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Functional Durability-related Bitumen Specification (FunDBitS)

Correlations between bitumen and asphalt properties

Low temperature cracking

Deliverable D.2c
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FunDBitS
Functional Durability-related Bitumen Specification

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Low Temperature Cracking

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Executive summary

Low temperature cracking is particularly important for evaluating the low temperature behaviour of asphalt mixtures. In this part report of deliverable D.2, several test procedures for determining the low temperature cracking properties of asphalt are included. These are:

- tensile stress restrained specimen test (TSRST), as specified in EN 12697-46;
- uniaxial tensile strength test (UTST), as specified in EN 12697-46;
- uniaxial relaxation test (RT), as specified in EN 12697-46;
- unrestrained thermal dilation test (TST),
- Indirect tension test for examining low-temperature strength and creep compliance (IDTC)
- Semi-circular bending tests (SCBT), as specified in EN 12697-44;
- Disk-Shaped Compact tension test (DCTT);
- Acoustic emissions test (AET);
- Uniaxial Thermal stress and strain test (UTSST)

However, for the following discussions, the failure temperature T_f as obtained in TSRST is used for assessing the feasibility of available bitumen characteristics. The reason for this choice on characteristic helping to describe the performance behaviour is the large number of test results available for this asphalt mixture charcteristic, which also is already standardised in EN asphalt specification. In currently discussed review of EN 13108-series categories based on the critical failure temperature T_f are being introduced.

The analysis of the possible relationships between bitumen properties and the mixture low-temperature cracking resistance, showed that:

- The bitumen properties primarily affect the failure temperature obtained in TSRST. Feasible correlation could be obtained for several binder properties. The TSRST failure stress as well as tensile strength values obtained in UTST are influenced strongly be mix properties (voids content, binder content) which reduced the direct influence of the bitumen properties.
- Conventional bitumen characteristics showed that Fraass breaking point temperature is suitable only for assessing the failure temperature obtained in TSRST test. In general only weak corelations were found between conventional bitumen characteristics and resistance to low-temperature cracking of asphalt mixtures.
- Bending beam test results showed that:
  - the temperature T(300 MPa), at which the bitumen creep stiffness is 300 MPa obtained from BBR is suitable for predicting the failure temperature of TSRST asphalt mix test with an accuracy of ± 5 °C. However, this property demands comparably high test effort and large bitumen samples. Later might be a problem when testing aged samples and/or extracted binders.
  - For decreasing test effort, the application of a single creep stiffness value obtained at one selected temperature (e. g. -20 °C) seems to be suitable for the specification of the bitumen impact on low-temperature cracking resistance of asphalt mix.
  - Because the low-temperature cracking resistance of an asphalt pavement is reduced during service life also by ageing effects, the bitumen low-temperature specifications shall be conducted on laboratory-aged binder samples. In this relation it is for further discussion if the testing should be then conduced only with aged test specimens or if both states – original and aged – should be assessed and an ageing index will be later calculated.

1 Asphalt test methods for low temperature cracking

Low temperature cracking is particularly important for evaluating the low temperature behaviour of asphalt mixtures. In this part report of deliverable D.2, several test procedures for determining the low temperature cracking properties of asphalt are included. These are:

- tensile stress restrained specimen test (TSRST), as specified in EN 12697-46;
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- Semi-circular bending tests (SCBT), as specified in EN 12697-44;
- Disk-Shaped Compact tension test (DCTT);
- Acoustic emissions test (AET);
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However, for the following discussions, the failure temperature T_f as obtained in TSRST is used for assessing the feasibility of available bitumen characteristics. The reason for this choice is the large number of test results available for this asphalt mixture charcteristic, which also is already standardised in EN asphalt specification. In currently discussed review of EN 13108-series categories based on the failure temperature T_f are being introduced.

2 Relationship found between conventional bitumen properties and asphalt low temperature cracking

Fraass breaking point tests is still the most common low temperature quality control test in several countries. Fraass breaking point tests were conducted on different bitumens which were used for preparing asphalt mix samples for evaluating the low-temperature cracking resistance.

Table 2-1: parameters of linear correlations analysed between Fraass breaking point results obtained on bitumen samples and the TSRST results (failure temperature and failure tensile stress) measured on asphalt mixtures

No.^{Ref}	Asphalt mix type	TSRST failure temperature			TSRST failure stress		
		$T_f = A \cdot Fraass + B$			$\sigma_f = A \cdot Fraass + B$		
		A	B	R²	A	B	R²
1	SMA 16	0,404	-15,6	0,09	0,0066	2,68	0,00
2	SMA 8	0,769	-15,4	0,715	-0,073	3,16	0,27
3	PA	-0,078	-28,6	0,01	0,018	1,20	0,10
4	AC 16 & SMA 11	-0,34	-33,2	0,17	-	-	-
5	AC 11	0,618	-19,8	0,25	-	-	-
6	AC 11	0,09	-26,0	0,03	*0,10*	*6,13*	*0,86*
7	AC 11	0,28	-27,8	0,46	-0,0009	4,16	0,00
8	AC 22 & MA 11	0,59	-13,0	0,21	-0,084	2,72	0,06
9	AC 16 with RA	0,56	-21,8	0,45	0,002	3,41	0,00

References:
1) Nordgren & Olsson 2012; 2) Büchler et al. 2009; 3) Renken 2007; 4) Sybilski and Ruttmar, 2011; 5) Nikolaides and Manthos, 2010; 6) Wojcjech et al., 2010; 7) Bagampadde et al., 2006; 8) Roos et al., 2010; 9) Leutner et al., 2006

Figure 2-1 indicates the correlation between the temperature value obtained with Fraass breaking point tests on the bitumen and the failure temperature obtained in TSRST on asphalt mixtures prepared from these binders. Various correlation coefficients were found and are summarized in Table 2-1. Most studies indicate low coefficients of linear correlation. A general trend can be observed indicating low TSRST failure temperatures when also the bitumen Fraass temperatures reach low values.

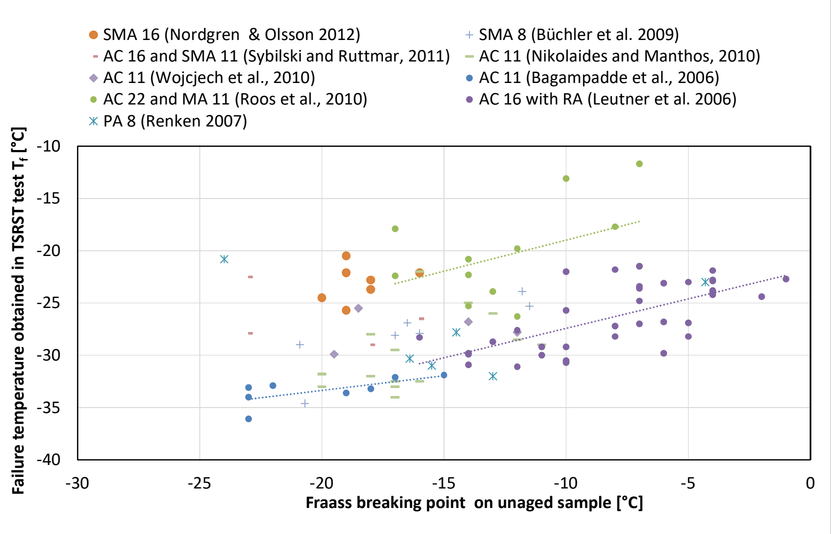

Figure 2-1: Fraass breaking temperature vs. TSRST failure temperature T_f

From Figure 2-2 it is on the other hand clear that there is no correlation between the temperature value obtained with Fraass breaking point test on the bitumen and the failure stress obtained in TSRST on asphalt mixtures prepared from these binders. Only in one case, where AC 11 was combined with 4 different binders, good correlation was found.

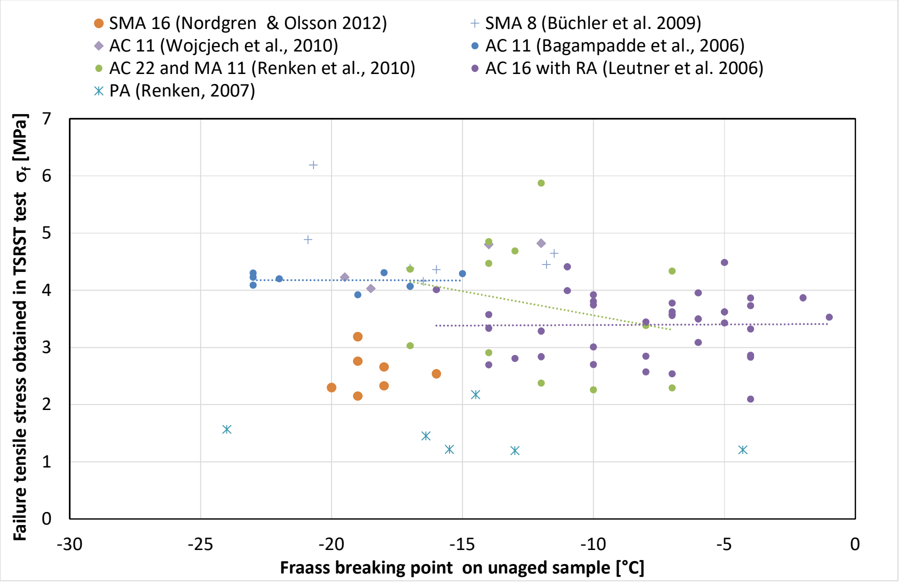

Figure 2-2: Fraass breaking temperature vs. TSRST failure stress σ_f

3 Relationships found between BBR test results and asphalt mix low-temperature cracking resistance

In several studies, Bending Beam Rheometer (BBR) tests were conducted on several bituminous binders which were used for preparing asphalt mix samples for evaluating the low-temperature cracking resistance. The bending beam test is also applied for assessing the low-PG temperature according to performance grade bitumen specification system. For PG grades, the higher temperature at which the creep stiffness obtained in BBR reaches a value of 300 MPa or at which the m-value reaches 0,3 is evaluated. The PG grade is the assessed temperature minus 10 °C.

In Figure 3-1 the correlation between the temperature value obtained in BBR T(S=300 MPa) on the bitumen and the failure temperature obtained in TSRST on asphalt mixtures prepared from these binders is indicated. Although either individual studies as well as all studies in total only indicate low coefficients of linear correlation a general trend can be observed indicating low (positive) TSRST failure temperatures when also the bitumen BBR temperature T(S=300 MPa) reach low values. From this graph it can be derived, that for ensuring a failure temperature in TSRST of a value below -25 °C, the bitumen BBR temperature should not be higher than -20 °C.

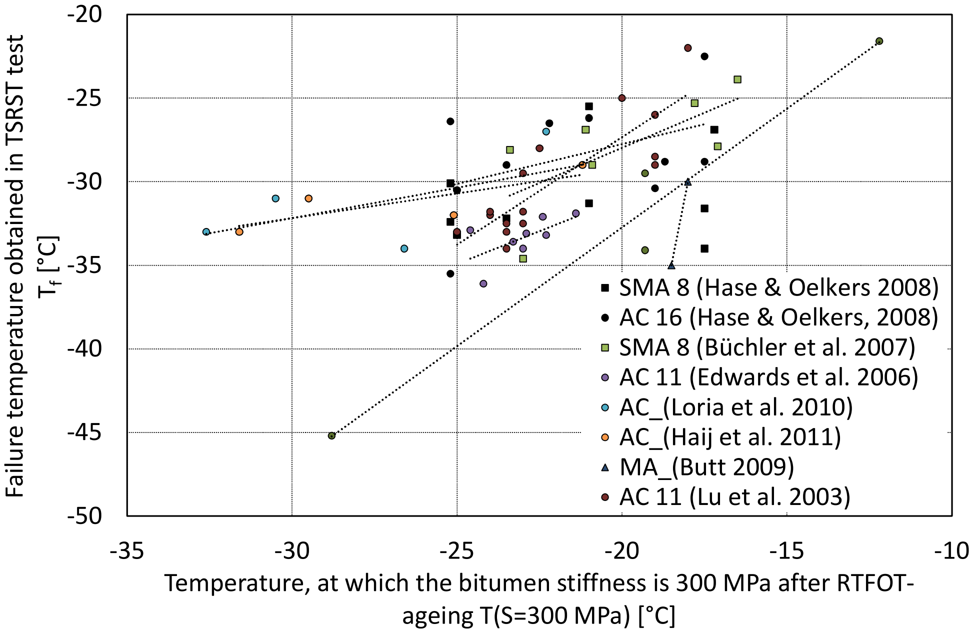

Figure 3-1: Temperature at which BBR stiffness is 300 MPa T(S=300) vs. TSRST failure temperature T_f

When adding the m-value criterion to this correlation, also studies which only give the resulting PG grade can be added to the general evaluation. As indicated in Figure 3-2 the results for the added study, where only the bitumens' PG grade is given for comparing to asphalt mix failure temperature fit well into the values measured before.

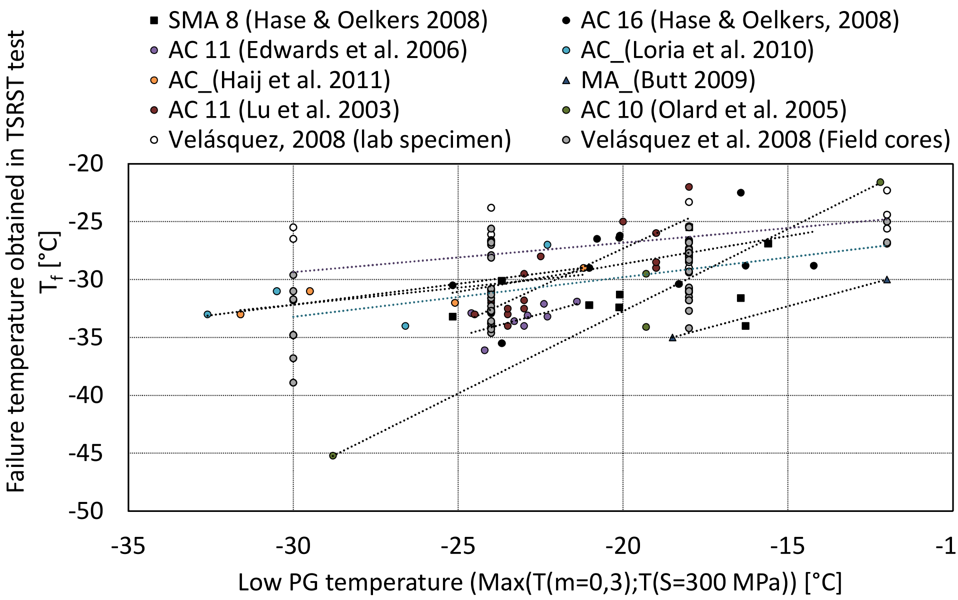

Figure 3-2: Low PG grade temperature vs. TSRST failure temperature T_f

However, the evaluation of the equi-stiffness temperature demands a high test effort on the bitumen. This is true when considering the large quantity of bitumen sample needed for conducting the BBR tests, especially when the test is conducted on aged samples. For checking, if BBR tests conducted on one single temperature could be sufficient for evaluating the low-temperature cracking resistance, Figure 3-3 shows the correlation between the creep stiffness measured at varied temperatures (between -16 °C and -20 °C) and the TSRST failure temperature. Again, the general trend of decreasing low-temperature cracking resistance of the asphalt mix with higher bitumen stiffness can be observed. However, compared to the relationship shown in Figure 3-1, even higher scatter is observed.

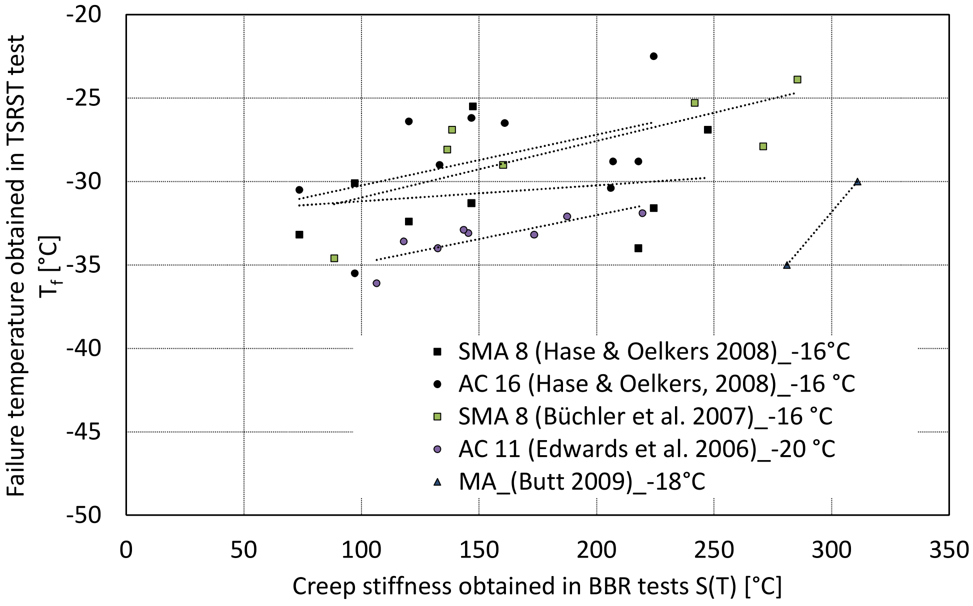

Figure 3-3: Creep stiffness obtained in BBR at varied temperatures S(T) vs. TSRST failure temperature T_f

As a summary of the analysed correlations between the bitumen BBR test results and the failure temperature obtained in TSRST tests on asphalt mix samples, Table 3-1 summarises the identified parameters of linear regression.

For the linear regression between the temperature at which a stiffness of 300 MPa is obtained in BBR test (T(S=300MPa) and the TSRST failure temperature the parameters vary considerably. The slope of the graphs as shown in Figure 3-1 is described by the regression parameter A. This value varies considerably between 0,295 and 1,421 (when the value obtained on only two MA samples are not considered). In parallel, the static parameter "B" results in values between -1,6 and -23,3. Overall, the coefficients of regression R² with values between 0,18 and 0,72 only identify a weak correlation.

The application of the low PG temperature which is the higher of the two BBR temperature results {T(S=300 MPa); T(m=0,3)} won't improve the correlation between asphalt mix and bitumens low temperature characteristics.

By using the creep stiffness obtained at a temperature between -16 °C and -20 °C in BBR test, better or same correlation to failure temperature measured in TSRST on asphalt samples can be obtained in four of five cases.

Table 3-1: Parameters of linear correlations analysed between BBR results obtained on bitumen samples and the TSRST failure temperature measured on asphalt mixtures

No.^{Ref}	**Asphalt mix**	**T(S=300 MPa)**			**low PG temperature**			**S(T)**			
		T_f = A·T(S=300)+B			*T_f = a·Max{T(S=300);T(m=0,3)}+b*			*T_f = A· S(T) +B*			
		A	B	R²	a	b	R²	T[°C]	A	B	R²
1 1)	SMA 8	0,533	-19,6	0,59	0,273	-25,4	0,10	-16	0,0339	-36,2	0,45
2 1)	AC 16	0,375	-20,5	0,18	0,482	-19,0	0,22	-16	0,0304	-33,3	0,22
3 2)	SMA 8	0,840	-11,2	0,46	not evaluated			-16	0,0339	-34,4	0,58
4 3)	AC 11	0,780	-15,4	0,38	0,78	-15,4	0,38	-20	0,0287	-37,8	0,68
5 4)	AC	0,363	-21,3	0,45	0,363	-21,3	0,45	not evaluated			
6 5)	AC	0,295	-23,3	0,64	0,295	-23,3	0,64	not evaluated			
7 6)	*MA*	*10*	*150*	*1**	*0,769*	*-20,8*	*1*	*-18*	*0,1667*	*-81,8*	*1*
8 7)	AC 10	1,286	-1,62	0,72	1,314	-1,042	0,73	not evaluated			
9 8)	AC 10	1,421	-4,33	0,96	1,421	-4,33	0,96	not evaluated			
10 9)	lab	not evaluated			0,254	-21,7	0,12	not evaluated			
11 9)	field	not evaluated			0,342	-23,0	0,25	not evaluated			

References:
1) Hase & Oelkers (2008); 2) Büchler et al. 2009; 3) Edwards et al. 2006; 4) Loria et al. 2010; 5) Haij et al. 2011; 6) *Butt 2009*
7) Lu et al. 2003; 8) Olard et al. 2005; 9) Velásquez et al. 2008
* only two samples tested

However, when plotting the parameters of regression A and B, which were obtained from the correlation between $T_{f,TSRST}$ and the BBR-temperature at which a bitumen stiffness of 300 MPa is reached, a good correlation is observed between these two parameters, compare Figure 3-4.

It can be concluded, that the correlation between TSRST failure temperature T_f can be estimated from the BBR result T(S=300 MPa) by following equation which only contains one parameter "A":

$$T_{f,TSRST} = A \cdot (T_{BBR}(S=300\ \mathrm{MPa}) + 18{,}59\ °C) - 28{,}35\ °C \tag{1}$$

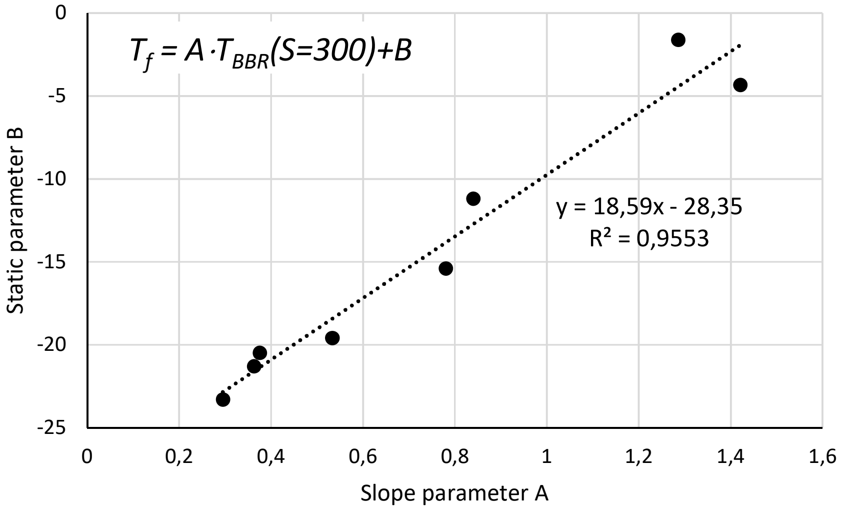

Figure 3-4: Correlation between slope parameter A and static parameter B for the linear regressions identified between BBR-temperature at which the creep stiffness is 300 MPa and the TSRST failure temperature

Note, that even the regression identified for the MA sample, which was not considered in this evaluation, meets the correlation between the parameters A and B feasibly well. However, the further effects on the parameter "A" can result from variations in asphalt mix properties, e.g. void content, mix and sample preparation (lab or site) or aging state of tested bitumen sample.

The overall quality of this identified correlation is depicted in Figure 3-5 where the calculated failure temperatures are compared to the actual measured values. It can be observed, that the two values still show differences of ± 5 °C.

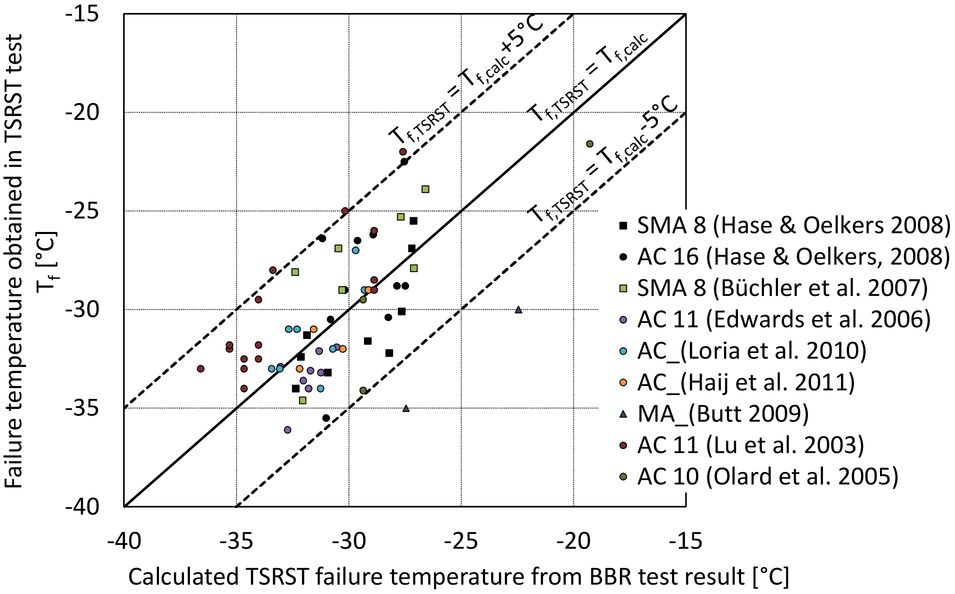

Figure 3-5: Correlation between slope parameter A and static parameter B for the linear regressions identified between BBR-temperature at which the creep stiffness is 300 MPa and the TSRST failure temperature.

4 Relationships found between force ductility test results and asphalt mix low-temperature cracking resistance

In several studies, force-ductility tests were conducted on bitumen which was further used for preparing asphalt mixtures. In Figure 4-1, the correlation between TSRST failure temperature and the maximum force measured in force ductility tests is shown for three studies. Note, that in one study, FD-tests were conducted at 5 °C, whereas the two SMA studies applied a FD-test temperature of 25 °C.

The results indicate for each study a feasible correlation between maximum force and failure temperature. An increase in FD maximum force is an indication for higher bitumen stiffness. This will result in reduced low-temperature cracking resistance as indicated by higher failure temperatures.

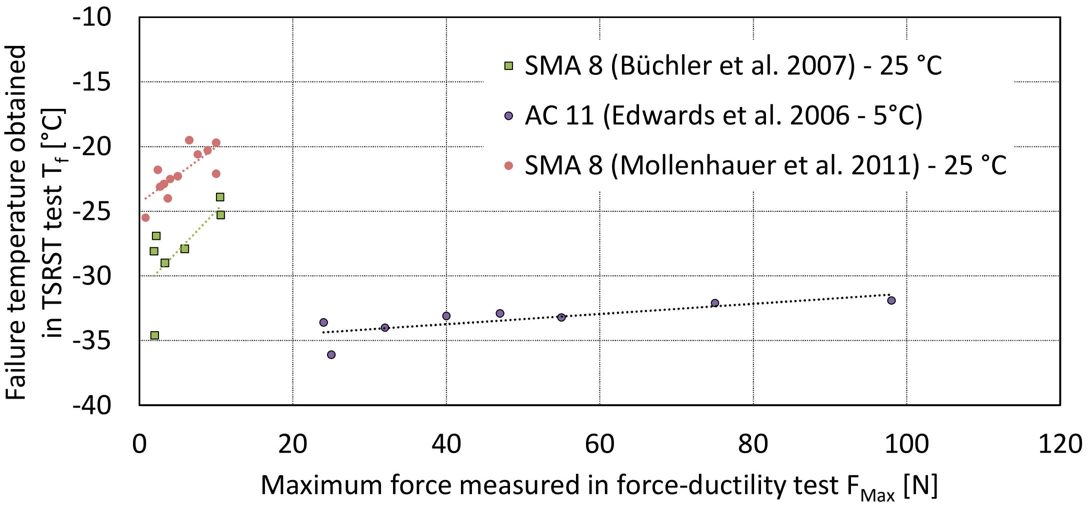

Figure 4-1: Maximum force obtained in FD-tests at varied temperatures vs. TSRST failure temperature T_f

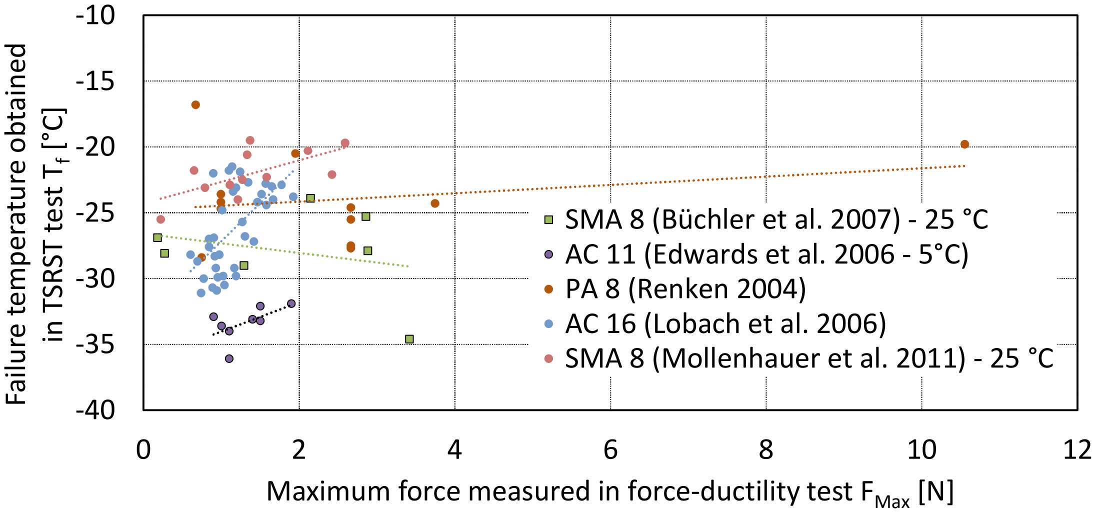

Figure 4-2: Deformation energy obtained in FD-tests at varied temperatures vs. TSRST failure temperature T_f

Nevertheless, the two studies, in which SMA samples were tested and the FD tests were conducted at the same temperature, found correlations indicating differences in the corresponding failure temperatures of about 5 °C. In order to decide on the feasibility of FD bitumen properties as a possible indicator for the asphalt low-temperature cracking resistance not enough data is available.

Other characteristics obtained in force-ductility tests like the deformation energy didn’t indicate consistent trends for the failure temperature as plotted in Figure 4-2. Some studies indicate lower failure temperatures with decreasing deformation energy other studies show the contrary trend. Both trends can be plausible, as low deformation forces obtained at soft binders result in low deformation energy. However in case of brittle binder property, also low deformation energy results are obtained with binder samples showing early failure in the test.

5 Relationships found between complex modulus test results and asphalt mix low-temperature cracking resistance

In several studies, DSR tests were conducted on bitumen samples. A common DSR test property given in many studies is the shear modulus measured at 60 °C and a test frequency of 1,59 Hz. As shown in Figure 5-1, some relations between complex modulus (measured at 60 °C) and the TSRST failure temperature can be observed. However, in these studies the found relations result from the general trend of bitumens with reduced viscosity showing positive low-temperature cracking properties.

It is believed, that DSR tests conducted at low temperatures which better represent the cracking temperatures of the asphalt mixtures (temperatures below -10 °C) would be a more suitable way for assessment of the cracking resistance effect of bitumen. However, no study was found where DSR tests were conducted at low temperatures.

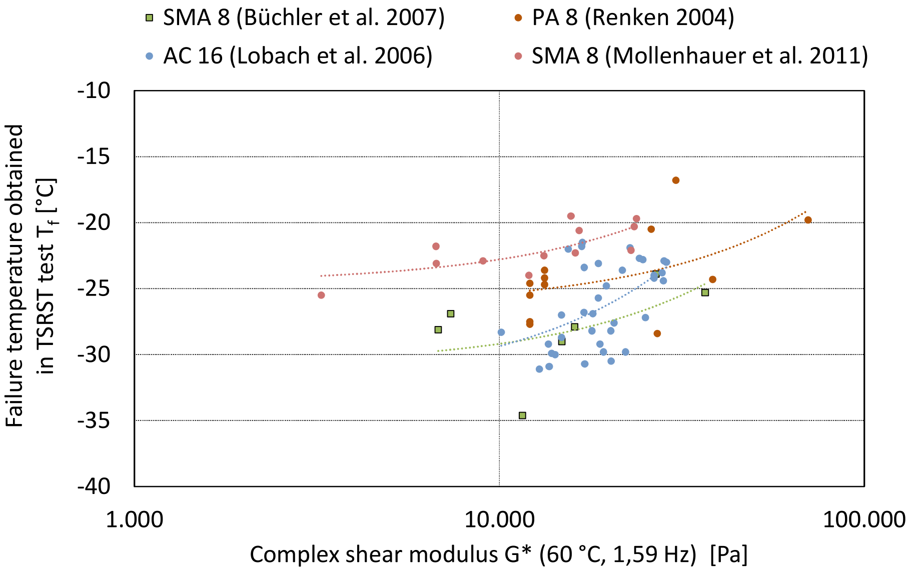

Figure 5-1: DSR complex shear modulus G* measured on vs. TSRST failure temperature T_f

6 Conclusions on relationships between bitumen properties and the resistance to low-temperature cracking of bituminous mixtures

Regarding the binder performance tests assessed in this study, the BBR tests shows the highest potential for the application for assessing the low-temperature cracking resistance in asphalt mixtures. Reason for this is the available experience with this test because of its application in performance grade specification system as used in the USA and Canada. Furthermore the other binder performance tests evaluated are mostly conducted in another temperature range compared to the usual failure temperatures measured on asphalt mixture samples. For these tests (force ductility, DSR) only general trends could be observed showing the general effect of binder viscosity on low-temperature performance. However these properties are not applicable for assessing the low-temperature cracking resistance effect of bitumen.

7 Bitumen ageing effect on low temperature cracking

Long-term ageing of bituminous binder will result in increased viscosity and stiffness. This will also affect the low-temperature cracking resistance of an asphalt mixture. In paper 498 (Büchler et al. 2009), seven SMA mixtures were tested by TSRST and UTST in two ageing stages. The "fresh" mix results were obtained on asphalt specimens, which were compacted just after mix preparation. The asphalt mixture samples "BSA" were stored for 4 days in a heating cabinet at 80 °C before sopecimen compaction. For the results of TSRST this ageing results in an earlier increase of the cryogenic stress development and higher cryogenic stress at a given temperature, compare Figure 7-1 (left). This also results in a shift of the failure temperature to a higher temperature.

At the same time binder stiffening also affects the tensile strength by increasing the strength at higher temperatures due to increased viscosity. However, at low temperature the tensile strength is decreasing after ageing because of increased brittleness of the material. These effects on the tensile strength will control also the effect of the failure stress observed in TSRST. In Figure 7-1 (right) the change in failure temperature and stress is marked with the arrows showing the change of test results obtained on unaged asphalt mix to laboratory-aged asphalt mixture for the seven tested SMA 8 samples. In four cases, the ageing results in a decrease of failure stress, whereas in three cases an increased failure stress is observed.

These effects of ageing as well as results of TSRST and UTST could also be observed in studies where samples from asphalt pavements were tested. Dressen et al. (2012) (paper 0036) evaluated the long-term ageining effect during 14 years of service lifetime on several Swiss asphat pavements. For AC 16 surface courses with a neat binder 80/100 the observations explained above with decreasing failure stress and increasing failure temperature could also be made. However, for AC 16 surface courses with polymer modified bitumen, the effect of ageing on the TSRST results were only small. This goes along with results obtained by BBR testing, which showed no stiffening effects due to long-term ageing.

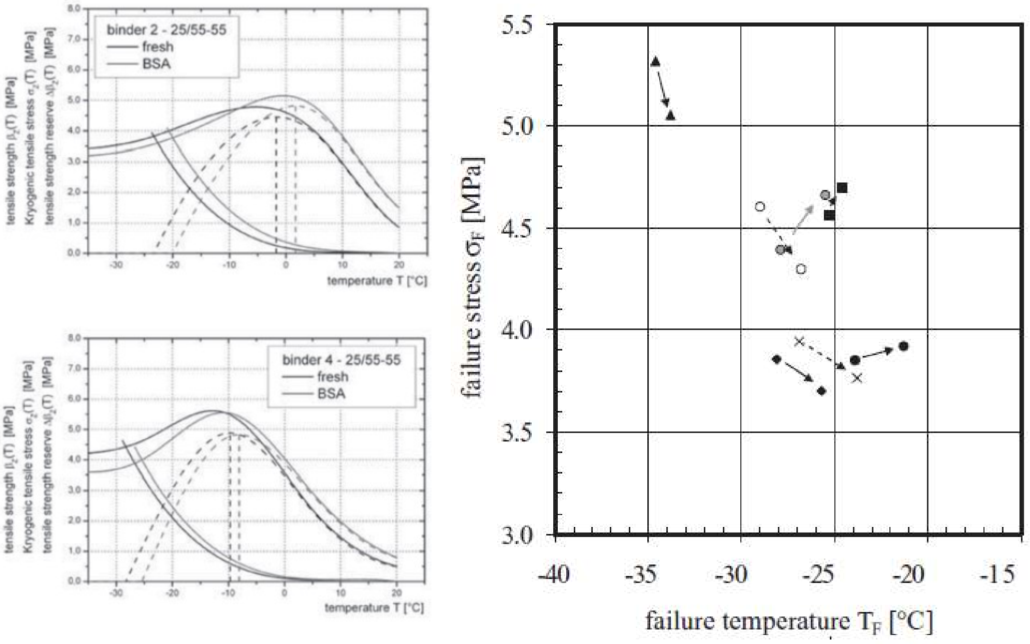

Figure 7-1: Effects of ageing on TSRST and UTST results
left: ageing effects on cryogenic stress and tensile strength development;
right: change of failure temperature vs. failure stress due to laboratory ageing
(Büchler et al., 2009)

Also for three SMA 8 samples from Slovenian motorways the effect of long-term ageing on low-temperature cracking resitsuance could be analysed in Mollenhauer et al. (2011) (paper 0510). As shown in Figure 7-2 three years of service lifetime results in the same effects as observed in laboratory tests.

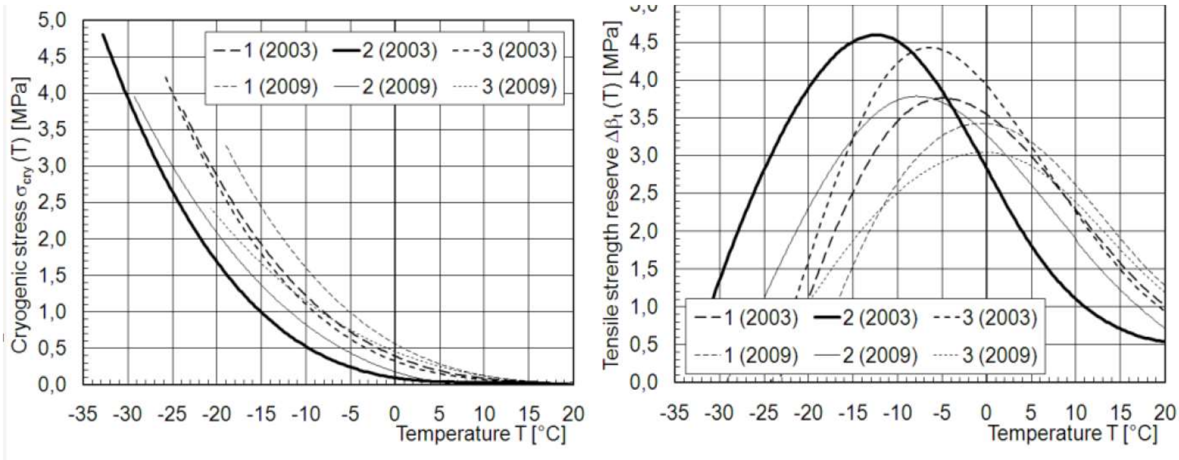

Figure 7-2: Effect of long-term ageing on low-temperature cracking resistance obtained in TSRST and UTST (Mollenhauer et al. 2011) – paper 0510.

These observations made on site and laboratory aged asphalt mix test samples indicate the importance of implementing ageing assessment to the type test of asphalt mixtures as well as of bituminous binders. Therefore, usually RTFOT and PAV tests are applied before testing the low-temperature properties of binders.

8 Conclusions on relationships between bitumen properties and the resistance to low-temperature cracking of bituminous mixtures

The analysis of the possible relationships between bitumen properties and the mixture low-temperature cracking resistance, showed that:

- The bitumen properties primarily affect the failure temperature obtained in TSRST. Feasible correlation could be obtained for several binder properties. The TSRST failure stress as well as tensile strength values obtained in UTST are influenced strongly be mix properties (voids content, binder content) which reduced the direct influence of the bitumen properties.
- Conventional bitumen characteristics showed that Fraass breaking point temperature is suitable only for assessing the failure temperature obtained in TSRST test. In general only weak corelations were found between conventional bitumen characteristics and resistance to low-temperature cracking of bituminous mixtures.
- Bending beam test results showed that:
  - the temperature T(300 MPa), at which the bitumen creepo stiffness is 300 MPa obtained from BBR is suitable for predicting the failure temperature of TSRST asphalt mix test with an accuracy of ± 5 °C. However, this property demands comparably high test effort and large bitumen samples. Later might be a problem when testing aged samples and/or extracted binders.
  - For decreasing test effort, the application of a single creep stiffness value obtained at one selected temperature (e. g. -20 °C) seems suitable for the specification of the bitumens impact on low-temperature cracking resistance of asphalt mix.
  - Because the low-temperature cracking resistance of an asphalt pavement is reduced during service life also by ageing effects, the bitumen low-temperature specifications shall be conducted on laboratory-aged binder samples.

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