Occasionally	CEN/TS 15324 (LSV) prEN 15325 (ZSV)	Not relevant data were found on studies correlating ZSV/LSV with asphalt mixture stiffness and/or elastic behaviour.
Oscillation Zero/Low Shear Viscosity (ZSV/LSV) Test				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. Already by BitVal project low correlation found.	Usually	EN 1427	It was proven again by many research results, reports and papers that the correlation to asphalt stiffness is low.
Penetration	Test method available in most of the labs. Large data background. Easy to use.		Usually	EN 1426	Very good correlation between penetration and asphalt stiffness.
Multiple Stress Creep and Recovery (MSCR) Test	Suitable for both unmodified and modified bituminous binders.	There is not sufficient set of data in most of the European countries.	Occasionally	EN 16659	MSCR is rather suitable for correlating rutting and non-recoverable creep compliance. It is recommended to focus in MSCR test in the future and to accept this test at least for PMBs as a standard required test.
Elastic Recovery Test	Simple and long-termly used test for polymer modified bituminous binders. Sufficient data available. Comparison between bitumen data and asphalt characteristics might be possible.	Applicable reasonably only to modified binders.	Usually	EN 13398	Not relevant data were found on studies correlating the Elastic Recovery Test with asphalt mixture stiffness and/or elastic behaviour.
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. Additionally calculated parameters like IG*I/sin(δ) for deformation behaviour and IG*I*sin(δ) for fatigue behaviour can be derived.	The precision of the test method has not yet been established	Often	EN 14770	Plenty of papers or research works have provided data on bitumen complex shear modulus and corresponding asphalt mixtures. The limitations have been found for comparison of master curve shape. At the same time additional data are needed to prove whether testing of bitumen and asphalt stiffness at different temperatures can have some impact on the resulting correlations. In general these characteristics seem to be the most appropriate for correlating asphalt stiffness.

BBR/DT	Suitable for predicting bitumen behavior in low-temperature range providing creep stiffness and the so called m-value. DT test is used to determine a bituminous binder's failure stress and strain at low temperatures.	There is limited data on BBR testing and almost no data on DT test in European countries. DT test was.	Usually (BBR)	EN 14771 (for BBR)	Similarly to BiTVal results only very limited data found where BBR results and asphalt stiffness were determined for same bituminous binders. It is henceforth not possible to provide relevant informa-tion if characteristics from both tests do correlate on or. Broader testing is needed in this area.

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