Functional Durability-related Bitumen Specification (FunDBitS)

Stiffness: Correlations and recommendations for further bitumen testing

Jan Valentin (CTU Prague)/ Cliff Nicholls (TRL)

Which tests and characteristics could used?

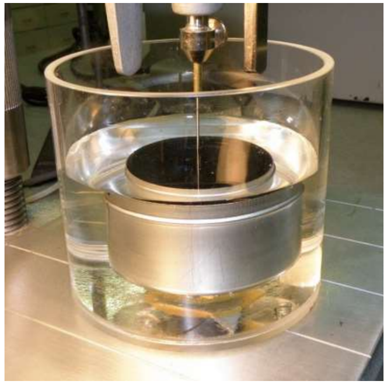
SUITABLE:

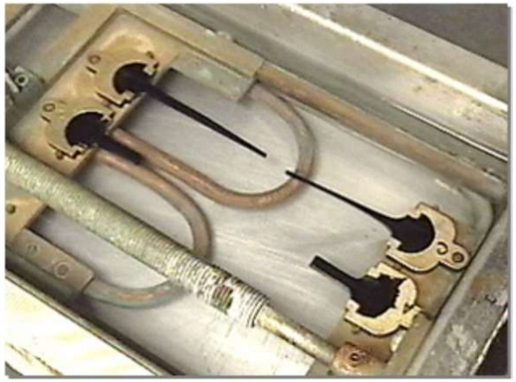
- DSR testing - complex shear modulus and phase angle (EN 14770)
- Penetration (EN 1426)
- BBR and Direct tension test (14771)

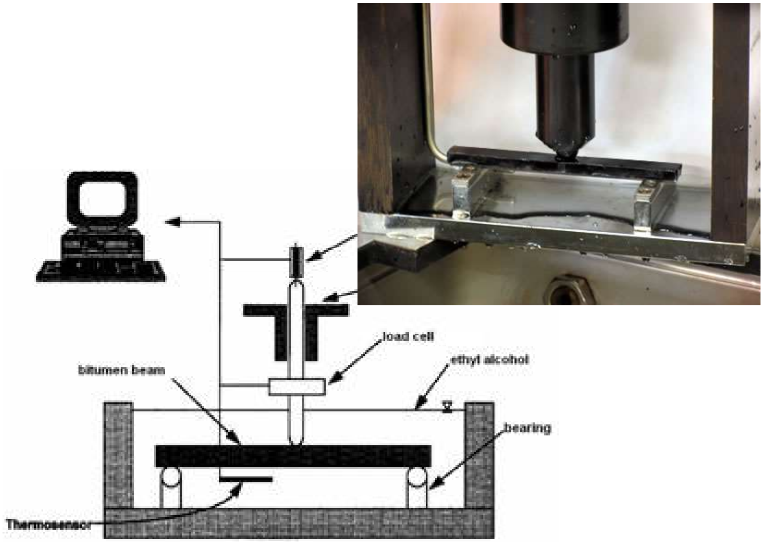
CONDITIONALLY SUITABLE:

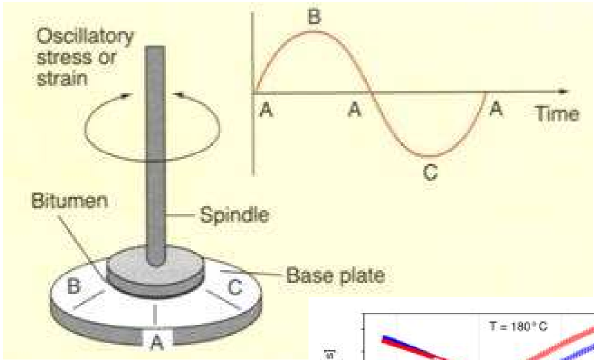
- Softening point (EN 1427)
- Elastic recovery test (EN 13398)
- MSCR test (EN 16659)
- ZSV/LSV tests (CEN/TS 15324 (LSV), prEN 15325 (ZSV))

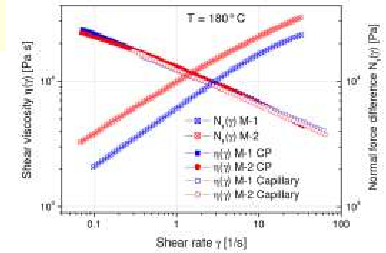
Which tests and characteristics could be used?



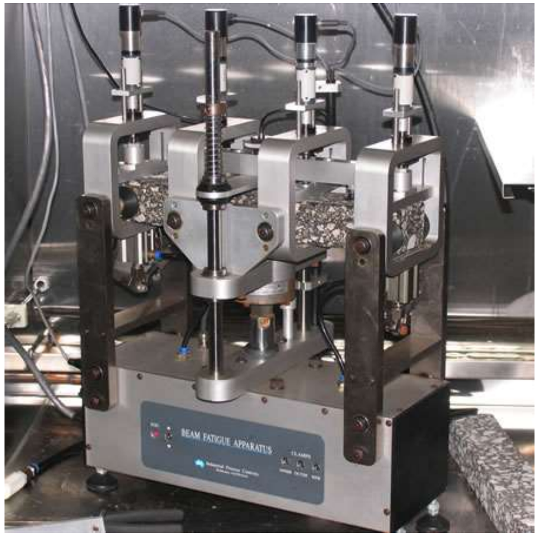








How is asphalt stiffness determined?



Known facts about asphalt/bitumen stiffness

- Question of asphalt stiffness is **a complex issue** that is still not gaining enough attention in daily work especially in relation to used bituminous binders.
- If bitumen is assessed usually shear modulus is determined (but this is not exactly the same type of behavior like stiffness).
- But neither for bituminous binders nor for asphalt mixtures advanced performance characteristics are regularly used for modulus assessments (master curve etc.).
- Asphalt stiffness can be determined according to EN 12697-26 by 6 methods → are there clear **correlations between the test methods?**

ANSWER IS SIMPLE NO!

Known facts about asphalt/bitumen stiffness

- Monitoring and assessment of stiffness characteristics should be done in close relation with rutting.
- Stiffness explains the durability behavior in moderate temperature range.
- Permanent deformation assessment is important for asphalt performance at elevated temperatures.
- **Behavior of bitumen in both ranges will not be identical due to its viscoelastic origin.**
- The biggest weakness in actual material testing is in the approach to the phenomenon of ageing – for asphalt we are simply not doing it.

What have we learnt from BiTVal?

- DSR was covered by many papers which, in general, supported that **there is 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.
- The relation also dependent on the aggregate skeleton of the mixture – do not underestimate this.
- Penetration was found to correlate well with mixture stiffness, especially at the same temperature and loading time (generally not as well as the DSR binder stiffness)
- It had potential for initial assessments because the test is simpler to perform than the DSR.

What have we learnt from BiTVal?

- The penetration index had a marginally worse correlation with the mixture stiffness than the penetration. No justification to use it.
- Softening point generally had a significantly worse correlation with the mixture stiffness than the penetration. No justification to use it.
- BBR test could not be discounted because there were only few papers with diametrically opposing conclusions.
- For Fraass test very limited data and no conclusions possible. The brittle temperature would not be expected theoretically to be related to asphalt stiffness.

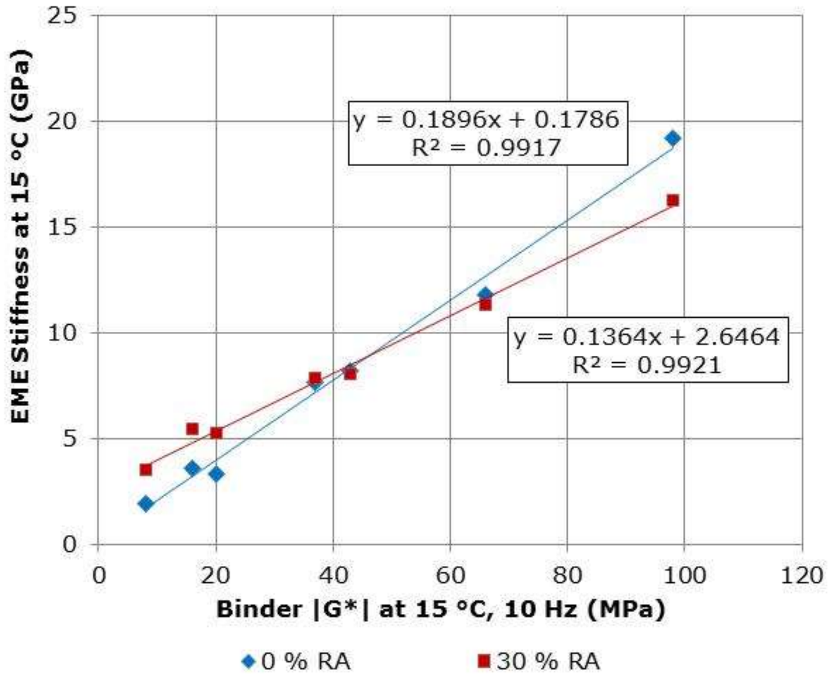
Significance of bitumen properties on asphalt stiffness

	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

(Iwanski & Mazurek, 2012)

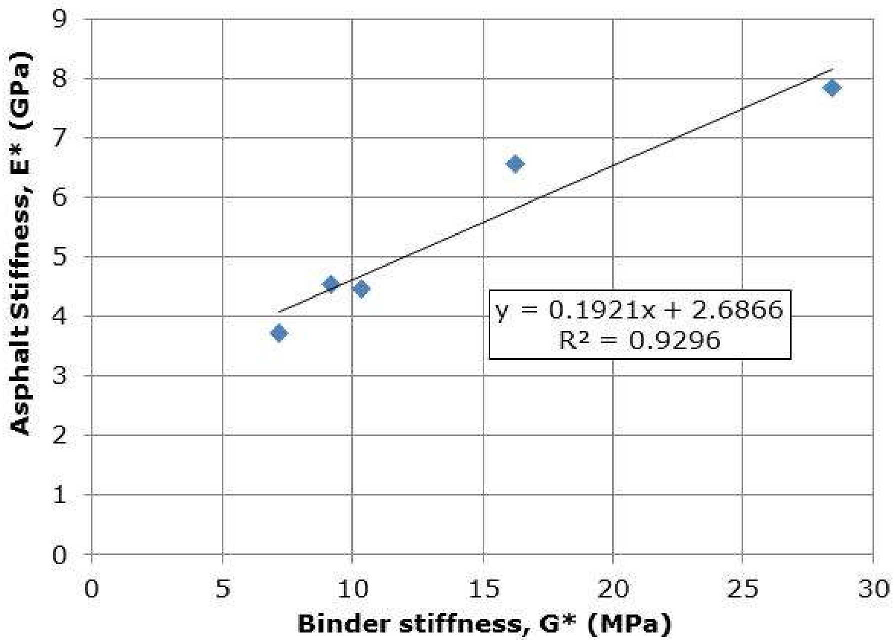
Findings indicate that the visco-elastic properties of bitumen complex modulus, phase angle and LSV play a major role in the relation with the values of the resilient (stiffness) modulus at 20° C but not on the voids content while the reverse is the case for penetration index.

Complex shear modulus vs. asphalt stiffness



(Hase, 2011)

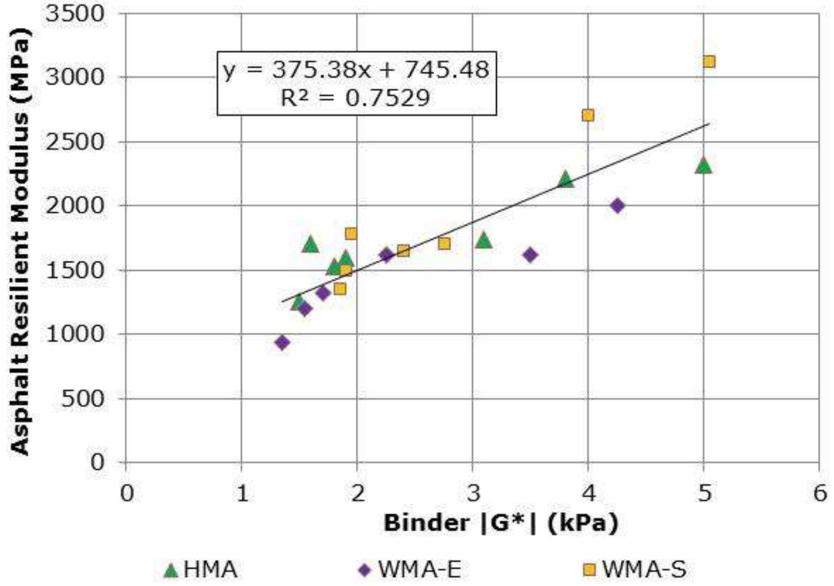
Mixtures with and without RA



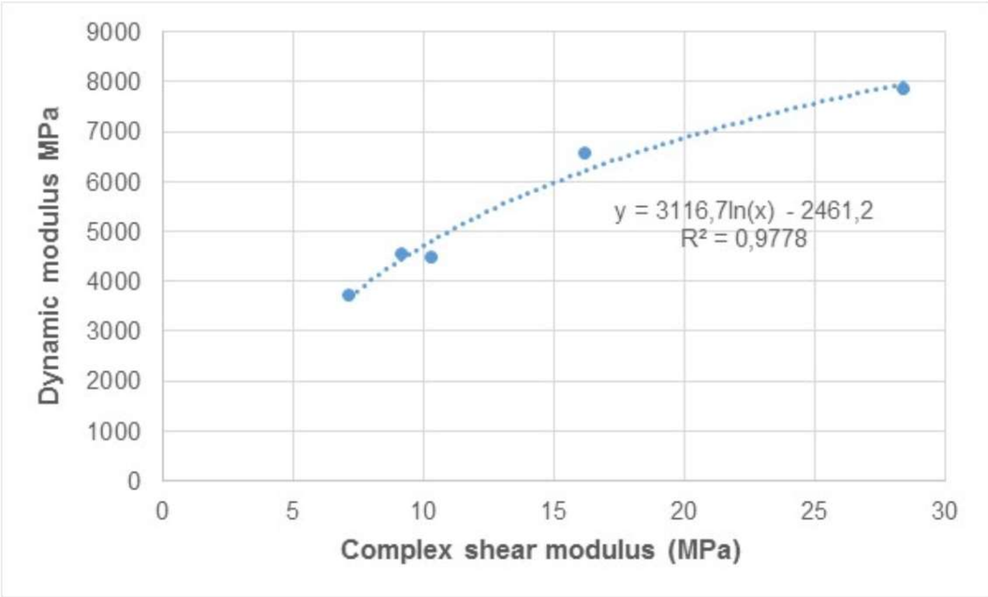
(Tabatabaee, 2010)

Mixtures with different PMBs

Complex shear modulus vs. asphalt stiffness



(Yang et al., 2014)



(Wen et al., 2010)

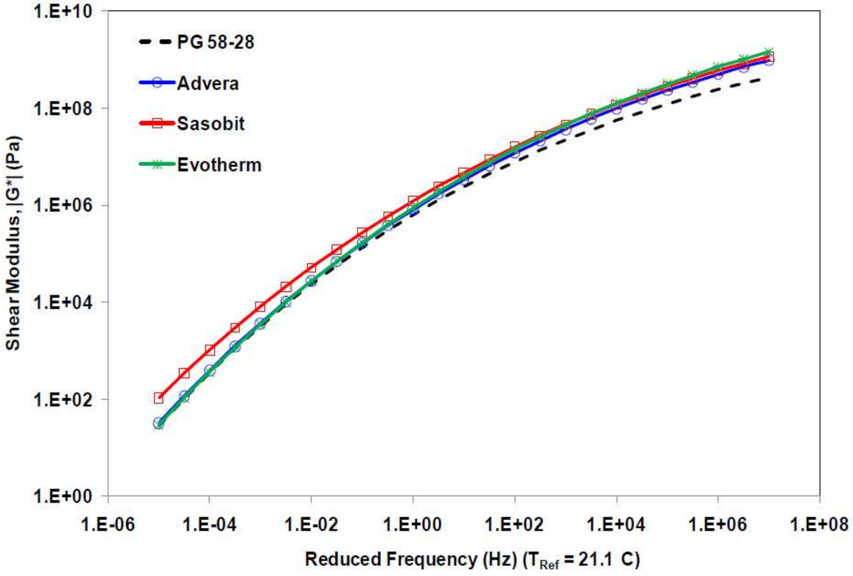
Complex shear modulus vs. asphalt stiffness – found correlations

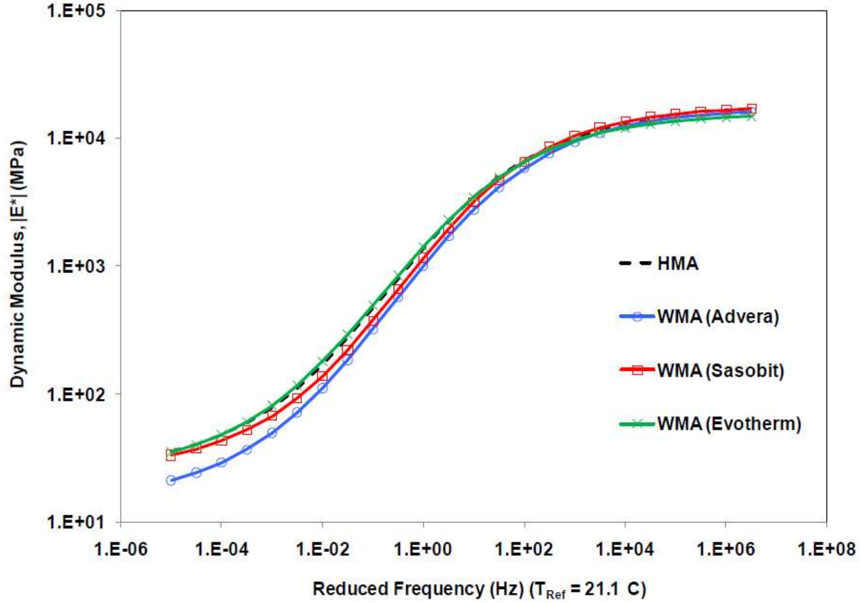
Paper		Test temp.	Data sets	Coefficient	Constant	R^2
Mangiafico *et al.*		15 °C	12	64,451	7895,3	0,916
Eckmann *et al.*		15 °C	4	0,2842	0,5298	0,984
Yang *et al.*		64 °C (bit)	21	375,38	745,48	0,753
Hase	No RA		7	0,1896	0,1786	0,992
	30 % RA		7	0,1364	2,6464	0,992
Tabatabaee and Tabatabaee			5	0,1921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

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

Bituminous binders tested at 60° C with f=1,59 Hz in control stress mode

Complex shear modulus vs. asphalt stiffness – use of master curve





(Zelelew et al., 2012)

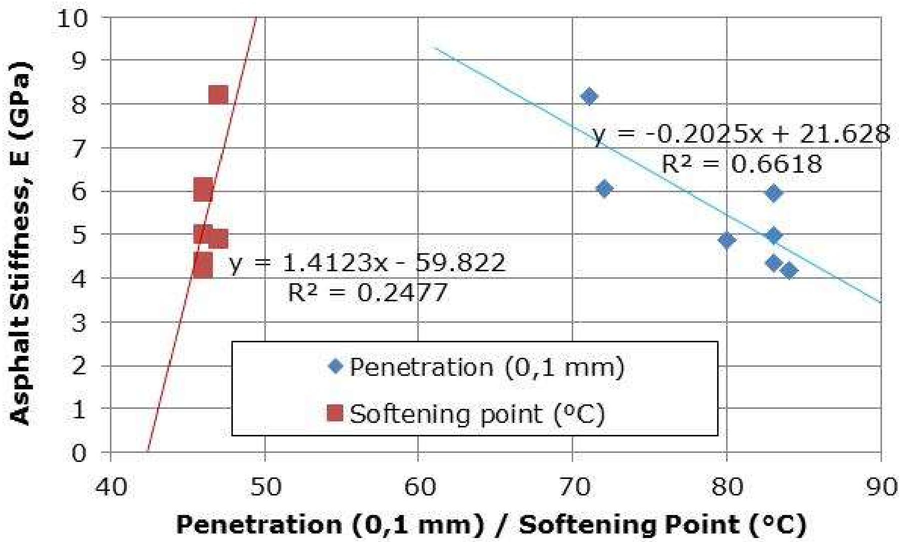
Complex shear modulus vs. asphalt stiffness – use of master curve

- 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:

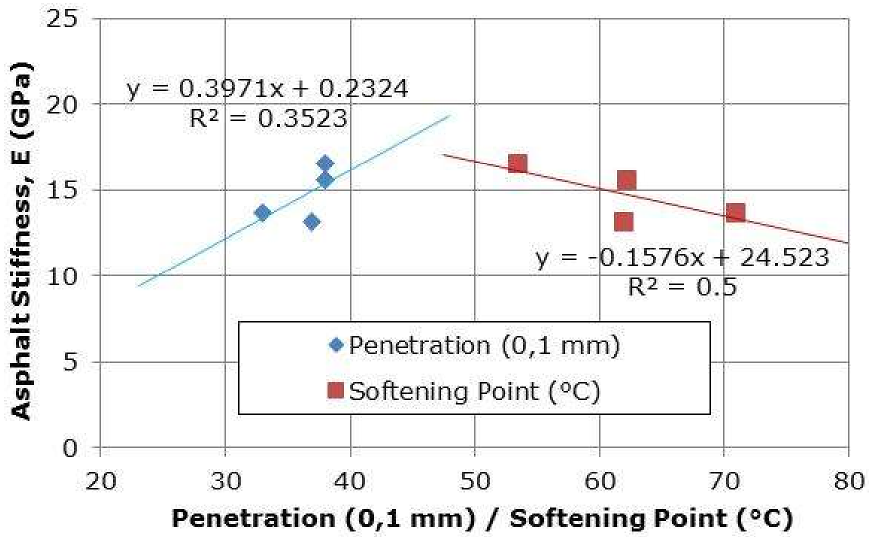
$$\frac{\left|E^{*}_{ENR}\right|}{\left(E^{\infty}_{ENR}-E^{0}_{ENR}\right)}=\frac{E^{0}_{ENR}}{\left(E^{\infty}_{ENR}-E^{0}_{ENR}\right)}+b*\frac{\left|E^{*}_{bit}\right|}{E^{\infty}_{bit}}$$

$$|E^{*}_{bit}| = 3\cdot|G^{*}|$$

Penentration and R&B vs. asphalt stiffness



(Nordgren and Olsson , 2012)



(Olard et al., 2012)

Penentration vs. 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

R&B vs. 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

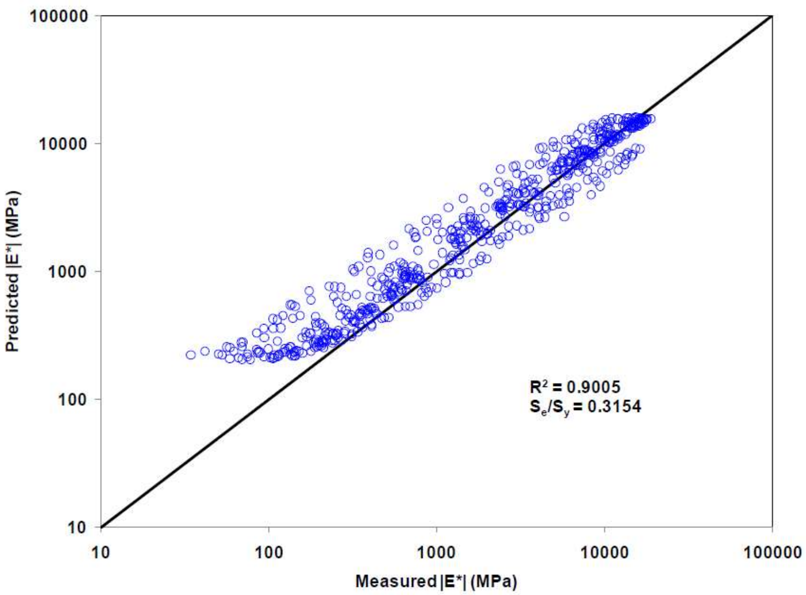
Predictive models of asphalt stiffness

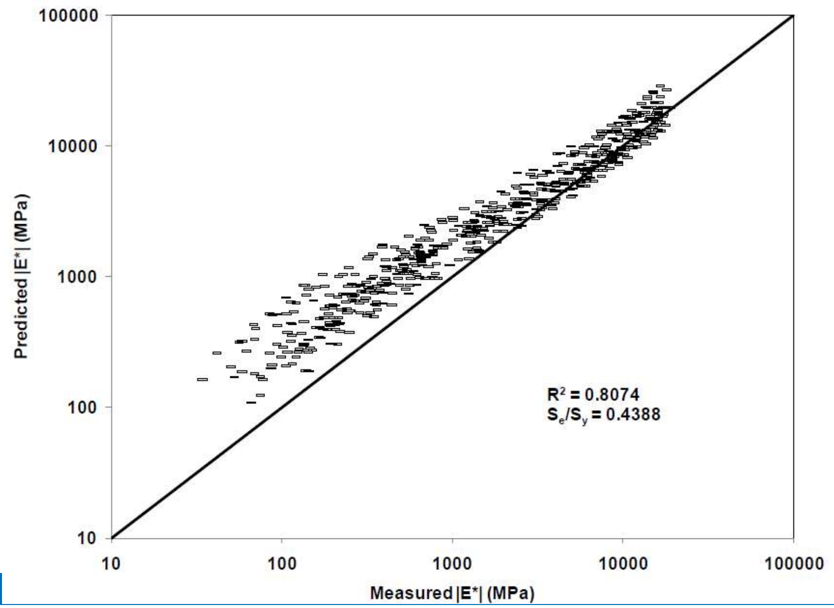
- The concept of models to predict the asphalt behavior makes use of multiple parameters. The models are more general in that the estimates are not restricted to a single mixture with different binders.

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

Predictive models of asphalt stiffness

- Comparison made for measured and predicted |E*|:
  - Hirsch model $R^2 = 0,9005$ Se/Sy (error) = 0,3154;
  - Witczak 1-40D model $R^2 = 0,8453$ Se/Sy (error) = 0,3934;
  - Witczak 1-37A model $R^2 = 0,8074$ Se/Sy (error) = 0,4388.

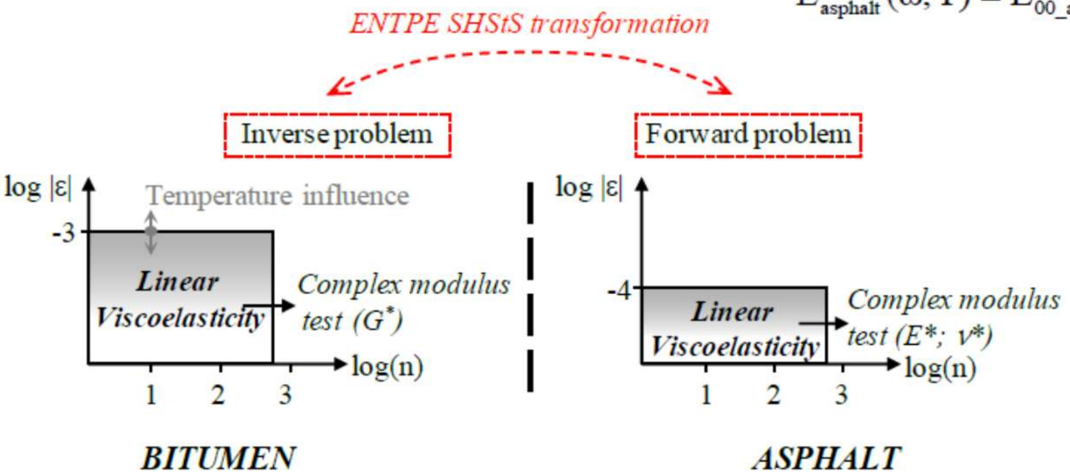




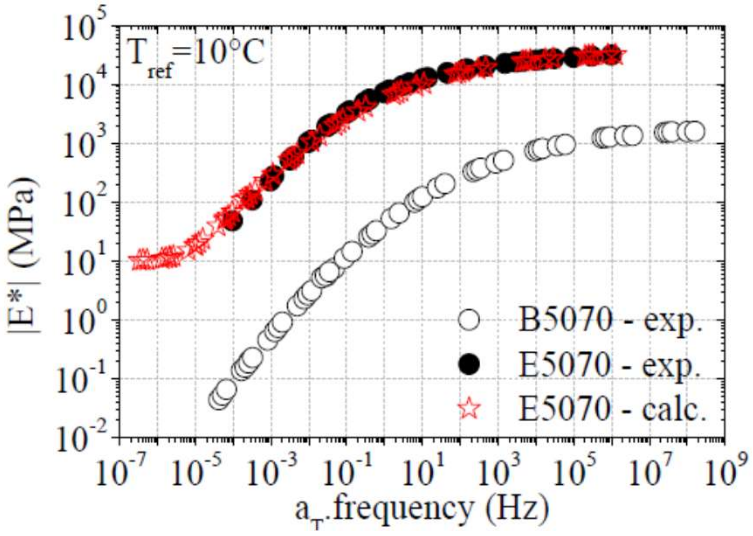
Predictive models of asphalt stiffness

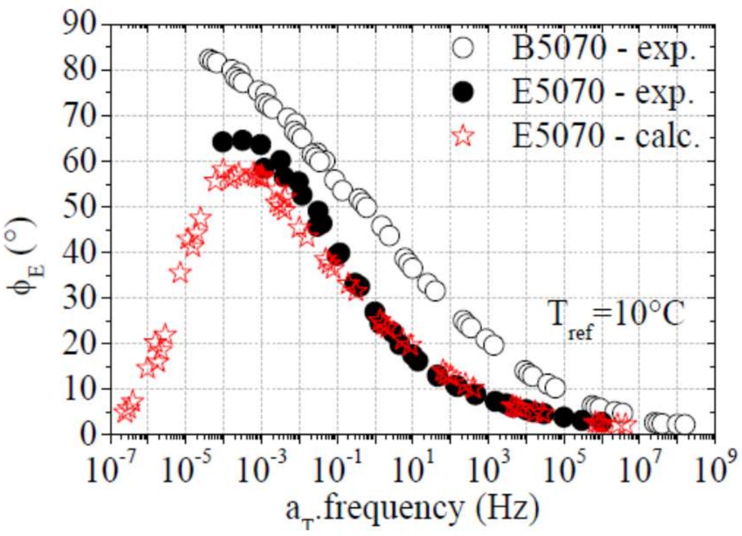
- ENTPE SHStS: forward and inverse problems related to stiffness assessment using experimental measurements of bitumen complex shear modulus performed with a DSR, while asphalt mixture complex modulus is measured using the three-dimensional complex modulus test developed at ENTPE.

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



Predictive models of asphalt stiffness





(Pouget et al., 2012)

- Experimental data of complex modulus of asphalt mixture with 50/70 bitumen and prediction of the modulus using previous equation and data of bitumen complex modulus.

CONCLUSIONS on stiffness

GENERAL FACTS

- Suitable tests for comparing bitumen vs. asphalt stiffness seems to exist ….. **BUT do we have sufficient data?**
- Asphalt stiffness determined by several methods with **non-uniform conditions**.
- Bitumen complex shear modulus values are determined at **different temperatures** than asphalt stiffness.
- Use of dynamic performance characteristics and tests for bitumen still under discussion ➡ BUT results demonstrate that complex shear modulus can be used for predicting or comparing the asphalt performance.

CONCLUSIONS on stiffness

COMPARISON TO BITVAL

- Softening point: low correlation coefficient between the softening point and the asphalt stiffness confirmed.
- Penetration index: conclusions of BiTVale confirmed. PI is not a suitable characteristic for comparing asphalt stiffness.
- BBR test: no new findings; question if there could be a theoretically relevant relation between creep stiffness and asphalt stiffness.
- Fraass breaking point: do not follow relationship to stiffness (no relevant data).

CONCLUSIONS on stiffness

Needle penetration:

- Reviewed papers confirmed a good correlation to stiffness.
- Nevertheless, neither research papers nor practical reports focus on extensive study of such relation.
- Bitumen and asphalt tests can be run at similar temperatures avoiding any impact of this factor.
- Easier to perform than DSR tests.
- No comparison with different asphalt stiffness test methods (WILL CORRELATIONS BE THE SAME?).
- Limited studies focusing on only paving grades or PMBs.
- Lower correlations if binders modified for WMAs.

CONCLUSIONS on stiffness

- **DSR characteristics:**
  - Most papers related to potential stiffness correlations are in the field of DSR bitumen testing (IG*I, δ).
  - A linear regression with a verified mean correlation coefficient R^2=0,88 shown (for 2PB, 4PB and IT-CY).
  - Promising could be also the assessment of correlation between SHRP parameter IG*I/sin(δ) and asphalt stiffness.
  - Bitumen and asphalt tests run usually at different similar temperatures ➞ what is the impact?
  - Data on comparing aged binders vs. aged asphalt mixtures missed ➞ we are assessing materials which do not reflect the real stage in the pavement.

Thank you for your attention