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BEHAVIOR OF STONE MASTIC ASPHALT AT LOW TEMPERATURES

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Abstract

This paper presents a detailed analysis of the influence of bitumen on low-temperature cracking of MAS 16 asphalt mixtures (stone mastic asphalt) used as wearing course on heavily trafficked roads. The study combines conventional bitumen tests (penetration, softening point, Fraass breaking point, ductility, Brookfield viscosity) with fundamental performance-related tests according to the SHRP methodology (Bending Beam Rheometer – BBR, Dynamic Shear Rheometer – DSR), as well as the Thermal Stress Restrained Specimen Test (TSRST) performed on asphalt mixtures.

Five bitumens, both unmodified and polymer-modified, from two different sources were analyzed. The results show that polymer-modified binders exhibit a more balanced behaviour under extreme temperatures, with larger plasticity ranges, lower stiffness at low temperatures and improved thermal stability at high temperatures. TSRST fracture temperatures of mixtures containing modified binders are significantly lower (−35…−37 °C), whereas the corresponding cryogenic fracture stresses are higher, compared to mixtures based on unmodified binders.

A good agreement was found between the stiffness limit temperature obtained from BBR tests and the fracture temperature determined by TSRST, confirming the relevance of fundamental binder testing for predicting mixture performance at low temperatures. Short-term ageing of bitumen (RTFOT) led to an increase of TSRST fracture temperature by 2–3 °C and to a performance decrease of up to 12 %, which highlights the need to define low-temperature performance requirements based on aged binder.

Keywords: stone mastic asphalt, low-temperature cracking TSRST, BBR, RTFOT ageing.

1. INTRODUCTION

Low-temperature cracking represents one of the main causes of premature deterioration of asphalt pavements in regions with temperate-continental or cold climates. The thermal contraction of the asphalt mixture, combined with the constraints imposed by the pavement structure and operational conditions, leads to the development of internal stresses which, once exceeding the tensile strength of the material, generate thermal cracks.

It is internationally recognized that thermal cracking is primarily related to the consistency and temperature susceptibility of the bitumen, as well as to the relaxation characteristics of the asphalt mixture. The relationship between temperature and bitumen stiffness is generally accepted as the key factor governing the extent of low-temperature cracking; lower viscosity (i.e., higher penetration) results in a slower increase in mixture stiffness as temperature decreases and therefore reduces the potential for thermal cracking [1,2].

The performance of asphalt mixtures cannot be adequately characterized solely by the empirical properties of the binder, since the pavement structure is subjected to complex environmental and loading conditions, and modified bitumens cannot be sufficiently described using simple parameters. In this context, the SHRP methodology introduced the classification of bitumens into Performance Grades (PG), based on the maximum and minimum design pavement temperatures, using fundamental tests (BBR, DSR, DTT) [3–5].

In Romania, the stone mastic asphalt (SMA) named MAS 16 is regulated by the AND 605 norm and SR EN 13108-5 standard, being used as a wearing course for technical class I–IV roads and category I–IV streets. MAS is widely used internationally as a wearing asphalt mixture for heavy-traffic roads, airfields, industrial zones, and port infrastructure, due to its favourable texture, resistance to permanent deformation, and binder-rich mastic, which offers high durability. However, the high binder content requires the use of an anti-drainage additive.

In this context, the main objective of the present study is to evaluate the influence of bitumen type (unmodified and polymer-modified) on the low-temperature cracking behaviour of MAS 16 asphalt mixtures, by correlating the binder properties with the mixture behaviour determined through the TSRST test.

2. MATERIALS AND METHODS

2.1. Types of Bitumen Analysed

Five bitumen types sourced from two suppliers (I and II) were analysed:

- I-A: unmodified bitumen 50/70 (source I)
- II-A: unmodified bitumen 50/70 (source II)
- I-B: polymer-modified bitumen 45/80-65 (source I)
- II-B: polymer-modified bitumen 45/80-65 (source II)
- I-C: unmodified bitumen 70/100 (source I)

The three unmodified bitumens (I-A, II-A, I-C) and the two polymer-modified bitumens (I-B, II-B) were used to prepare MAS 16 mixtures according to AND 605 norm and SR EN 13108-5 standard requirements.

2.2. Bitumen Tests

Classical tests were performed according to SR EN 12591 and SR EN 14023 (penetration, softening point, ductility, Fraass breaking point, elastic recovery, storage stability (for modified bitumens), mass change and softening point increase after ageing, residual penetration, adhesion, chemical composition - SARA fractions) and the results are summarized in Table 1.

The SHRP methodology included:

- Brookfield viscosity at 135 °C, 150 °C, and 160 °C (SR EN ISO 2555);
- DSR tests (SR EN 14770) to determine the complex shear modulus G^* and phase angle δ, as well as the parameters $G^*/sin\delta$ and $G \cdot sin\delta$ before and after RTFOT and PAV aging;
- BBR tests (SR EN 14771) to determine stiffness modulus S and slope m at low temperatures.

According to SHRP criteria, the Direct Tension Test (DTT) (SR EN 13587) was not required, since all bitumens met the BBR requirements.

2.3. TSRST Testing of Asphalt Mixtures

MAS 16 asphalt mixtures were prepared using identical gradations, varying only the bitumen type. The TSRST (Thermal Stress Restrained Specimen Test [6]) was carried out on prismatic specimens kept at constant length under the following conditions:

- initial temperature: T_0 = +20 °C;
- cooling rate: −10 °C/h;
- continuous monitoring of cryogenic stress σ_{cry} (T);
- determination of the fracture temperature $T_{failure}$ and failure stress $\sigma_{cry,failure}$.

To account for the thermal lag between chamber air and the core of the specimen, a reference instrumented specimen was used for temperature correction.

2.4. Bitumen Aging

Short-term aging was simulated using the RTFOT (Rolling Thin Film Oven Test). The aged bitumen was then used to prepare MAS 16 asphalt mixtures, which were tested via TSRST. Results were compared with those of mixtures containing unaged bitumen.

3. RESULTS AND DISCUSSION

3.1. Comparative Analysis of Unmodified and Modified Bitumens

The results of conventional tests (Table 1) show significant differences between unmodified and polymer-modified bitumens:

Table 1. Bitumen characteristics

Characteristic	I-A	II-A	I-B	II-B	I-C
Penetration at 25°C (0,1mm)	60	60	59	52	84
Softening point (°C)	47,0	48,1	74,3	73,5	44,8
Ductility at 25°C (cm)	>150	>150	-	-	>150
Fraass breaking point (°C)	-12	-13	-20	-16	-14
Elastic recovery at 25°C at 10°C (%)	-	-	91 71	86 63	-
Storage stability Ring and Ball difference (°C)	-	-	2,6	0,7	-
Chemical composition - saturated - aromatic - resin - asphaltene (%)	4,26 39,80 34,91 20,66	6.89 32,92 39,41 20,78	-	-	4,36 41,66 32,97 20,84
Colloidal index	0,33	0,38	-	-	0,34
Adhesion (%)	91,97	-	93,75	-	-
After RTFOT aging					
Change of mass	+0,07	+0,04	-0,07	-0,16	+0,02

Characteristic	I-A	II-A	I-B	II-B	I-C
(%)					
Increase in softening point (ºC)	5,0	6,7	5,1	5,1	5,3
Penetration at 25ºC (0,1mm)	44,4	40,4	45,2	32,9	52,2
Retained Penetration (%)	72,4	67,4	76,7	62,9	61,9
Elastic recovery at 25ºC (%)	-	-	78,8	81,0	-
Ductility at 25ºC (cm)	>150	106	-	-	>150

Key findings:

- I-B and II-B polymer-modified bitumens have softening points >73 °C, far higher than unmodified bitumens (~47–48 °C), indicating improved thermal stability.
- Fraass breaking points are lower (−20 °C for I-B bitumen, −16 °C for II-B bitumen), showing better resistance to low-temperature cracking.
- Unmodified bitumens show less favourable Fraass values (−12…−14 °C), indicating higher susceptibility to cold-weather cracking.

Chemical composition reveals low saturates and high aromatics for I-A, II-A, and I-C bitumens, with colloidal instability indices of 0,33–0,38, typical of "sol" - type bitumens. Their higher Fraass breaking points compared with modified binders suggest lower flexibility at negative temperatures.

3.2. Plasticity Range and Performance Indices

The plasticity range was evaluated both from classical parameters (softening point – Fraass breaking point) and from SHRP-based grades. Figures 1 and 2 illustrate the plasticity intervals and the corresponding performance grades.

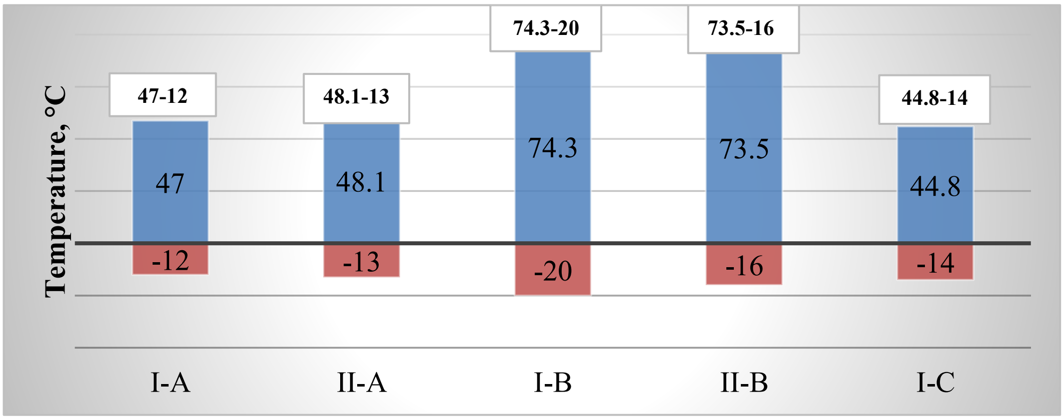

Figure 1. Plasticity range determined from the conventional tests for the investigated bitumens

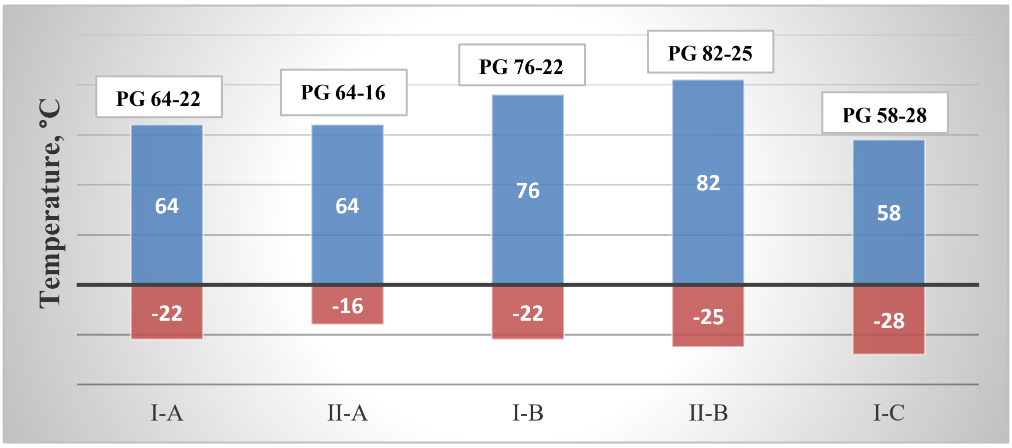

Figure 2. Performance grading of the investigated bitumens based on the SHRP methodology

Using the performance index PI = [(max − min) / max] × 100, the values summarized in Table 2 were obtained based on the plasticity ranges examined in the studies shown in Figure 1 and Figure 2.

Table 2. Performance indices obtained for the plasticity range of the studied bitumens

Characteristic – Performance	[U.M]	Performance indices, IP, %				
		Bitumen				
		I-A	II-A	I-B	II-B	I-C
Plasticity Range Ip (R&B–Fraass)	ºC	59	61,1	94,3	89,5	58,8
Performance Index IP (R&B–Fraass)	%	0,3	3,8	37,6	34,3	0
Plasticity Range Ip (SHRP)	ºC	86	80	98	107	86
Performance Index IP (SHRP)	%	7	0	18	25	7

The IP performance indices (Table 2) highlight:

- IP values of 37,6% (I-B bitumen) and 34,3% (II-B bitumen) for the classic plasticity range (R&B-Fraass);
- IP values of 18% (I-B bitumen) and 25% (II-B bitumen) for the SHRP plasticity range.

Unmodified bitumens have low performance indices, confirming their less favorable behavior at extreme temperatures.

3.3. Brookfield Viscosity

The Brookfield viscosity (Figure 3) decreases with increasing temperature, but the differences at 135 °C are significant:

- unmodified bitumens: 0,311–0,406 Pa·s;
- polymer-modified bitumens: 1,895–1,935 Pa·s.

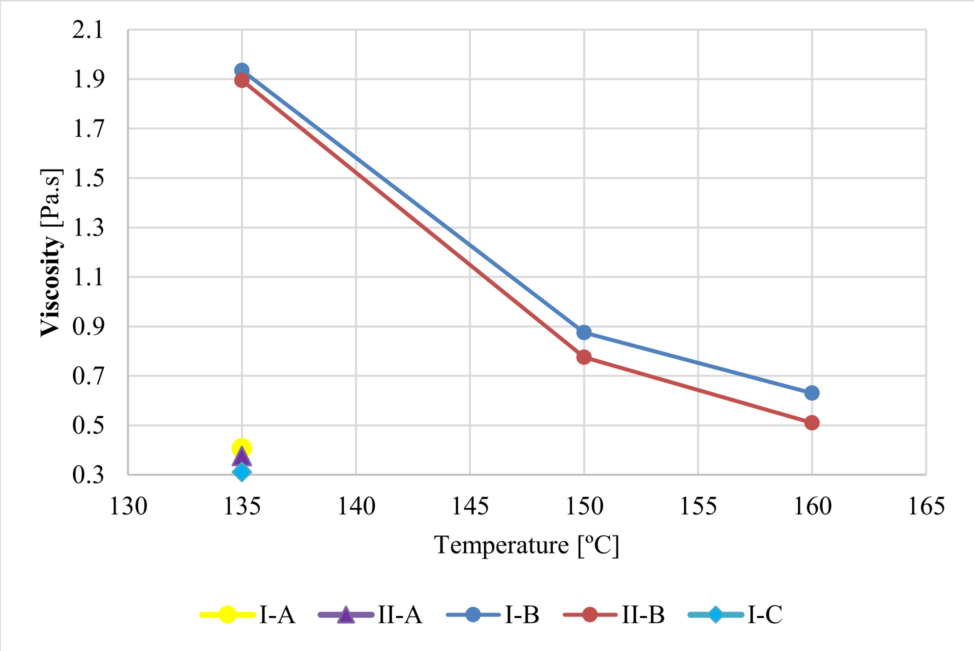

Figure 3. Brookfield viscosity of the investigated bitumens

Analyzing the obtained results, it can be observed that the polymer-modified bitumens (I-B and II-B) exhibit a significant increase in viscosity compared to the unmodified binders, which leads to improved behaviour of the asphalt mixtures prepared with such binders when subjected to elastic-range deformations under traffic-induced loading conditions.

3.4. DSR and BBR Results

DSR tests (Table 3) show that:

- all binders satisfy SHRP criteria for rutting resistance ($G^*/\sin\delta \geq 1{,}0$ kPa for original binder and $\geq 2{,}2$ kPa after RTFOT at the high PG temperature);
- the polymer-modified binders tend to exhibit higher $G^*/\sin\delta$ values, improving rutting resistance;
- for PAV-aged binders, $G\cdot\sin\delta$ values remain below 5000 kPa at the fatigue evaluation temperature, meeting SHRP fatigue criteria.

The BBR results (Figure 4, Figure 5) indicate:

- lower S stiffness modulus for modified bitumens at low temperatures;
- higher creep slope, which means lower sensitivity to temperature variation and better stress relaxation capacity.

Table 3. Results of SHRP tests for the analysed bitumens: viscosity and DSR

Characteristic	**Method Determination**	**Unit**	**Unmodified bitumen 50/70**		**Polymer-modified bitumens 45/80**		**Unmodified bitumen 70/100**
			I-A	II-A	I-B	II-B	I-C
Brookfield viscosity at 135º C at 150º C at 160º C	SR EN ISO 2555	Pa.s	0,406	0,375	1,895 0,875 0,630	1,935 0,775 0,510	0,311
DSR G*/sinδ (min. 1,0 kPa)	SR EN 14770	kPa	1,37	1,25	1,75	1,15	1,85
After PAV at 100º C							
DSR G*sinδ (max. 5000 kPa)	SR EN 14770	kPa	1700	943	574	760	344

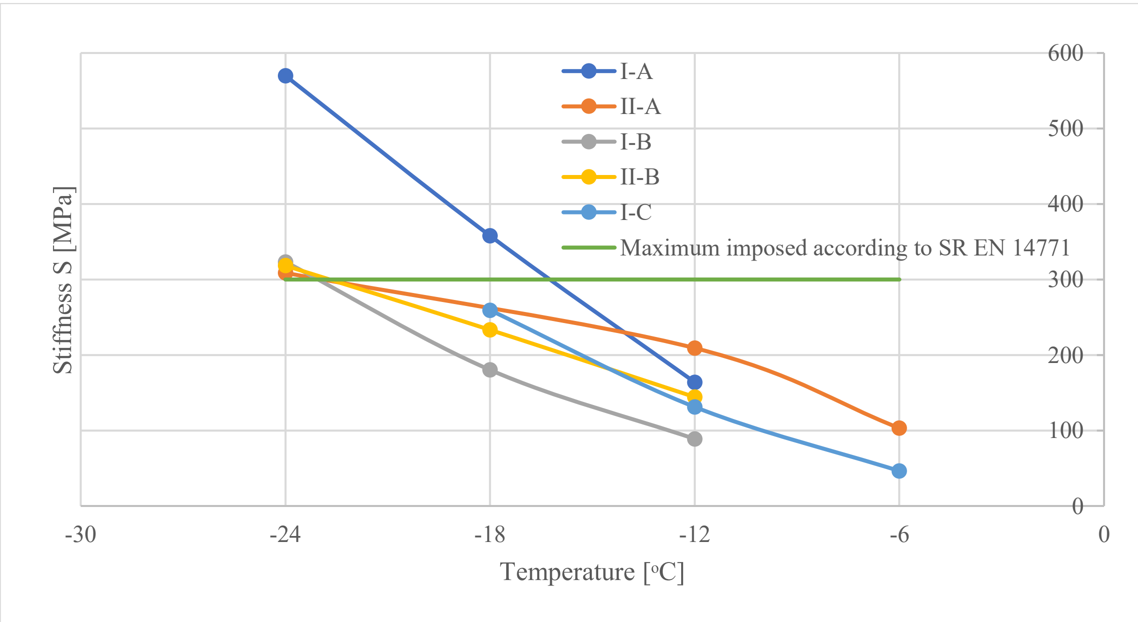

Figure 4. Variation of the stiffness modulus of bitumens with temperature, determined by the BBR test (Low Temperature Crack Resistance)

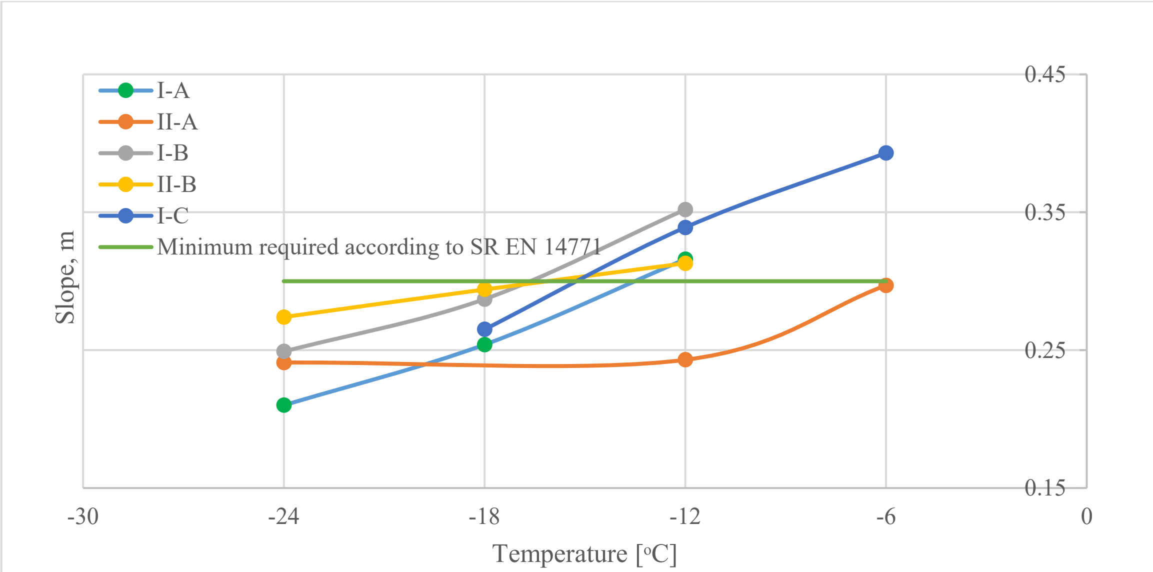

Figure 5. Variation of the creep slope of bitumens with temperature, determined by the BBR test (Low Temperature Crack Resistance)

Even though for some unmodified bitumens the modification with polymers does not significantly change the performance grade (PG) at low temperatures, the general trend shows an improvement in the viscoelastic response.

3.5. Behavior of MAS 16 mixtures in the TSRST test

The TSRST test on MAS 16 mixtures prepared with the five bitumens (Figure 6, Figure 7) shows:

- failure temperatures near the threshold of the requirements for unmodified I-A and II-A bitumens (≈ −25…−26 °C), corresponding to low performance in severe climatic conditions;
- significantly lower failure temperatures for modified bitumen mixtures: −35 °C (I-B bitumen), −37 °C (II-B bitumen), and −33 °C for I-C bitumen;
- maximum values of failure stress $\sigma_{cry,failure}$ for the II-B bitumen mixture, indicating a higher capacity to absorb cryogenic stresses, while the II-A unmodofied bitumen mixture has the lowest values.

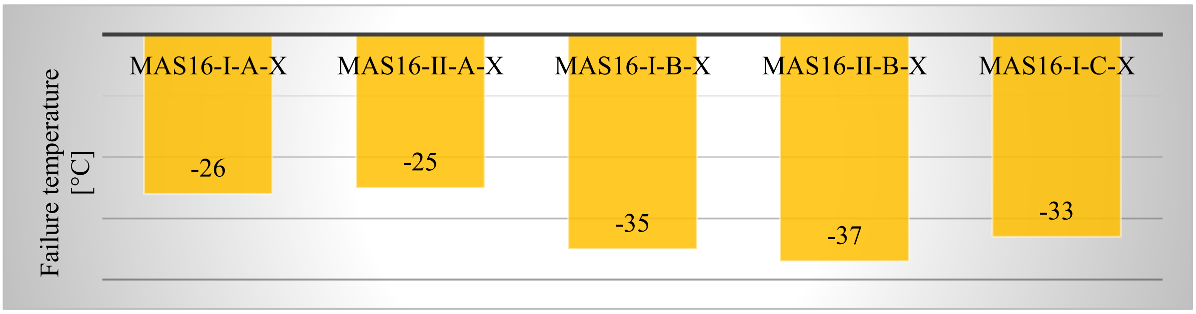

Figure 6. Variation of the failure temperature TSRST [ºC], depending on the type of bitumen

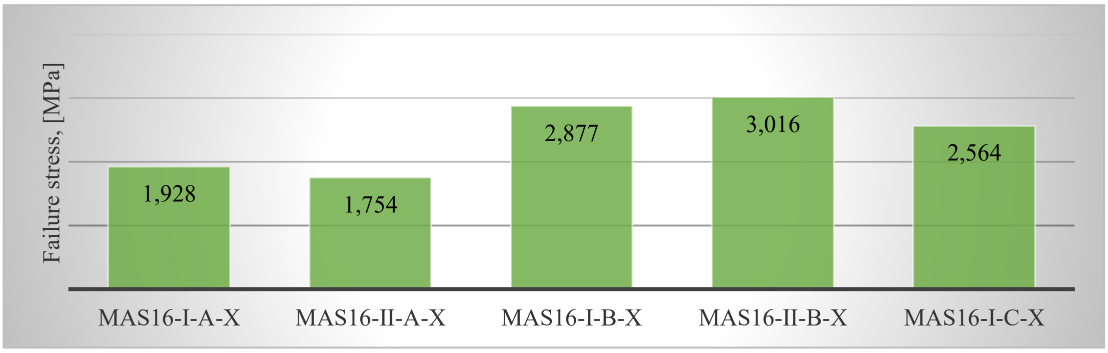

Figure 7. Variation of the failure stress, $\sigma_{cry,failure}$, [MPa], depending on the type of bitumen

The best performance at low temperatures — reflected in the lowest breaking temperature and highest breaking stress — is achieved for the mixture prepared with II-B bitumen, and the poorest for the mixture with II-A bitumen.

3.6. Correlation between binder properties and mixture performance

Correlation of Fraass breaking point, BBR, and TSRST values (Figure 8) shows a similar trend in results: bitumens with lower BBR temperatures and more favorable Fraass breaking points generally lead to mixtures with lower TSRST failure temperatures. The temperature determined by BBR — which defines the low-temperature performance class — is closest to the TSRST, suggesting the potential of BBR as a tool for predicting cold-temperature behaviour of mixtures.

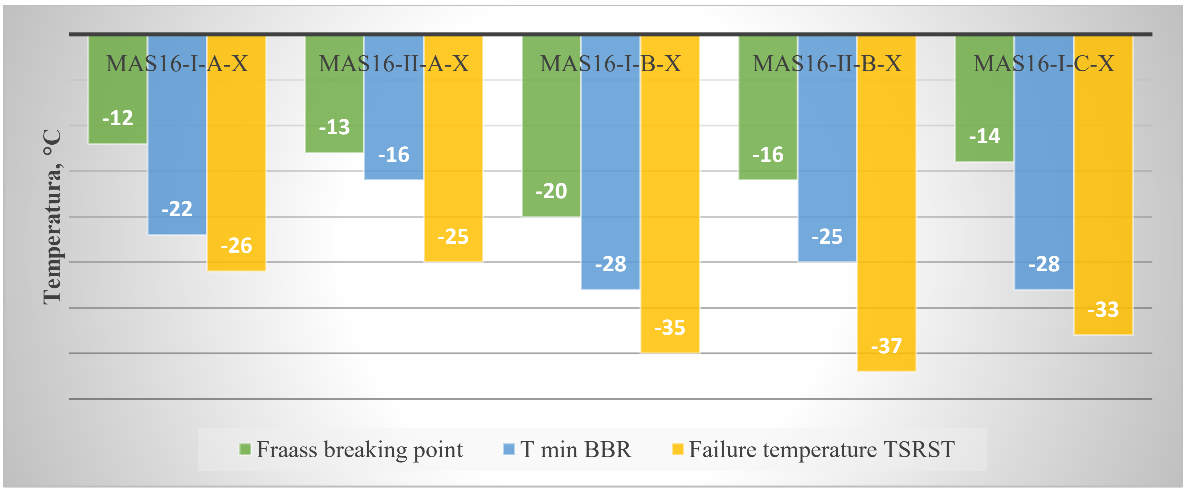

Figure 8. Representation of bitumen and mixture behavior at low temperatures

However, the correlation coefficient R^2 for simple linear correlations among the Fraass, BBR, and TSRST parameters was below 0.70, indicating the need to expand the database for a robust statistical analysis.

3.7. Effect of bitumen aging on cold cracking

Short-term aging (RTFOT) causes an increase in the TSRST breaking temperature by 2–3 °C (up to −23 °C) for mixtures with unmodified bitumen I-A and II-A (Figure 9), as well as a reduction in low-temperature performance of 12% and 8%, respectively. This confirms that the stiffening of the binder through aging increases the susceptibility of mixtures to cracking at low temperatures.

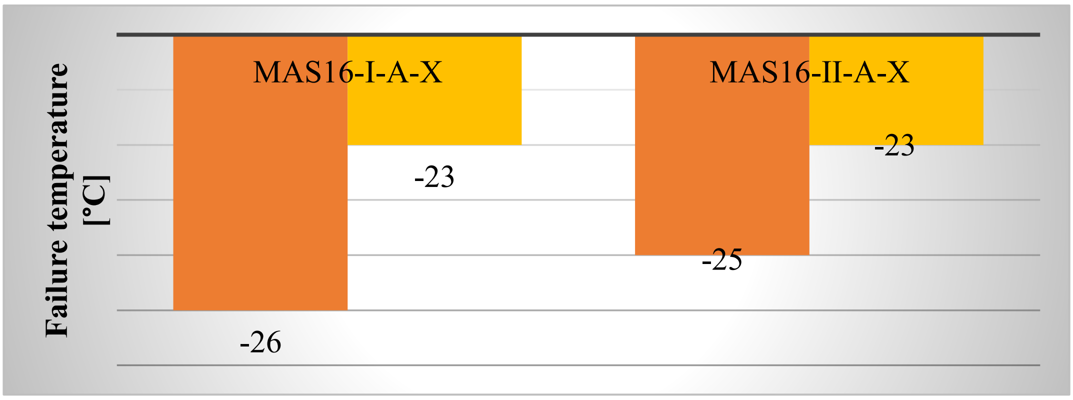

Figure 9. TSRST failure temperature for the mixture with unaged bitumen and aged bitumen

4. **CONCLUSIONS**

From this study can be drawn some important conclusions:

- The type of bitumen has a decisive influence on cracking at low temperatures. Polymer-modified bitumens (I-B and II-B) give MAS 16 asphalt mixtures superior performance, being characterized by lower TSRST temperatures and higher tensile strengths compared to unmodified bitumens;
- Unmodified bitumens are at the limit of acceptable performance at low temperatures, especially after aging, which makes them less suitable for pavements exposed to severe climatic conditions, even if they meet classic regulatory requirements;
- The fundamental BBR and DSR tests are essential for characterizing performance at extreme temperatures. The stiffness limit temperature determined by BBR is closest to the TSRST failure temperature and can be used as a predictor of mixture behavior;
- Short-term aging of bitumen significantly reduces performance at low temperatures, requiring performance specifications to be defined based on results obtained on samples aged in the laboratory (RTFOT, PAV);
- Integrated binder-mixture evaluation is essential. Bitumen properties must be analyzed using both conventional and fundamental tests, and the results must be correlated with the behavior of the mixture in tests such as TSRST to ensure appropriate structural and material design of asphalt pavements according to climatic and traffic conditions.

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