Study of the low temperature characteristics of binders and the asphalt mixtures produced with them

Dafinka Pangarova[1, a], Alexander Nikolov[2, b]

[1] *Chemistry, Central institute of road technologies national and European norms and standards, Sofia, Bulgaria*
[2] *Research and development, Patpribor OOD, Sofia, Bulgaria*

[a] dafny1@abv.bg
[b] a.nikolov@patpribor.com

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ABSTRACT

The asphalt pavements performance at low service temperatures is highly dependent on binders' behavior at low temperatures. At present it is only recommended in the specification for polymer modified binders to be tested the performance characteristic – stiffness at -16oC with BBR according to EN 14771. For the rest of the binders it is only required to be tested the Fraas breaking point according to EN 12593. There is no specification limiting the threshold stiffness value.

Binders, modified with organic, inorganic polymers and paraffin waxes have been tested. The rheological properties were examined at different service temperature intervals, where the low temperature intervals were tested according to Fraas breaking point and BBR test methods. Both short term and long term aging have been carried out according to EN 12607-1 and EN 14771 respectively.

For asphalt mixtures prepared with the same binders the indirect tensile strength has been tested according to EN 12697-23, but at low temperature. The aim of the study is to be found correlations between the low temperature properties of the binders and the asphalt mixtures prepared with them.

Keywords: Low-Temperature, Polymers, Stiffness, Viscosity

1. INTRODUCTION

The cracking resistance of asphalt pavements is one of the factors influencing their durability. Low temperature cracking results from shrinking of the binders, which occurs in case maximum tensile strength is reached [1].
The open cracks allow penetration of water, which freezes and causes partial destruction of the asphalt pavement. The deicing salts spread for winter maintenance also go through these cracks and deice the water kept inside, which leads to a deeper cracking and downgrade of the construction.
The reviewed literature on this subject points out that the binder characteristics influence the behavior of the asphalt pavements at low temperatures [2, 3, 4, 5, 6].
The climate in our country is a continental one, with high summer temperatures and low temperatures during the winters, which is a critical issue for the flexible pavements, causing thermal low temperature cracking. This study is an attempt to investigate the influence of different bituminous binders on the mechanical properties of the asphalt mixtures at low ambient temperatures.

2. Materials

The tests have been performed for five different binders that are used in asphalt mixtures for wearing courses, as follows:

- bitumen grade - 50/70;
- modified bitumen consisting of bitumen grade 70/100 and 3% long-chain paraffin waxes obtained by the Fischer-Tropsch method (Sasobit);
- modified bitumen consisting of bitumen grade 70/100 and 2% poly-phosphoric acid (Innovalt);
- polymer modified bitumen consisting of bitumen grade 70/100 and 4,4% thermoplastic elastomer Kraton D-1101, and
- polymer modified bitumen consisting of bitumen grade 70/100 and 2% terpolymer Elvaloy.

Asphalt mixtures for wearing course were prepared from the various bituminous binders included in the study, using the same aggregates. The sieving curve of the asphalt mixtures is given in figure 1. Asphalt mixtures were prepared in a laboratory mixer according to BDS EN 12697-35. It is equipped with a heater with a thermostatic control. Compaction is carried out according to BDS EN 12697-30. The recipe is as follows:
- Mineral aggregates, grade 4/8 mm - 40%
- Mineral aggregates, grade 0/4 mm - 54%
- Mineral filler - 6%

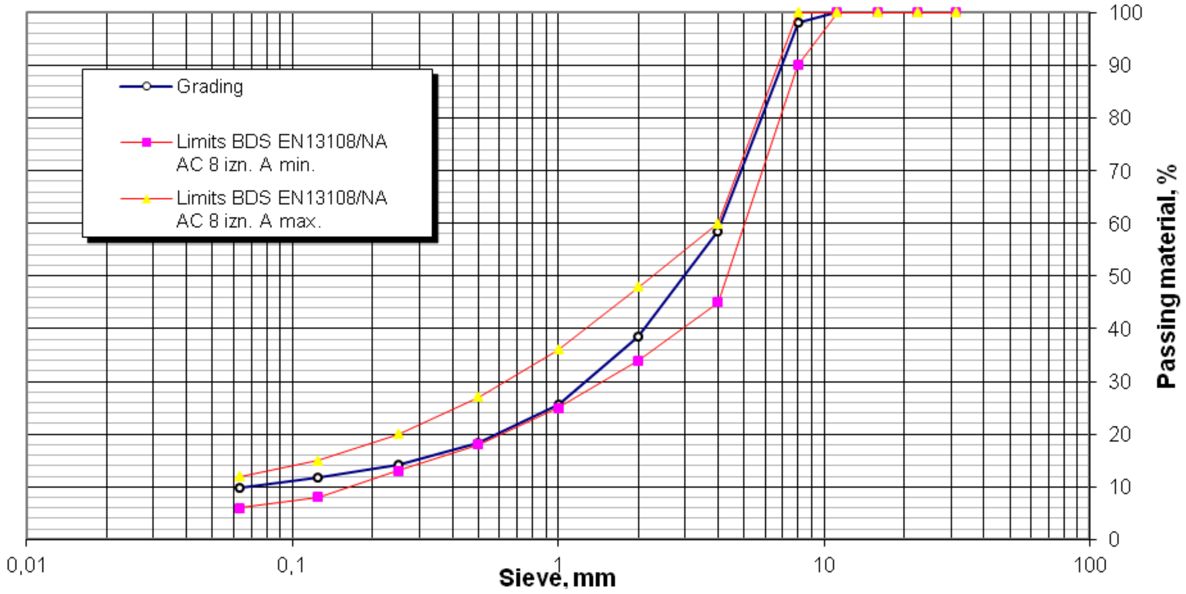

Figure 1
Sieving curve of the asphalt mixture

The conditions for preparation of the asphalt mixtures are presented in Table 1.

№	Conditions	50/70	70/100 + 3% Sasobit	70/100 + 2% Innovalt	70/100+ 4,4% Kraton D 1101	70/100+2 % Elvaloy
1	Mixing temperature, °C	162	145	176	192	190
2	Compaction temperature, °C	149	133	165	173	172
3	Number of impacts (per side)	75	75	75	75	75

Table 1: Conditions for preparation of laboratory mixtures

3 Test Methods

The binders have been tested according to the specifications given in EN 12591 and EN 14023. In addition, the stiffness and m-value at -16°C were determined according to EN 14771; also, a long term aging was performed at 100°C for 20 hours according to EN 14769. Additionally, the penetration index PI before and after exposure to short term aging and the penetration viscosity number PVN_{135} were calculated since the two parameters characterize the temperature sensitivity of binders [7]. The following formulas were used to calculate the parameters:

$$PI = \frac{20 - 500A}{1 + 50A} \qquad A = \frac{LogP - Log800}{25 - T} \qquad (1)$$

$$PVN_{135} = 1.5x \frac{4.258 - 0.7967LogP - LogV}{0.795 - 0.1858LogP} \qquad (2)$$

where
PVN = Penetration viscosity number
PI = Penetration index
P = Penetration at t 25°C, 5 sec, dmm
V = Kinematic viscosity at 135°C, Pa.s.
T = Softening point, °C.

The asphalt concrete mixes were tested for characteristics included in BDS EN 13108-1. It was studied the short and long term aging of the asphalt mixtures. According [8] asphalt mixtures were prepared with different binders and at different conditions. One part of the asphalt mixtures were placed in an oven at 135°C for 4 h simulating short term ageing of the asphalt mixture. Another part of them was used as compacted samples, which were placed in a different oven at 85°C for 5 days simulating the long term ageing of the asphalt pavement.
Thermal Stress Restrained Specimen Test has been used to study the low temperature cracking in asphalt pavement by many researchers. This test method has been currently standardized in EN 12697- 46. A comprehensive research study [9] shows that for both test parameters –indirect tensile strength and fracture strength there is significant correlation between laboratory and field data. According to this study direct tensile test provides useful information for the complete evaluation of low temperature behavior of asphalt mixtures.
The creep compliance and indirect tensile strength test according to AASHTO T 322 (2011) is used as a suitable performance test for low-temperature cracking in hot asphalt mixtures in the United States.
The creep compliance and strength test using the indirect tensile test device are also carried out according to AASHTO T 322 2011. The holding device, which is used for performing the test is similar to the one used for the determination of the indirect tensile strength at 25°C ASTM D 6931 2012 [10] or AASHTO T 283 2011, but it is equipped with a climatic chamber, where the temperature can be adjusted from -30°C to +30 °C and the speed of the applied load is lower - 12.5 mm/min instead of 50 mm/min.
The equipment for TSRST is complex, expensive and very few laboratories are able to perform the test. At the same time many laboratories are able to perform the ITS.

Therefore the asphalt specimens within this study were tested to be determined their indirect tensile strength at 0ºC.

4 Experimental Results

The results of tests for the bituminous binders included in this study are presented in Table 2.

№	Characteristics	Bituminous binders				
		50/70	70/100+ 3% Sasobit	70/100 + 2% Innovalt	70/100+ 4,4% Kraton D 1101	70/100 +2% Elvaloy
Before exposure to aging						
1	Penetration at 25ºC, 0,1mm	51.0	45.0	42.0	54.0	67.0
2	Softening point, ºC	51.5	74.0	67.5	69.9	62.9
3	Fraass breaking point, ºC	-16.5	-18.5	-17.5	-21.5	-21.5
4	Viscosity at 135ºC, Pa.s	0.561	0.289	1.431	1.638	1.724
5	Elastic recovery, %	_	_	_	85	82.5
6	Stiffness, MPa	199	238	243	143	140
7	m- value	0.303	0.283	0.300	0.336	0.385
After exposure to short term aging, according to EN 12607-1						
1	Mass change, %	0.05	0.03	0.08	0.02	0.14
2	Penetration at 25ºC, 0,1mm	32	33	32	40	51
3	Retained penetration, %	62.7	73.3	76.2	74.1	76.1
4	Softening point, ºC	60.9	79	81.6	74.5	68.5
5	Increasing of the softening point, ºC	9.4	5.0	14.1	4.6	5.6
6	Elastic recovery, %	_	_	_	83.5	80
7	Fraass breaking point, ºC	-13	-13	-14.5	-18.5	-18
8	Stiffness, MPa	207	277	275	166	157
9	m- value	0.286	0.250	0.270	0.303	0.363
After exposure to long term aging, according to EN 14769 (PAV, 100ºC, 20h)						
1	Fraass breaking point, ºC	-11	-13	-11	-16	-12
2	Stiffness, MPa	249	279	291	199	189
3	m- value	0.257	0.230	0.250	0.276	0.321
Calculated parameters						
1	PI(25-T_{sp})	-0.79	3.18	1.97	3.02	2.39
2	PI(25-T_{sp})(RTFOT)	0.18	3.15	3.42	2.96	2.64
3	PVN_{135}	-0.47	-1.48	0.58	1.07	1.43

Table 2: Test results for bituminous binders

From the results in Table 2 it follows that as a whole binders modified with organic polymers have lower Fraass breaking point, higher PVN_{135} values and PI, lower stiffness and higher m-value at –16ºC as compared to conventional bitumen and bitumens modified with long-chain paraffin waxes and inorganic polymer.
As can be seen from Figures 2, 3 and 4, the trend remains at short term aging for the stiffness, m-value and Fraass breaking point, while at long term aging the trend remains, except for the Fraass breaking point. Most probably this is due to a different aging mechanism affected by the various modifiers (some of which start chemical interaction with the neat bitumen).

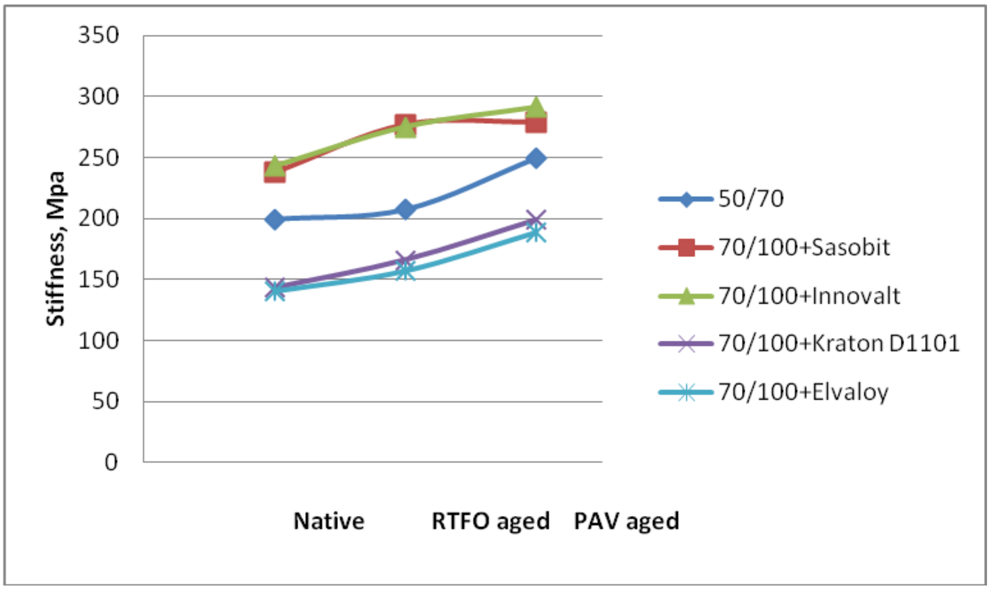

Figure 2: Change of stiffness at -16 ºC in the process of aging

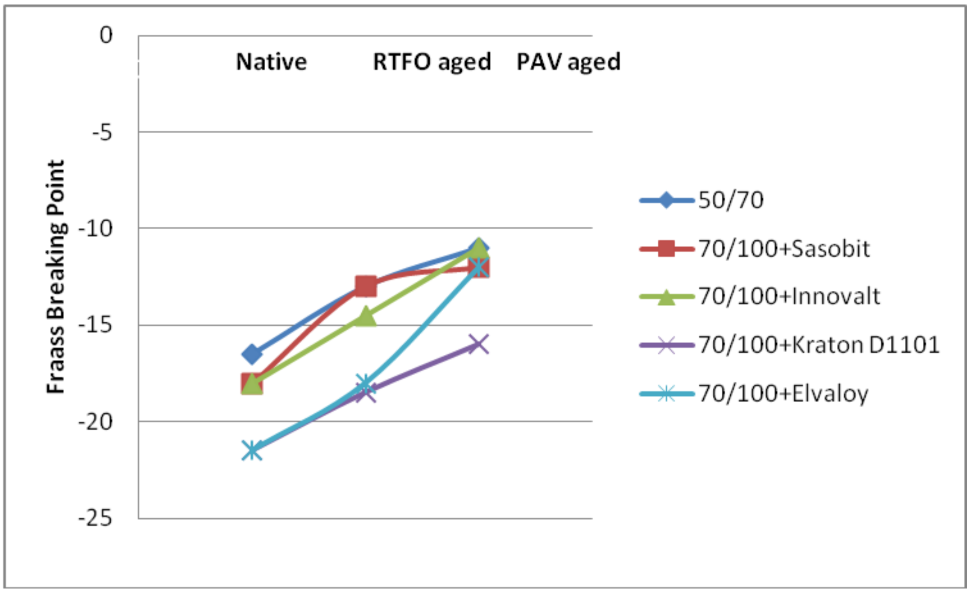

Figure 3: Change of m-value at -16 ºC in the process of aging

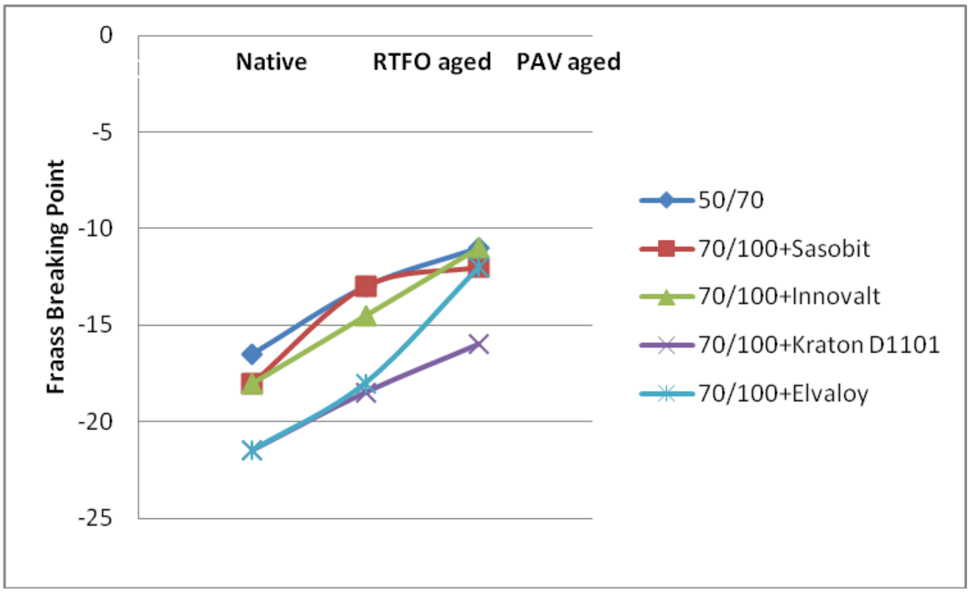

Figure 4: Change of Fraass breaking point in the process of aging

The test results for asphalt mixtures with different bituminous binders are presented in Table 3.

№	Characteristics	Asphalt concrete with binder:				
		50/70	70/100 + 3% Sasobit	70/100 + 2% Innovalt	70/100+ 4,4% Kraton D-1101	70/100+2% Elvaloy
1	Maximum density - BDS EN 12697-5, Mg/m^3	**2.482**	**2.479**	**2.475**	**2.474**	**2.477**
2	Bulk density - BDS EN 12697-6, Mg/m^3	**2.413**	**2.405**	**2.420**	**2.424**	**2.428**
3	Voids in the mineral aggregate - BDS EN 12697-8, % by volume	**15.3**	**15.5**	**14.8**	**14.6**	**14.6**
4	Residual porosity - BDS EN 12697-8, % by volume	**2.8**	**3.0**	**2.2**	**2.0**	**2.0**
5	Marshall stability - BDS EN 12697-34, kN	**9.8**	**8.6**	**8.7**	**13.2**	**10.5**
5.1	Marshall stability – after short term ageing for 4 hours at 135 ^oC BDS EN 12697-34, kN	**8.0**	**8.2**	**8.7**	**10.3**	**11.2**
5.2	Marshall stability – after long term ageing for 5 days at 85 ^oC BDS EN 12697-34, kN	**8.5**	**8.2**	**8.7**	**10.7**	**11.4**
6	Marshall flow - BDS EN 12697-34, mm	**3.3**	**2.4**	**3.5**	**3.6**	**3.7**
6.1	Marshall flow - after short term ageing for 4 hours at 135 ^oC BDS EN 12697-34, mm	**2.4**	**2.0**	**2.2**	**2.2**	**2.9**
6.2	Marshall flow - after long term ageing for 5 days at 85 ^oC BDS EN 12697-34, mm	**2.5**	**1.6**	**2.1**	**2.6**	**1.6**
7	Voids filled with bitumen - BDS EN 12697-8, % by volume	**81.9**	**80.7**	**85.0**	**86.2**	**86.5**
8	Water sensitivity - BDS EN 12697-12, %	**79**	**73**	**96**	**87**	**86**
9	Indirect tensile strength at 0^oC, GPa . 10^{-3}	**3.8**	**3.8**	**3.4**	**4.4**	**4.5**
9.1	Indirect tensile strength (at 0^oC) - after short term ageing for 4 hours at 135 ^oC, GPa . 10^{-3}	**3.7**	**3.7**	**3.9**	**4.4**	**4.4**
9.2	Indirect tensile strength (at 0^oC) - after long term ageing for 5 days at 85 ^oC, GPa . 10^{-3}	**3.5**	**3.6**	**3.7**	**4.4**	**4.4**

Table 3: Test results of the asphalt concrete specimens with different binders

From the results in Table 3 it follows that as a whole asphalt concrete specimens prepared with binders modified with organic polymers have higher Marshal stability, lower water sensitivity before and after short and long term aging in comparison with conventional bitumen and bitumen modified with long chain paraffin waxes and inorganic polymer, as illustrated on Fig. 5 to Fig 7. The values of the ITS follow the same tendency. The specimens prepared with organic polymers have higher values of ITS and are less sensitive to short and long term aging than those produced with neat bitumen and bitumen modified with Innovalt and Sasobit.

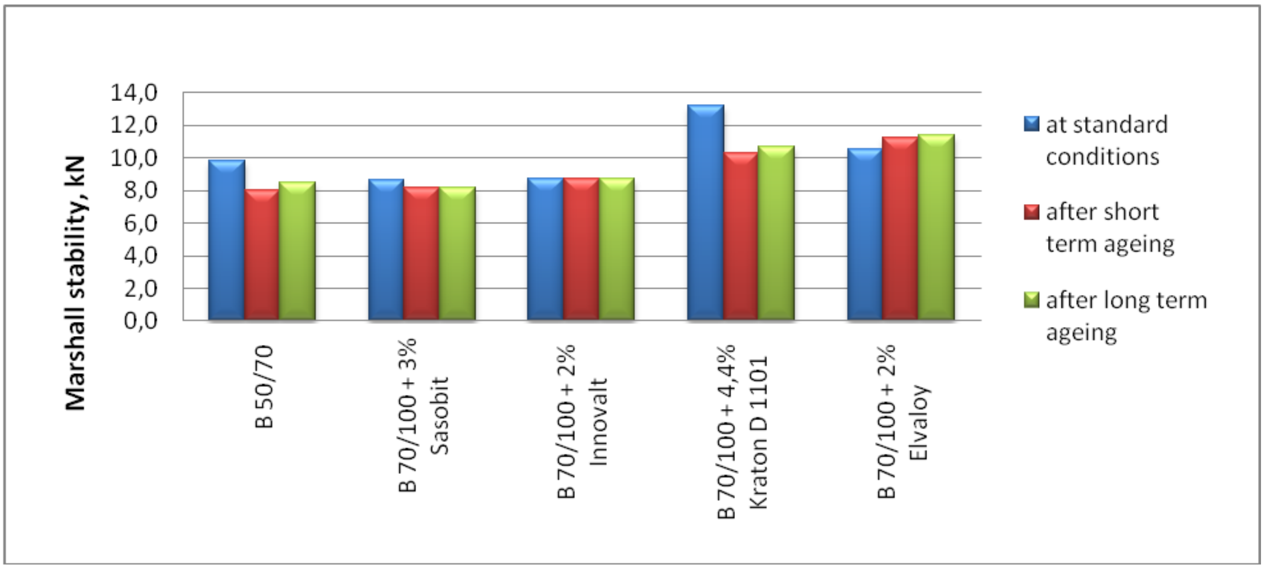

Figure 5: Marshal Stability

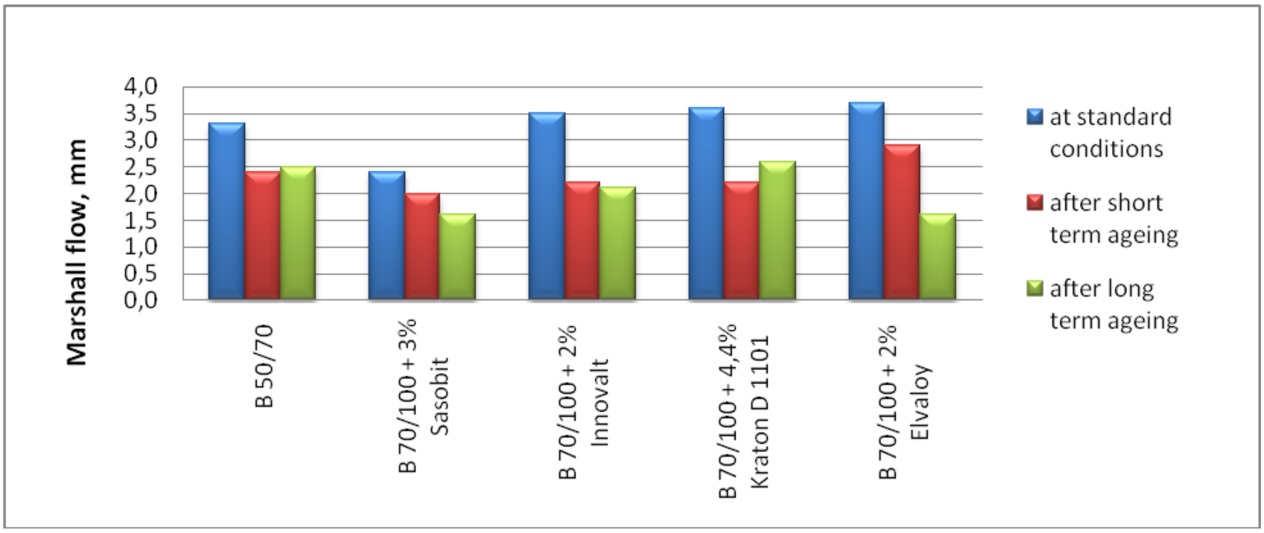

Figure 6: Marshal Flow

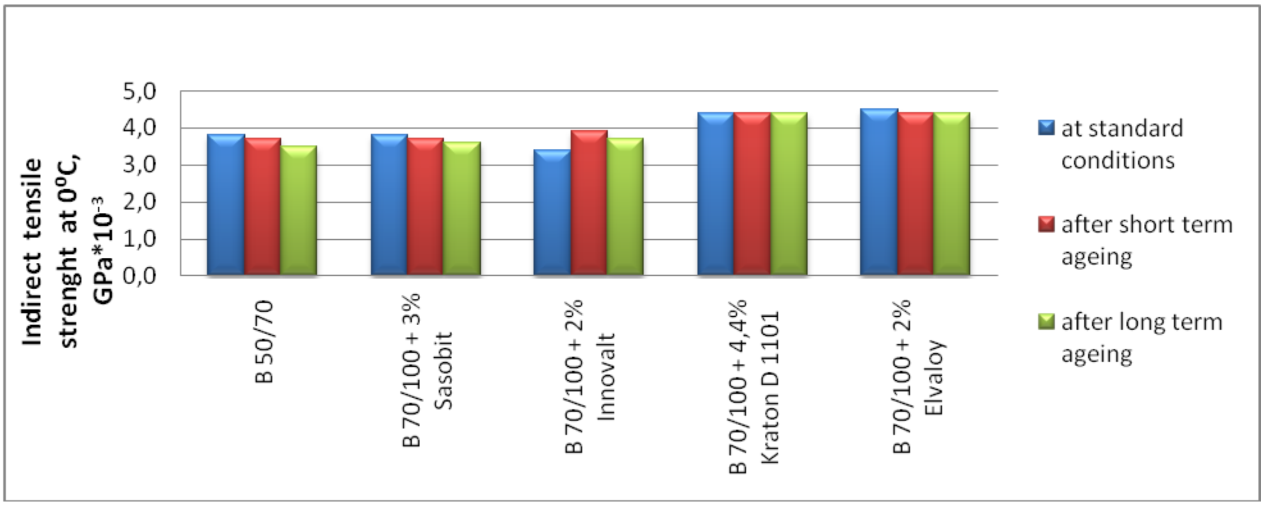

Figure 7: Indirect Tensile Strength at 0 °C

Univariant correlations have been calculated between the different characteristics of bituminous binders, which determine their behaviour at low temperatures and their temperature sensitivity, as well as the correlation between those characteristics and the indirect tensile strength at 0ºC for in-laboratory asphalt mixtures prepared with different binders. The correlation coefficient R^2 for a pair of variables is a standard measure of the relationship between them. The high correlation coefficient could be an indicator of a relationship between two characteristics. Bearing in mind that the typical limits of reproducibility for the various test methods for bituminous binders characteristics are from 5% to 10%, values of R^2 over 0,90 for a pair of binders characteristics, and R^2 over 0,80 for a pair of binder characteristics and indirect tensile strength at 0ºC could be an indication of a high correlation [11].
Table 4 presents the correlation coefficients for pairs of characteristics of binders and the coefficients characterizing the correlation of those characteristics with the indirect tensile strength at 0ºC for the laboratory prepared asphalt mixtures in the form of correlation matrix. Correlation coefficient has been calculated using function PEARSON in Excel, which returns the Pearson product moment correlation coefficient, r, in a dimensionless index that ranges from -1.0 to 1.0 inclusive and reflects the extent of a linear relationship between two data sets.
The correlation coefficients were calculated once with inclusion of all studied binders and a second time just for the materials modified with organic and inorganic polymers because they are from one and the same rheological type.

The results presented in Table 4 indicate that there is a correlation between:

- the stiffness at -16°C before and after exposure to short term and long term aging and the indirect tensile strength at 0 ºC before and after exposure to short term and long term aging;
- the m-value at -16°C before and after exposure to short term and long term aging and the indirect tensile strength at 0ºC before and after exposure to short term aging;
- the m-value at -16°C and stiffness at -16°C after exposure to long term aging;
- the Fraass breaking point before and after exposure to short term aging and the indirect tensile strength at 0ºC before and after exposure to short term aging;

Upon exclusion of conventional bitumen and bitumen modified with long chain paraffin waxes, it follows that there is a very high correlation between:

- the Fraass breaking point before exposure to short term aging and PVN_{135};
- the stiffness -16°C before exposure to aging and the Fraass breaking point before and after exposure to short term aging, as well as the penetration index, after exposure to short term aging;
- the stiffness at -16°C before and after exposure to short term aging and the Fraass breaking point before and after exposure to short term aging;
- the stiffness at -16°C after exposure to short term aging and the penetration index after exposure to short term aging;
- the m-value at -16°C before aging and PVN_{135}
- the m-value at -16°C after exposure to short term aging and the penetration index after exposure to short term aging
- the indirect tensile strength at 0 ºC and PVN_{135};
- the indirect tensile strength at 0 ºC after exposure to short term aging and the penetration index after exposure to short term aging.

2. CONCLUSION

From the study results the following conclusions could be reached:

- High correlation exists between the Fraass breaking point and the stiffness -16ºC;
- Upon inclusion of bitumen from one and the same rheological type and polymer modified with inorganic polymer, a high correlation is found between the empirical and the service-oriented characteristics, describing the behaviour of binders at low temperatures;
- There is a correlation between the indirect tensile strength of asphalt mixtures at 0ºC and a number of empiric and service-oriented characteristics of the binders, describing the behaviour of binders at low temperatures;
- In order to confirm the correlations it is advisable to extend this study by inclusion of a greater number of binders and different types of asphalt mixtures.

Table: 4 Correlation matrix for binder properties and ITS, $R^2 > 0.9$ for all binders has been marked with red background and $R^2 > 0.9$ for 3 modified binders has been marked with yellow background. $R^2 > 0,8$ for correlations between binder properties and ITS has been marked by green background.

	Fraass	Fraass (RTFOT)	Fraass (PAV)	PVN_{135}	PI(25-SP)	PI(25-SP) (RTFOT)	Stiffness	Stiffness (RTFOT)	Stiffness (PAV)	m-value	m-value (RTFOT)	m-value (PAV)	ITS, 0°C	ITS, 0°C , STA**	ITS, 0°C, LTA***
Fraass															
Fraass(RTFOT)															
Fraass(PAV)															
PVN_{135}	0.654; 0.907*														
PI(25-SP)	0.673; 0.803*			0.163; 0.477*											
PI(25-SP)(RTFOT)		0.354; 0.860*													
Stiffness	0.808; 0.999*			0.715; 0.917*	0.115; 0.787*										
Stiffness(RTFOT)		0.788; 0.983*				0.277; 0.939*									
Stiffness(PAV)			0.476; 0.571*												
m-value	0.787; 0.819*			0.829; 0.985*	0.178; 0.315*		0.873; 0.833*								
m-value(RTFOT)		0.767; 0.693*				0.081; 0.964*		0.862; 0.813*							
m-value(PAV)			0.093; 0.037*						0.902; 0.842*						
ITS, 0°C	0.887; 0.997*			0.550; 0.938*	0.317; 0.751*		0.948; 0.998*			0.831; 0.863*					
ITS, 0°C, STA		0.991; 0.993*				0.366; 0.913*		0.839; 0.998*			0.815; 0.771*				
S, 0°C, LTA			0.553; 0.756*						0.913; 0.994*			0.817; 0.780*			

* Only 3 polymermodified binders are included(70/100+Kraton D-1101/ Innovalt(PPA)/ Elvaloy; ** Short term aging; *** Long term aging

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