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Performance characterization of warm mix asphalt for porous wearing courses and base layers produced with highly polymer modified bitumen

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Abstract

Increasing road traffic demands have led to the need for longer lasting, higher performing pavements. To improve pavement durability, extend its service life and reduce maintenance costs, highly polymer modified bitumen (HiPMB) containing ad hoc styrene polymers has been introduced to the market. The objective of this study is to evaluate the performance of warm mix asphalt (WMA) produced with HiPMB to be used for porous wearing courses and base layers of motorway pavements. Specifically, three HiPMBs (two available on the European market and one under development, each one with styrene polymer content ≥ 7.5%) are examined and compared with a reference polymer modified bitumen (PMB) containing 3.8% SBS polymers. The porous mixtures were subjected to workability analysis, indirect tensile strength (ITS), semi-circular bending (SCB) and Cantabro tests (all carried out after both dry and wet conditioning). As for the base mixtures, testing included indirect tensile stiffness modulus (ITSM) and indirect tensile fatigue tests (ITFT), in addition to workability and ITS analysis. The results indicate that, in some cases, asphalt mixtures produced with HiPMB perform better than asphalt mixtures produced with PMB. The issues in terms of adhesion with aggregates observed for the HiPMBs could explain some penalized performance characteristics of the related mixtures.

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Keywords: pavement; asphalt; highly modified asphalt (HiMA); styrene polymer; vinyl group.

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1. Introduction

In recent decades, SBS (styrene-butadiene-styrene) polymer modified bitumen (PMB) has been increasingly used in road pavements instead of plain bitumen in order to produce enhanced asphalt concrete (AC), able to cope with the continuous increase in traffic volumes and loads, as well as more aggressive weather conditions (Zhu et al., 2014). However, SBS PMBs show some drawbacks, including storage stability issues and relatively poor resistance to heat, oxidation and UV radiation, making AC no longer able to meet increased pavement performance requirements (Zhu et al., 2014). These factors reduce the effectiveness of AC in combating distress phenomena such as rutting, thermal cracking and fatigue, increasing the need for advanced solutions.

To address the above limitations, new styrene polymers with high vinyl content in polybutadiene have recently been introduced, enabling the polymer dosage in bitumen to be feasibly increased up to 9% (Wu et al., 2024). The use of highly polymer modified bitumen (HiPMB) in conventional paving applications has been proven to improve the performance – increasing the resistance to major pavement distresses (i.e., rutting, thermal cracking, fatigue cracking) – and longevity of the pavement (Habbouche et al. 2021; Jaskula et al., 2020; Rivera et al., 2022; Zhang et al., 2021). However, the available data remains limited, especially concerning non-standard mixtures.

In this context, the present study aims at evaluating the mechanical performance of open- and dense-graded warm mix asphalt (WMA) produced with HiPMBs of different formulation through a laboratory characterization. In addition, a reference WMA mixture prepared with a conventional SBS PMB currently used in motorway applications in Italy was selected for comparison purposes.

2. Experimental program

2.1. Materials

The laboratory investigation involved four open-graded and four dense-graded WMAs for porous wearing courses and base layers, respectively. Both sets of WMAs were produced using a reference SBS PMB and three HiPMBs. The four binders selected differ in terms of polymer dosage/type and base bitumen employed. Specifically, the SBS PMB and HiPMB_A binders contain the same base bitumen (70/100) with 3.8% radial SBS polymers and 7.5% high-vinyl styrene polymers, respectively. For HiPMB_A, storage stability was evaluated at the asphalt plant following production, showing satisfactory performance, i.e., a softening point difference of 0.5 °C between the top and bottom parts after the tube test. For the binders HiPMB_O and HiPMB_V, the exact formulation (i.e., polymer dosage/type and base bitumen) is undisclosed, since they were collected from the market without any additional information given by the producers. The main properties of the studied binders are shown in Table 1, whereas an extensive characterization of these binders is provided in Carlucci et al. (2025).

Table 1 – Properties of the binders.

Property	SBS PMB	HiPMB_A	HiPMB_O	HiPMB_V
% polymer	3.8	7.5	≈ 7.5	≈ 9.0
Viscosity@135°C (Pa·s)	1.6	1.4	2.6	2.4
Penetration at 25 °C (0.1 mm)	32	31	53	61
Softening point by Ring and Ball (°C)	74.8	75.2	87.3	79.7

The mix design of all WMAs was based on the Italian technical specifications for motorway pavements. Specifically, the open-graded WMAs were composed of basaltic aggregates, calcareous filler, 15% reclaimed asphalt pavement RAP (obtained from the milling of open-graded wearing courses) and 5.3% total binder content (by aggregate weight), whereas the dense-graded WMAs were composed of limestone aggregates, 30% RAP and 4.3% total binder content (by aggregate weight). For all mixtures, 0.5% WMA chemical additive (by total binder weight) was added. In the case of open-graded mixtures, 0.3% of cellulose and glass fibers (by aggregate weight) was also added to prevent drain-down issues. The mixtures are coded as OG/DG_P/HA/HO/HV, where the first two letters

indicate the mixture type (OG = open-graded, DG = dense-graded) and the further letters denote the binder type (P = SBS PMB, HA = HiPMB_A, HO = HiPMB_O, HV = HiPMB_V).

2.2. Mixtures production and compaction

All mixtures were produced in the laboratory following a standardized protocol by means of a laboratory mixer (EN 12697-35). Before mixing, the binders were heated at a convenient temperature in order to guarantee the equiviscosity condition and mixed with the chemical additive. Then, pre-heated aggregates, hot bitumen, RAP, fibers (only for open-graded mixtures) and pre-heated filler were mixed in sequence at a temperature equal to 130 °C. After mixing, all asphalt mixtures were kept in an oven at 120 °C (compaction temperature) for 1 hour. Subsequently, a set of specimens was compacted using the Marshall compactor (specimens required for the Cantabro tests) according to EN 12697-30, whereas another set was compacted by means of a gyratory shear compactor (specimens required for all the other tests) according to EN 12697-31 to obtain 100 mm and 150 mm diameter cylindrical specimens. From each 150 mm gyratory-compacted specimen, four semi-circular specimens (dimensions: 150 mm length × 75 mm radius × 50 mm thickness) were extracted for semi-circular bending (SCB) testing (open-graded mixtures), two 150 mm diameter × 55 mm height specimens for indirect tensile strength (ITS) evaluation, and two 150 mm diameter × 50 mm height specimens for indirect tensile stiffness modulus ITSM tests and indirect tensile fatigue tests ITFT (dense-graded mixtures).

2.3. Testing program

All mixtures were investigated in terms of volumetric, workability and mechanical properties. As for the mechanical characterization, the open-graded mixtures were evaluated in terms of strength, raveling and fracture properties through ITS, Cantabro and SCB tests, whereas the dense-graded mixtures were assessed for stiffness and fatigue behaviour by means of ITSM tests and ITFT, in addition to ITS evaluation. The experimental program is detailed in Table 2.

Table 2 – Testing program on open- and dense-graded mixtures (the numbers indicate the test repetitions).

Mixtures	Volumetric properties and workability	ITS @25 °C		Cantabro @25 °C		SCB @10 °C		ITSM @20 °C	ITFT @20 °C
		Dry	Wet	Dry	Wet	Dry	Wet		
OG_P/HA/HO/HV	10	5	5	5	5	4	4	\	\
DG_P	3	3	3	\	\	\	\	6	4
DG_HA/HO/HV	3	3	3	\	\	\	\	12	6

2.4. Test procedures

The volumetric properties of the compacted specimens were assessed in terms of air void content (AV) in compliance with EN 12697-8. The bulk density of each specimen was calculated in accordance with EN 12697-6, by adopting procedure D (geometric method) for open-graded mixtures and procedure B (saturated surface dry SSD method) for dense-graded mixtures.

The workability of the mixtures was evaluated by calculating from the gyratory data the compaction energy index (CEI), representative of the energy expended by the roller to compact the mixture to the required density before opening to traffic, as proposed by Mahmoud & Bahia (2004). CEI was calculated as the area under the compaction curve from the 8th gyration to a compaction level equal to 80% of the maximum density for open-graded mixtures, and up to the gyration corresponding to 92% of the maximum density for dense-graded ones.

The strength properties were evaluated through indirect tensile test at 25 °C in accordance with EN 12697-23. ITS tests were performed on 100 mm diameter specimens compacted at 50 gyrations for the open-graded mixtures and 150 mm diameter specimens compacted at 120 gyrations for the dense-graded ones, considering both dry-conditioned specimens (72 hours in a climate chamber at 25 °C) and wet-conditioned ones (72 hours in a water bath at 40 °C

followed by 3 hours at 25 °C in a climate chamber). Thus, water sensitivity was evaluated using the ITSR parameter (ITS_{wet}/ITS_{dry}).

The Marshall-compacted specimens were tested for evaluating the raveling resistance by means of Cantabro tests carried out at 25 °C, following EN 12697-17. The particle loss (PL) of the specimen during the test was calculated as a parameter representative of the raveling resistance of the mixture. The specimens were tested after both dry and wet conditioning.

The cracking resistance was evaluated through SCB tests on half-disc specimens at 10 °C after both dry and wet conditioning. SCB data were elaborated to determine the fracture toughness K_{IC} in accordance with EN 12697-44. Additional energy dissipation-related parameters were also calculated, i.e., the fracture energy (G), which is related to the overall ductility of the material (Biligiri et al., 2012), and the flexibility index (FI), which is representative of the material ductility in the crack propagation phase (Ozer et al., 2016a, 2016b).

The ITSM test was performed at 20 °C on cylindrical specimens through a servo-pneumatic machine in accordance with EN 12697-26 – Annex C. The test consisted in applying an impulsive loading with a rise-time of 124 ms along the vertical diameter of the specimen to induce a target maximum horizontal deformation of 7.5 ± 2 μm. The ITSM value was calculated as the average of two measurements taken along two perpendicular specimen diameters and was considered representative of the mixture stiffness.

The resistance to cyclic loading was evaluated by performing ITFT at 20 °C, in accordance with EN 12697-24 – Annex E. The test was performed in controlled load mode by applying a haversine pulse (0.1 s load, 0.4 s rest), whereas the specimen horizontal deformation was measured via two LVDTs. The stress range was calibrated to target specific initial horizontal strain levels ε_0. The complete specimen fracture was considered as the failure criterion to determine the number of loading cycles to failure N_f. The test was carried out on the specimens preliminarily subjected to ITSM tests. The fatigue curve (N_f vs. ε_0), plotted on a bi-logarithmic scale, was considered as representative of the fatigue response of the material. Furthermore, the strain corresponding to one million cycles (ε_6) was also estimated to further compare the different mixtures.

3. Results and analysis

3.1. Open-graded mixtures

Figure 1a shows the compactability results in terms of average CEI and AV values evaluated after 50 gyrations. Results highlight that all mixtures (including the reference mixture OG_P) are characterized by similar CEI and AVs and meet the minimum AV requirement of the technical specifications for motorway pavements (20%). This means that no significant effect on compactability can be attributed to the binder type.

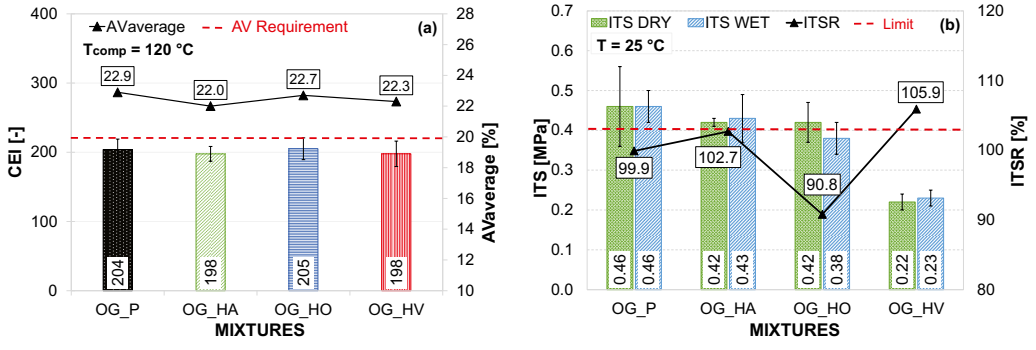


Fig.1. OG mixtures: (a) CEI values vs. air void content at 50 gyrations, (b) ITS values in dry and wet conditions and ITSR values.

Figure 1b reports the average ITS values in both dry and wet conditions, along with the average ITSR. Results show that the mixtures produced with HiPMBs exhibit slightly lower strength properties as compared to the reference mixture OG_P and barely satisfy the Italian ITS specification requirement (ITS ⩾ 0,4 MPa), except for the OG_HV

mixture that shows a significantly penalized ITS (thus not meeting the minimum requirement). This finding can be attributed to the softer consistency of the HiPMBs, which affects directly the cohesion properties of the mixture, especially in the case of the HiPMB_V binder (Carlucci et al., 2025). From the comparison between dry and wet conditions, it can be observed that the action of water does not seem to affect the performance of any OG mixture, since they all show ITSR values greater than 90%, as required by the technical specifications.

Regarding the raveling resistance, Figure 2 shows that all the OG mixtures with HiPMBs generally exhibit lower PL values in both dry and wet conditions as compared to the reference mixture OG_P, thus meeting the specification requirement (PL ≤ 20% in dry conditions), except for the OG_HA mixture that exhibits a dry PL value of 20.6%. The higher PL observed for the OG_P and OG_HA mixtures can be attributed to the higher consistency and stiffness properties of the binders contained in these mixtures (same base bitumen), as reported by Carlucci et al. (2025). From the dry vs. wet comparison, it can be noted that all the OG mixtures with HiPMBs are affected by the action of water. The PL increase of OG_HA (65%) and OG_HV (90%) is lower or comparable to that of the reference mixture OG_P (100%), whereas it is more evident for the OG_HO mixture (200%).

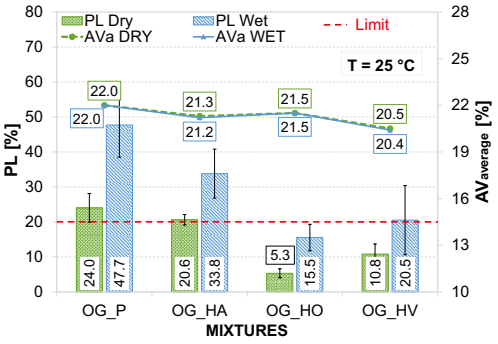


Fig.e 2. Particle loss values vs. air voids in dry and wet conditions.

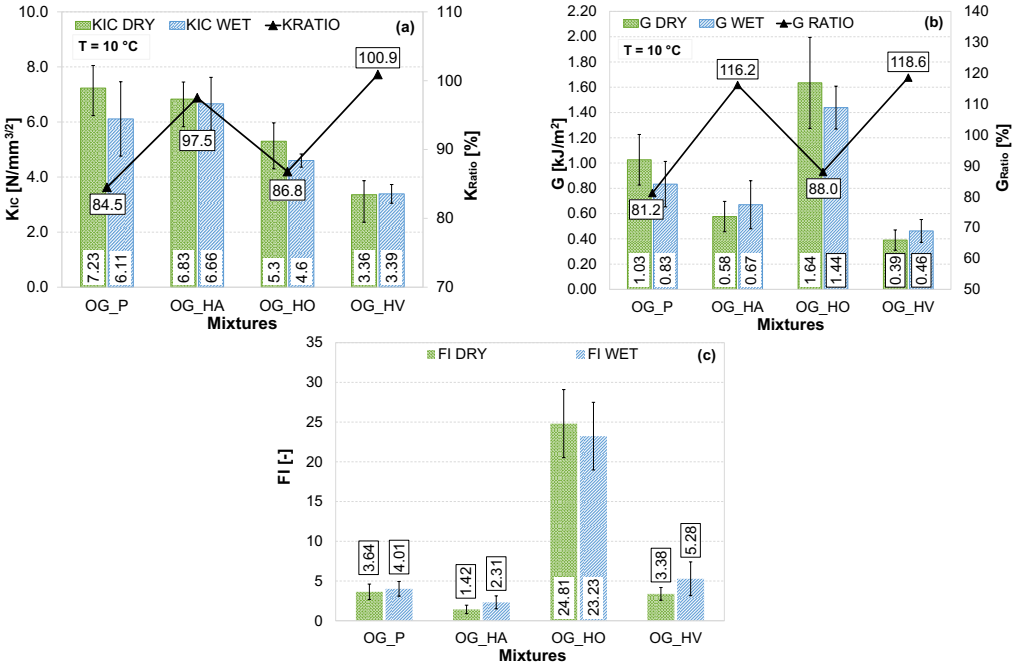


Fig. 3. SCB results: (a) fracture toughness K_{IC}, (b) fracture energy G, (c) Flexibility Index FI.

Figure 3a and 3b show the results of the SCB tests in terms of average K_{IC} and G values for both dry and wet conditions. As can be noted from Figure 3a, all the OG mixtures produced with HiPMBs exhibit lower fracture toughness as compared to the reference mixture OG_P, except for the OG_HA mixture, which demonstrates comparable performance to the reference one (same base bitumen). This result is consistent with the previous ITS trend (Figure 1) and highlights the role of the binder stiffness (Carlucci et al., 2025) on the fracture resistance of the mixture during the initiation phase. Figure 3b shows that the fracture energy of the mixtures OG_HA and OG_HV is lower than that of the reference mixture, whereas the OG_HO mixture exhibits a significantly higher amount of energy dissipated during cracking, indicating greater overall ductility compared to the other mixtures. This finding is confirmed by the *FI* trend (Figure 3c), showing for the OG_HO mixture a *FI* value which is about 8 times higher than all other mixtures, denoting high ductility during the crack propagation. The OG_HV mixture exhibits *FI* values comparable to the reference mixture OG_P, while the OG_HA mixture shows values that are about 50% lower. Finally, the K_{ratio} and G_{ratio} values (ratio between wet and dry results) shown in Figures 3a and 3b indicate that the detrimental effects of water exposure are more pronounced for the OG_P and OG_HO mixtures compared to the other two mixtures.

3.2. Dense-graded mixtures

Figure 4a shows the compactability results in terms of average CEI and AVs after 120 gyrations for the dense-graded mixtures. Result analysis indicates that the workability and volumetric properties are dependent on the type of HiPMB used. More in details, DG_HA and DG_HO mixtures appear less workable than the reference mixture. Despite the different propensity to be compacted, all the DG mixtures with HiPMBs exhibit AV values that meet the technical specification requirement (i.e., $3\% \leq AV \leq 5\%$).

Figure 4b, reporting the ITS results in dry and wet conditions, shows that all the DG mixtures produced with HiPMBs display reduced ITS values as compared to the reference mixture DG_P, but they meet satisfactorily the technical specification requirements (0.95 MPa ≤ ITS ≤ 1.90 MPa). Analogously to the ITS analysis on the open-graded mixtures, this result is likely attributable to the lower consistency of the HiPMBs with respect to the reference SBS PMB (Carlucci et al., 2025), which results in lower cohesion properties for the studied mixtures compared to the reference one. As for the water sensitivity analysis, it can be observed that no significant strength reduction occurs after water conditioning, as confirmed by the ITSR value, which exceeds 90% for all mixtures.

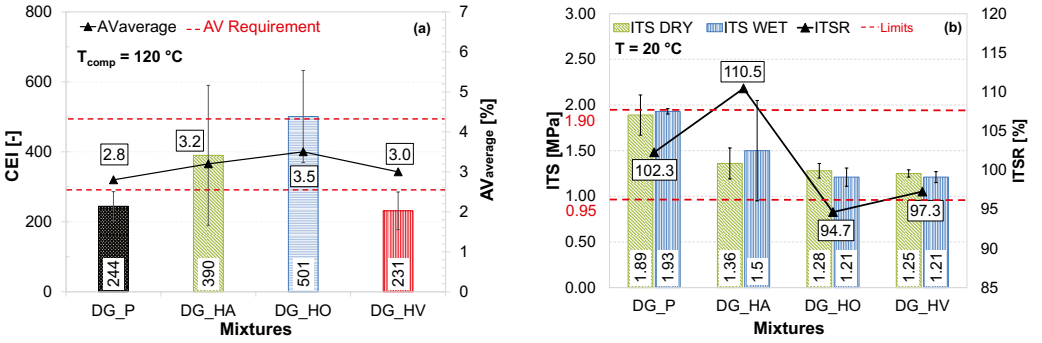


Fig.4. DG mixtures: (a) CEI values vs. air void content at 120 gyrations, (b) ITS values in dry and wet conditions and ITSR values.

Figure 5 shows the average ITSM values measured at 20 °C along with the corresponding average AV content for each mixture. The figure shows that the mixtures DG_HO and DG_HV are characterized by reduced stiffness as compared to the reference mixture DG_P (average reduction of 35%). Conversely, the DG_HA mixture exhibits a stiffness comparable to that of DG_P (same base bitumen). Since AV contents show no significant variation among the mixtures, this analysis confirms the predominant role of the bitumen consistency on the stiffness response of the mixture. Therefore, considerations similar to those drawn from the ITS analysis can be made.

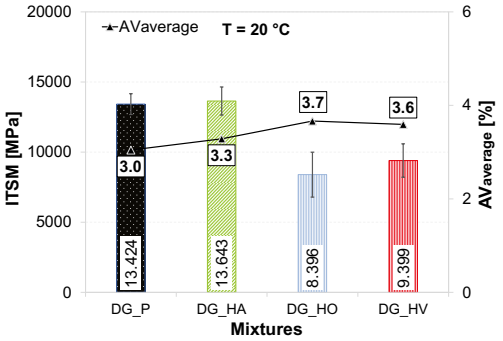
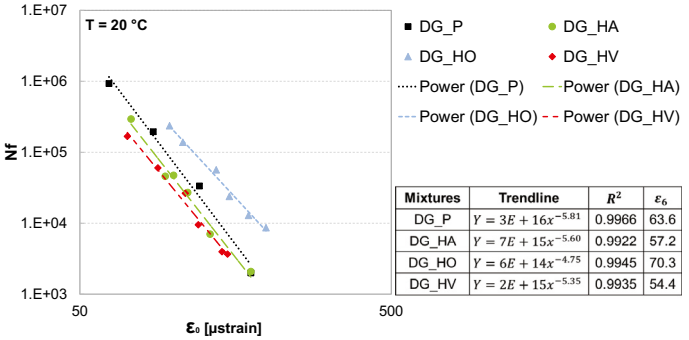


Fig. 5. ITSM results.

The ITFT results, depicted in the Figure 6, show that the DG_HO mixture exhibits a markedly higher resistance to cyclic loading with respect to the reference mixture DG_P and to the other two mixtures with HiPMBs. This can be attributed to the lower stiffness of the binder HiPMB_O (Carlucci et al., 2025), which makes the mixture less prone to fatigue cracking. Conversely, for the DG_HA and DG_HV mixtures, no improvement in the fatigue resistance is observed compared to the reference mixture. This behaviour can be related to the adhesion issues found for the HiPMBs, as reported by Carlucci et al. (2025).



Mixtures	Trendline	R^2	ε_6
DG_P	$Y = 3E + 16x^{-5.81}$	0.9966	63.6
DG_HA	$Y = 7E + 15x^{-5.60}$	0.9922	57.2
DG_HO	$Y = 6E + 14x^{-4.75}$	0.9945	70.3
DG_HV	$Y = 2E + 15x^{-5.35}$	0.9935	54.4

Fig. 6. ITFT results.

4. Conclusions

This paper describes an experimental investigation aimed at evaluating the workability and mechanical performance of asphalt concrete produced with three HiPMBs of different composition through WMA technology, as part of a wider research project concerning the characterization of HiPMB for paving applications. Specifically, both open- and dense-graded mixtures were produced and investigated through laboratory activities, and compared with a reference mixture manufactured with SBS PMB, currently used in Italy for motorway pavements. As an outcome of this research, it emerged that:

- The use of high content of engineered styrenic polymers for bitumen modification allows to achieve volumetric and workability properties for both open- and dense-graded mixtures that are generally comparable to those of mixtures manufactured with typical SBS PMB, even by adopting WMA technology.
- The mixtures produced with HiPMBs tend to exhibit lower ITS values compared to the reference mixture containing the SBS PMB binder. This result is likely attributable to the consistency of the HiPMBs, which are softer than the reference binder, especially in the case of the HiPMB_O and HiPMB_V binders.
- For the open-graded mixtures, Cantabro tests showed that HiPMB mixtures had lower particle loss than the reference mixture, suggesting that the reduced binder consistency improves ravelling resistance.

- The SCB tests conducted on the open-graded mixtures indicated that the mixtures produced with the HiPMBs are characterized by lower fracture toughness compared to the reference mixture due to the lower consistency/stiffness of the HiPMBs with respect to the reference SBS PMB. The mixture ductility strongly depended on the type of HiPMB used, resulting in better performance compared to SBS PMB in some cases (binder HiPMB_O) and in worse performance in other cases (HiPMB_A and HiPMB_V).
- No issues in terms of water susceptibility emerged for the open-graded mixtures containing the HiPMBs.
- The ITSM tests conducted on the dense-graded mixtures confirmed that, in general, HiPMB mixtures tend to be less stiff (by approximately 35%) than the mixture produced with the SBS PMB binder. However, the mixture with HiPMB_A showed stiffness comparable to that of the reference mixture (same base bitumen in the two modified binders).
- The ITFT performed on the dense-graded mixtures highlighted that only the mixture with binder HiPMB_O shows significantly higher resistance to cyclic loads compared to the reference mixture. The same cannot be said for the other two HiPMB mixtures, which appear to perform worse than the reference mixture. This result could be attributed to the adhesion issues observed between HiPMBs and typical aggregates in a previous investigation (Carlucci et al., 2025).

In conclusion, the results obtained from this laboratory characterization support the combined use of engineered HiPMBs and WMA technology to produce asphalt mixtures for motorway paving applications with satisfactory performance. The penalized mechanical response of some investigated mixtures highlights that the formulation of HiPMBs, intended not only in terms of high content of polymer, is critical to obtain high-performing asphalt mixtures.

Future work will focus on the advanced characterization of these mixtures both at the mixture level and at the pavement level, using a viscoelastic continuum damage (VECD) approach.

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