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Additional procedures for characterizing the performance of recycled polymer modified asphalt mixtures

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ABSTRACT

Great efforts have been made in recent years to improve the mechanical properties of asphalt mixtures by replacing conventional mix components with innovative ones or by adding materials such as polymers. Hence, the innovative-sustainable road materials to be investigated through laboratory tests require articulated procedures, the research here presented aims to provide an experimental-methodological approach to analyse the mechanical performance of untraditional hot asphalt mixtures made up using a polymer compound of recycled plastics. Three Asphalt Concrete 20 (AC20) Hot Asphalt Mixtures (HMA) were analysed by measuring base properties (i.e., indirect tensile strength and moisture damage) and advanced features (i.e., stiffness, fatigue, cracking and rutting resistance). As a result, the addition of polymer compound using dry process might lead firstly to change the laboratory mixing procedure than the traditional hot limestone asphalt solutions. The main benefits derived from the adoption of this innovative technology compared to the conventional ones are as follows: a) an improvement of resistance to moisture damage (at 15 °C); b) a suitable stiffness at 10, 20 and 40 °C; c) an increment of the cracking resistance (at 10 °C) and d) a good rutting resistance in terms of rut depth (at 60 °C).

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1. Introduction

Considering the increment of traffic loads and the significant variation of average weather conditions due to the climate changes, the road asphalt pavement of the future should be able to mitigate the climate change impacts in terms of air temperature and at the same they need to have higher mechanical performances to bear higher load stresses. Hence, innovative adaption technologies [1] need to be investigated to design adequate road asphalt pavement in next future both considering the viscoelastic nature of bituminous binder since a) the bitumen behaviour both depends from temperature and loading rate and b) the performance of an asphalt mixture is influenced by the rheological properties of bitumen [2–4].

Hence, to improve the service life of asphalt pavement reflecting the principles of Circular Economy more virgin and wastes materials have been investigated as bitumen modifiers enhancing the physical and rheological properties of bitumen [5–8]. On this way a Polymer Modified Bitumen (PMB) has been obtained.

Generally, a lot of benefits can be gained using a PMB since in dependence of the physico-chemical properties of polymer adopted as modifier it can be more flexible, less susceptible to aging process or to the permanent deformations [9–11].

Moreover, considering the variabilities derived from the original polymers and bitumen properties, the use of PMB can also improve the mechanical properties of asphalt concrete manufactured [12–15]. For example, Ahmed et al. [16] compared the properties of asphalt mixtures made with three different types of binders: two neat bitumens (60/70 and 80/100) and a PMB (60/70 neat bitumen mixed with 1.3% Elvaloy® polymer by the total weight of the bitumen). The OBC was 4.55% for all three mixtures. The results showed that the asphalt mixture with PMB had the highest indirect tensile strength (10.97 MPa vs 9.32 MPa of HMA with 60/70 neat bitumen and 6.60 MPa of HMA with 80/100 neat bitumen) and the highest resilient modulus (4645 MPa vs 3142 MPa of HMA with 60/70 neat bitumen and 1405 MPa of HMA with 80/100 neat

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bitumen).

In any case the improvement derived from the adoption of polymer modifier can be really achieved only if a a good compatibility is reached between the original binder and the polymer adopted both to design a PMB able to exhibits a good resistance to permanent deformations without becoming too viscous at lower temperatures range and to avoid phase separation overtime [17]. Therefore, considering that a) the key elements of PMB are profoundly dissimilar between them in terms of physical and molecular properties [18,19]; b) the properties of original bitumen are related to the quality of the crude oil extracted [20] and c) the modifier's nature and its physical dimensions, forms (granular or shreds) and the can affect the properties of PMB [21–24], it is clear the achievement of a good result as PMB is a very difficult task. In fact, the literature well clarified as some critical issues are still present in modified bitumen. As confirmed by Zani et al [25] one of the main criticisms is the storage stability. In fact, these researchers [25],have studied five PMBs in terms of physical (softening point, penetration grade, elastic recovery, viscosity), chemical (SARA analysis) and rheological properties (frequency sweep test) making an advanced storage stability analysis using DSR frequency sweep tests on bottom and top samples of cigar tuben samples stored for 3, 5 and 7 days (180 °C), respectively. Authors proved that the chemical incompatibility between the neat binder and polymer could cause instability during storage; in detail it has been demonstrated that only three of the five binders tested were able to bear storage periods longer than three days without losing their initial rheological properties, while all binders showed reduced rheological properties between three and five days of storage. Otherwise, Zhu et al. [26] shows as for PMB, the cost is quite relevant in dependence of the dosage of the added polymer that can be estimated around 3.5% by weight in the final product for a typical SBS polymer.

To overcome the critical issues derived from the use of PMB, another procedure has been studied by the researchers to improve the performances of asphalt mixtures [27]. In detail a dry modification process was investigate introducing the modifiers (fibres and polymers) directly into the asphalt mixture during the mixing process at the asphalt plant [28].

In line with Circular Economy and the reduction of environmental impact, assuring that this type of modification process requires only one plant, the dry process is still used to introduce recycled and secondary materials (tire rubber, plastic wastes etc.) also in substitution of recycled aggregates [29–33]. For example, Movilla-Quesada et al. [34] which investigated the effects of adding coarse (5–10 mm) and fine (0.25–2 mm) particles of crushed scraps of plastics, such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polyvinyl chloride (PVC), to AC16S asphalt mixtures designed with 4.7% OBC by the total weight of the mixture.. The results showed that the Marshall stability of the reference solution was 13 kN, while that for the mix with 20% plastic fine particles was 15 kN, and that for the mix with 10% plastic coarse particles was 16 kN. At 60 °C, the rut depth was 3.301 mm for the reference mixture but 1.410 mm and 0.712 mm for the mixes with 10% and 20% fine plastic scrap, respectively, and 1.534 mm and 0.704 mm for the mixes with 10% and 20% coarse scrap plastic, respectively.

However, as previously shown for the PMB also the dry process presents some critical issue highlighted by the literature. In detail, it is clear that because of the short mixing times and the reduced mixing forces, combined with the low quantity of modifier added the polymer modified asphalt using dry process are poorly reproducible in laboratory scale [35].Considering the critical issues explained above and related to the different modification processes adopted to improve the mechanical performances of bituminous asphalt mixtures, the present study aims to provide an experimental-methodological approach to investigate the physico-mechanical properties of asphalt mixtures produced using PMB and dry process. In detail an advanced numerical analysis was conducted basis on the experimental data, to find the key parameters and the laboratory test procedures that should be adopted to ascertain the attitude of asphalt mixtures to resist to the damage phenomena. The research study was conducted on three binder layers asphalt: a) a traditional HMA with limestone aggregates and neat bitumen (HMA_{NB}); b) an HMA modified with PMB containing SBS (HMA_{PMB}), and c) an HMA modified by a dry process using a polymeric compound as asphalt modifier (HMA_{PMA}).

2. Materials

2.1. Limestone aggregates

A dense graded asphalt concrete with maximum aggregates' size of 20 mm (AC20) for a binder course was designed with four different sizes of limestone aggregates provided by a local quarry in southern Italy. Two coarse (limestone 10/18 and limestone 6/12) and two fine aggregates, i.e., limestone sand (0.25–4 mm) and limestone filler (0.063 – 2 mm), respectively, were used to develop the grading curves of the asphalt mixtures. Table 1 **– Part a** shows some of the main physical properties of the limestone particles.

2.2. Bitumen

Two types of binders were used: a 50/70 penetration-grade neat bitumen provided by a refinery in southern Italy and b) a commercially hard modified bitumen, PMB 10/40–70, obtained through the addition of 5% of SBS to a 70/100 penetration-grade neat bitumen. A preliminary evaluation of the collected bitumen samples was conducted through traditional bitumen tests such as, the penetration, ring-and-ball, and viscosity tests, as per the European Standard protocols (see Table 1 **– Part b**)

2.3. Plastomeric compound

The polymer compound used in this study was composed of a) polypropylene (PP), polyethylene (PE) and polyethylene terephthalate (PET) recycled plastics subjected to a crushing treatment process to achieve final dimensions lower than 2 mm; b) a mixture of optimized plastomeric polymers and copolymers such as Low-Density Polyethylene (LDPE) and EVA and c) additives of different types to ensure that the final polymer compound would be in the form of semi-smooth and flexible granules. The main physical properties of the polymer compound are shown in Table 1 **part c**. Since the melting point of the plastomeric polymer is greater than 180 °C, which is higher than the neat bitumen mixing temperature, it was introduced into the asphalt mixture using the dry process, as described in the following sections.

All the data reported in Table 1 have been evaluated as mean value of the results derived from a double repetition of the same test.

2.4. Asphalt mixtures

Three AC20 HMAs were designed for this study: a traditional HMA using a traditional 50/70 neat bitumen; a modified asphalt mixture using an SBS PMB 10/40–70 and an asphalt mixture manufactured using neat bitumen with the addition of the plastomeric compound in dry way. The percentage composition of each HMA investigated is reported in Table 2.

3. Methods

Fig. 1 displays the main steps of the methodology adopted to conduct the research study here presented. First of all a complete characterization of primary materials (aggregates, bitumen and polymer) was conducted. Secondly, the Grading Curve, the Optimum Bitumen Content and the dosage of plastomeric polymer compound were defined and a procedure for the specimen preparation was designed. Finally, a several laboratory test program was conducted to establish the mechanical

Table 1

Part a) Mechanical and volumetric properties of the limestone aggregates – Part b) Bitumen properties – Part c) Polymer features.

Part a)

Aggregate-particle Size mm	**Los Angeles value,** % (EN1097-2)	**Shape index,** % (EN933-4)	**Flat index,** % (EN933-3)	**Sand equivalent,** % (EN933-8)	**Apparent specific gravity,** gr/cm^3 **[G_{sa}]** (EN1097-6)	**Bulk specific gravity,** gr/cm^3 **[G_{sb}]** (EN1097-3)
10/16	20.6	4	8	–	2.694	2.686
6/12	20.1	8	11	–	2.713	2.685
Sand (0.25–4)	–	–	–	95.3	2.718	2.689
Filler (0.063–2)	–	–	–	–	2.737	2.737

Part b)

Test	Unit	Standard	Neat bitumen 50/70	PMB
Specific gravity	g/cm^3	EN 15,326	1.02	1.03
Penetration @ 25 °C	dmm	EN 1426	68	52
Softening point	°C	EN 1427	48	87
Viscosity at 60 °C	Pa•s	EN 13,702	186	251
Viscosity at 100 °C	Pa•s	EN 13,702	3.220	9.967
Viscosity at 135 °C	Pa•s	EN 13,702	0.413	1.340
Viscosity at 150 °C	Pa•s	EN 13,702	0.250	0.769
Mixing temperature	°C	EN 13,702	156–161	170 – 185
Compaction temperature	°C	EN 13,702	146–150	160–175

Part c)

Characteristics	Units	Value
Color	–	White
Dimensions	mm	2–4
Softening point	°C	160
Melting point	°C	180–190 °C
Apparent density at 25 °C	gr/cm^3	0.40–0.60

Table 2

Mix design for all investigated mixtures.

Components of the mixtures	HMA_{NB}	HMA_{PMB}	HMA_{PMA}
	Percentages by total weight of the mixture		
Limestone 10/16	23.92%	23.92%	23.87%
Limestone 6/12	31.58%	31.58%	31.51%
Limestone sand	36.36%	36.36%	36.29%
Limestone filler	3.83%	3.83%	3.82%
Neat bitumen	4.30%	–	4.30%
PMB	–	4.30%	–
Polymeric compound, 5% by total weight of the bitumen[1]	–	–	0.20%

[1] The dosage of the plastomeric compound was selected considering the middle point of the manufacturer-recommended range (4–6% by total weight of the bitumen).

performances of the designed asphalt mixtures evaluating their resistances to the main causes of damage (moisture damage, cracking, and rutting) as follow:

a) The Moisture Damage resistance was evaluated determining the indirect tensile strength ratio (ITSR) according to EN12697-12;
b) The resistance to cracking failure mechanism was investigated through fatigue tests for the analysis of the crack-initiation phase according to EN 12697–24 – ANNEX E, and Semi-circular bending (SCB) test for the evaluation of resistance to crack-propagation. Both tests were conducted at 10 °C;
c) The resistance to rutting phenomena was examined both considering the behavior of the asphalt in terms of stiffness (ITSM) evaluated at 10, 20, and 40 °C, according to EN 12697–26 – Annex C. and the susceptibility of the asphalt materials to permanent deformations determined through the wheel tracker tests conducted in water conditions according to EN 12697-22.

3.1. Specimen preparation

In literature it is well established how the air voids content is one of the most important factor that affects the mechanical properties of asphalt mixtures [36–38] in terms of rutting [39], fatigue and low temperature cracking and thermal properties [40]. Starting from this assumption, different mixing and compaction processes were adopted for each modified investigated solution (HMA_{PMB} and HMA_{PMA}) to achieve the same volumetric properties of the reference mixture (HMA_{NB}) in terms of air voids, voids of mineral aggregates (VMA), voids filled with asphalt (VFA) and compaction grade ($\%G_{mm}$). Fig. 2 displays how the procedures adopted to prepare HMA_{NB} and HMA_{PMB} solutions (the blue section in Fig. 2) adhere to common laboratory practices; otherwise, focusing on mixing process HMA_{PMA} solution, which include the addition of polymer compound by dry process (phase 1bis and 1ter in green section of Fig. 2), an innovative mixing protocol was defined to ensure complete dissolution of the polymer compound improving the effect of polymer addition in laboratory-scale production. This specific production process for HMA_{PMA} solution was defined in order to solve the problems related to the bitumen-polymer interaction if a dry modification process has adopted. On this way, more attempts were made to properly adding the polymeric compound avoiding pre-heating phase, but not melted polymers remains were observed inside the mixture, so a pre-heating process has been considered.

All the specimens prepared were prepared using cylindrical moulds (150 mm in diameter). The compaction process was performed applying 600 kPa of pressure at a 1.25° external angle using a 150-mm-diameter mold, since the maximum aggregate size was greater than 16 mm (EN 12697-31)

Since it is known that the energy applied by gyratory compaction on asphalt specimens during the compaction phase has a cone-shaped distribution [41], a non-uniform distribution of V_a can be observed from the top plate to the bottom plate and close to the mold [42,43], while a good homogeneity of V_a was reached in the middle region of each specimen. Accordingly, to assure that all investigated solution should be tested in the same volumetric properties features, a sawing system was used to cut the prepared specimens into three sections.

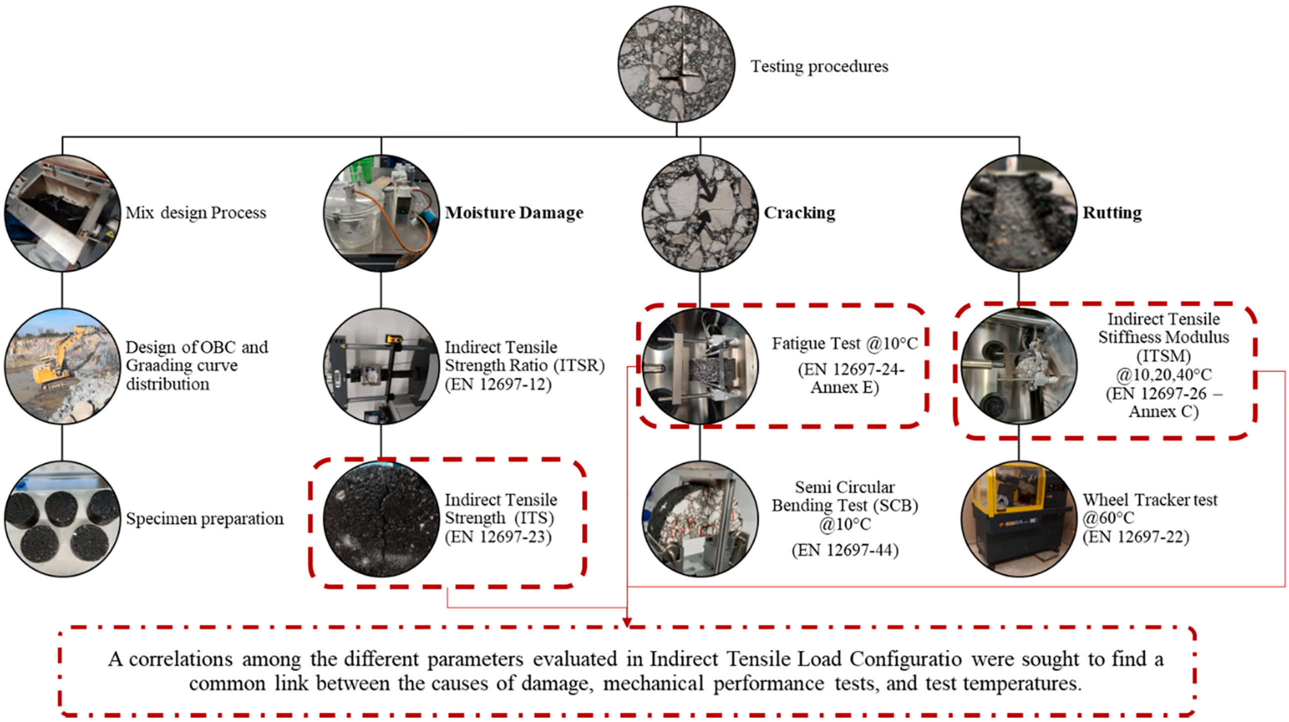


Fig. 1. Workfolw of research program.

On these specimens the ITS and ITSR values were evaluated since:

3.2. Test procedures

As described earlier, the mechanical properties of the HMAs were investigated considering the principal causes of damage. The following test procedures were adopted.

3.2.1. Indirect tensile stiffness modulus (ITSM)

The stiffness modulus was calculated using an indirect tensile load configuration according to EN 12697–26 – ANNEX C maintaining the strain level below 50 με and applying 10 conditioning pulses to define an adequate peak load, further followed by five pulses for stiffness measurement. The ITSM was calculated using the equation in Table 3. The ITSM test was conducted at three different temperatures– 10, 20, and 40 °C since 10 °C match the temperature set used for the ITS assessment, while the 20 °C and 40 °C temperatures represents the typical local spring and the summer temperatures in the binder layers of the roads in southern Italy.

On each specimen prepared, at each temperature investigated, two test repetitions were conducted in order to control the results. In detail, this control phase was conducted considering control charts as statistical process control tool to ascertain the state of control of the procedures adopted; then a performance diagram and Analysis of Variance statistical (ANOVA) was carried out to evaluate if the introduction of different modifiers involves statistically significant differences on the mean value of stiffness modulus

3.2.2. Resistance to permanent deformation

The susceptibility of the bituminous materials to deformation was assessed in terms of the ruts formed because of repeated number of loaded wheel passes in water conditions at a constant temperature of 60 °C, using the Double Wheel Tracker as per Procedure B in EN 12697-22.

3.2.3. Fatigue test

The behavior of the bituminous mixtures under repeated load fatigue testing was evaluated via an indirect tensile test, in accordance with EN 12697–24 – ANNEX E; repeatedly applying a haversine load with a 0.1 s loading time and 0.4 s rest time. The test temperature was fixed at 10 °C and the fracture life was determined as per Method 2 (energy ratio) in EN 12697-24 – Annex E (see Table 3).

3.2.4. Semi-circular bending (SCB) test

The SCB test method was used to determine the tensile strength and fracture toughness of the asphalt mixtures for assessing the potential for crack propagation to ascertain the resistance of an asphalt mixture to crack propagation. The SCB test was conducted at 10 °C, in compliance with the previous mechanical tests adopting the formula shown in Table 3.

4. Results and discussion

4.1. Specimen preparation

The results deriving from the different compaction effort adopted for the modified asphalt solutions, in order to achieve the same volumetric properties of reference asphalt mixture (HMA_{NB}), were investigated from the analysis of the compaction curves (obtained plotting the mean $\%G_{mm}$ values were against the number of gyrations). Starting from these curves it is possible to observe that:

a) Considering the primary compaction phase (up to 40 gyrations) all the investigated solution exhibits a good overlap between them, and almost the same values of $\%G_{mm}$ were achieved;
b) Otherwise, beyond 40 gyrations, the two modified asphalt mixtures (HMA_{PMB} and HMA_{PMA}) exhibited lower densification curves than did the reference mixture (HMA_{NB}). Consequently, the air void contents at N_{des} and $N_{max,}$ 100 and 160 gyrations, respectively for HMA_{NB} did not overlap for all three mixtures. Specifically, at 100 gyrations, $\%G_{mm}$ was 96% for HMA_{NB}, 95.0% for HMA_{PMB}, and 95.1% for HMA_{PMA}; hence, the corresponding air void percentages were 4.0%, 5.0%, and 4.9%, respectively.

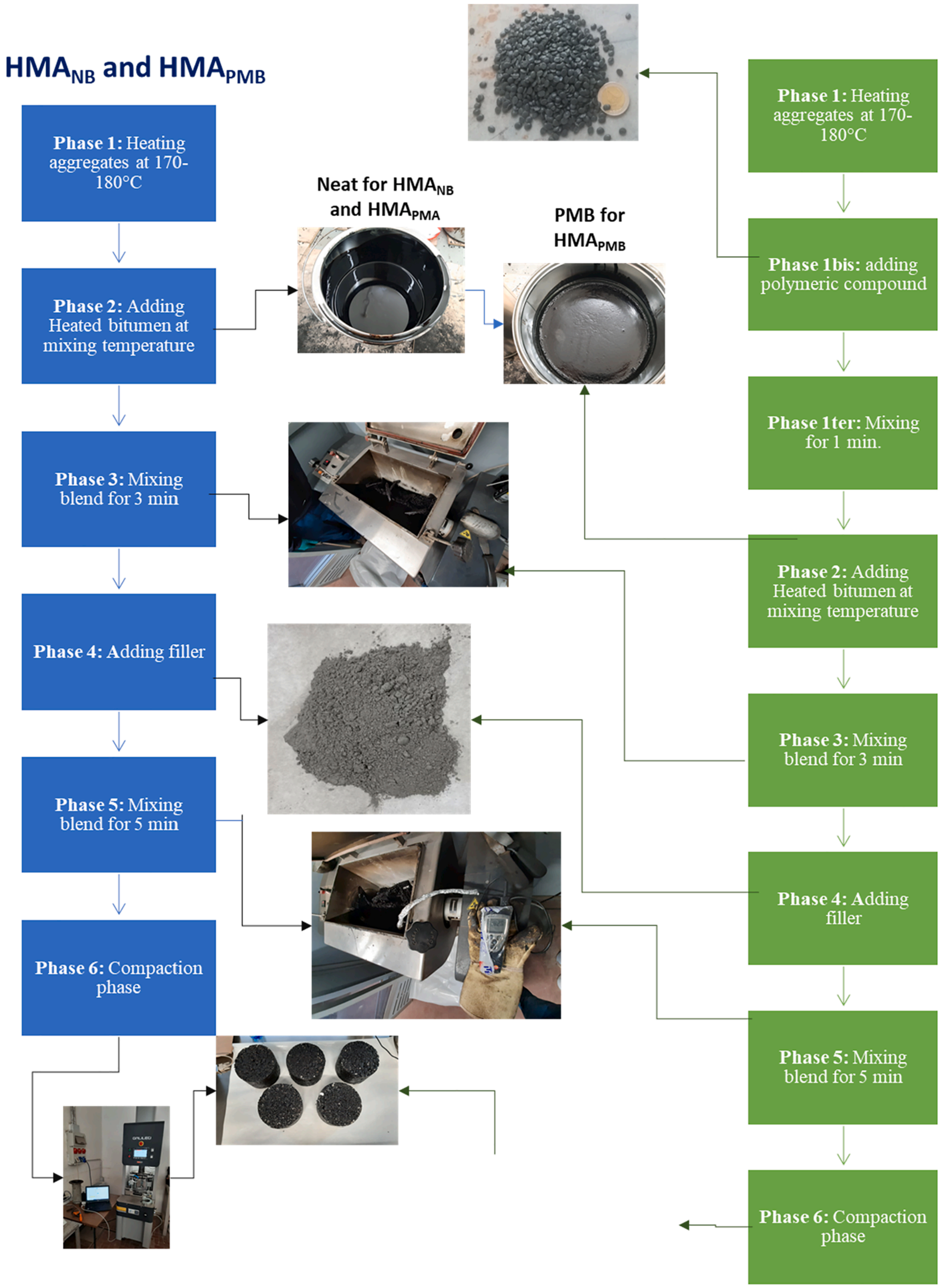


Fig. 2. Steps in preparation of HMA specimens.

According to these results, a preliminary conclusion can be made because the alternative asphalt mixtures did not exhibit the same volumetric properties as HMA$_{NB}$ did since they differed in the V_a values. A similar situation was observed at 160 gyrations, for which %G$_{mm}$ was 97.70% for HMA$_{NB}$, 96.9% for HMA$_{PMB}$, and 97.0% for HMA$_{PMA}$.

These differences between the asphalt mixtures, evaluated in terms of compaction level, are surely due to the rheological properties of the different bitumen adopted. In fact, as shown in Table 1-**part b)**, the PMB bitumen is characterized by higher viscosity by changing temperature than neat bitumen; consequently, PMB not only needs higher mixing and compaction temperature, but it also needs a greater compaction effort to assure adequate air voids properties. On the other hand, referring to the PMA solution, the increment of the compaction effort is surely due to the introduction of the polymeric compound which by melting alters the compaction effort of the asphalt solution since no other differences occurs between them.

Starting from these analyses, 112 gyrations was found to be the appropriate N$_{des}$ for HMA$_{PMA}$ and HMA$_{PMB}$ to achieve the same %G$_{mm}$ as that calculated for HMA$_{NB}$ at 100 gyrations and 180 gyrations was found to be the appropriate N$_{max}$ for HMA$_{PMA}$ and HMA$_{PMB}$ to achieve the

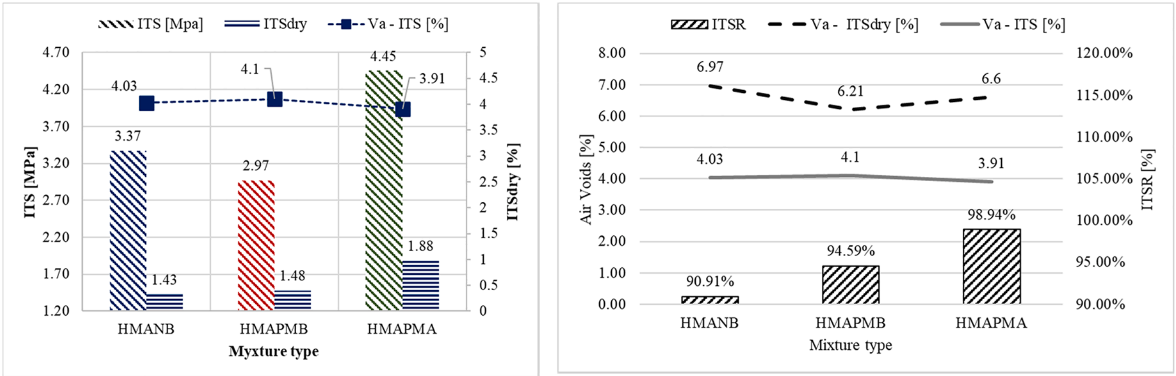
Table 3
Mechanical behaviour equations.

Test	Temperature	Standard	Cause of damage investigated	Formula	Parameter description
ITS	10 °C	EN 12697–23	Moisture damage	$ITS = \frac{2P}{\pi DH}$	ITS is the indirect tensile strength (GPa) P is the peak load (kN) D is the diameter of the specimen (mm) H is the height of the specimen (mm)
ITS	10 °C	EN 12697–23	Moisture damage		
ITS	10 °C	EN 12697–23	Moisture damage		
ITSR	15 °C	EN 12697–12	Moisture damage	$ITSR = \frac{ITS_{wet}}{ITS_{dry}} x100$	ITS_{wet} is the mean ITS value estimated in wet condition (kPa) ITS_{dry} is the mean ITS value estimated in dry condition (kPa)
ITSR	15 °C	EN 12697–13	Moisture damage		
ITSR	15 °C	EN 12697–14	Moisture damage		
ITSM	10 °C	EN 12697–26 - ANNEX C	Structural behaviour	$ITSM = \frac{F \times (\nu + 0.27)}{z \times h}$	F is the peak value of the applied vertical load (N) z is the amplitude of the horizontal deformation obtained during the load cycle (mm) h is the mean thickness of the specimen (mm) ν is Poisson's ratio (assumed to be 0.35).
ITSM	10 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	10 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	20 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	20 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	20 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	40 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	40 °C	EN 12697–26 - ANNEX C	Structural behaviour		
ITSM	40 °C	EN 12697–26 - ANNEX C	Structural behaviour		
Fatigue	10 °C	EN 12697–24 - ANNEX E	Fatigue resistance	$w_n = \frac{n}{\varepsilon_{R,n}} \bullet 10^6$	n is the number of the cycles $\varepsilon_{R,n}$ is the resilient strain
Fatigue	10 °C	EN 12697–24 - ANNEX E	Fatigue resistance		
Fatigue	10 °C	EN 12697–24 - ANNEX E	Fatigue resistance		
SCB	10 °C	EN 12697–44	Crack propagation	$\sigma_{\max} = \frac{F_{\max}}{Dt}\left[\frac{N}{mm^2}\right] K_{lC} = \sigma_{max} Y_1 \sqrt{\pi a}\left[\frac{N}{mm^{1.5}}\right]$	D is the diameter of the specimen (mm) t is the thickness of the specimen (mm) Fmax is the maximum force on the specimen (N) σ_{max} is the stress acting at the point of failure of the specimen (N/mm^2) α is the notch depth of the specimen (mm) Y1 is the normalized Mode I stress intensity factor
SCB	10 °C	EN 12697–44	Crack propagation		
SCB	10 °C	EN 12697–44	Crack propagation		
Wheel Tracker	60 °C	EN 12697–22	Rutting	$RD = ruthdepthat10.000cycles$	
Wheel Tracker	60 °C	EN 12697–22	Rutting		
Wheel Tracker	60 °C	EN 12697–22	Rutting		

same $\%G_{mm}$ as that calculated for HMA_{NB} at 160 gyrations.

These results support the hypotheses established during the first phase of the study, in which we proposed the development of different appropriate mixing processes and compaction efforts for HMA_{NB}, HMA_{PMB}, and HMA_{PMA} to achieve comparable volumetric properties.

Fig. 3**a** shows the mean values of *ITS* for the mixtures and the mean values of V_a measured for the specimens, which were used for assessing *ITS* at 10 °C (blue squares); which are almost the same among the different mixtures. The differences in *ITS* at 10 °C (vertical-coloured bars in Fig. 3**a**) can be due only to the difference in materials used for the



a) b)

Fig. 3. *ITS analysis. a)* $ITS_{10^\circ C}$ vs V_a vs ITS_{dry}*, b) Air Voids ITS* vs *Air Voids* ITS_{dry} vs *ITSR.*

mixtures, such as the PMB and the polymer compound. In detail, it is possible to see how the HMA$_{PMA}$ exhibited the highest *ITS* (32% greater on average than that of HMA$_{NB}$ and 50% greater on average than that of HMA$_{PMB}$) while the average value *ITS* of HMA$_{NB}$ (blue bar in Fig. 3**a**) exceeded that of HMA$_{PMB}$ by 13%.

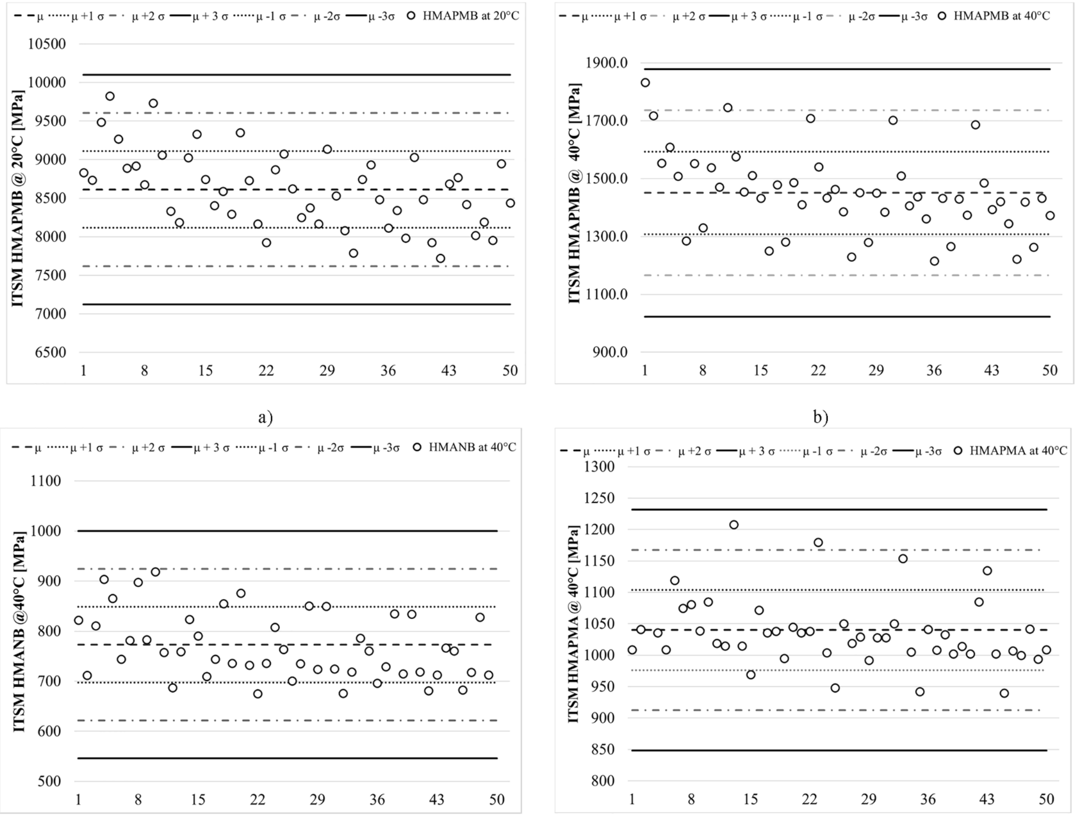
From a detailed analysis of Fig. 3, some considerable the following observations can be made:

- Fig. 3**a** shows that ITS$_{10^\circ C}$ covers a range twice as broad as that covered by ITS$_{dry}$. This result can be surely motivated considering the different procedures used for specimens preparation, since the specimens adopted for ITS$_{dry}$ evaluation were compacted at 50 gyrations number to maximize the influence of the water conditioning effect as opposed to ITS specimens which were compacted at 160 gyrations for HMA$_{NB}$ and 180 gyrations for HMA$_{PMB}$ and HMA$_{PMA}$. These differences could have led to the higher air void content in the specimens prepared for ITS$_{dry}$ testing (see Fig. 3**b**) than in those prepared for ITS$_{10^\circ C}$ testing (+75% for HMA$_{NB}$, +51% HMA$_{PMB}$, +69% HMA$_{PMA}$).
- HMA$_{PMB}$ exhibited the lowest mean *ITS* (2.97 MPa for HMA$_{PMB}$ vs 3.37 MPa for HMA$_{NB}$ and 4.45 MPa for HMA$_{PMA}$), while the ITS$_{dry}$ values were comparable among all the mixtures (1.48 MPa for HMA$_{PMB}$, 1.43 MPa for HMA$_{NB}$, and 1.88 for HMA$_{PMA}$). This is related to the PMB used and the polymer compound introduced, since no differences existed in terms of the grading curves, volumetric properties, or bitumen concentrations among the mixtures investigated.
- Fig. 3**c** illustrates the resistance due to moisture damage evaluated in terms of ITSR. No significant differences were observed between the dry and wet conditions at 15 °C for HMA$_{NB}$ and HMA$_{PMB}$ i.e., 9% and 5% ITS reductions, respectively. The mean ITS$_{dry}$ value of the HMA$_{PMA}$ was 31% higher on average than that of the HMA$_{NB}$ and 27% higher on average than that of the HMA$_{PMB}$. The mean ITS$_{wet}$ value of HMA$_{PMA}$ was 43% higher on average than that of HMA$_{NB}$ and 37.7% higher on average than that of HMA$_{PMB}$.

On the basis of these results, it can be preliminarily concluded that the adoption of the proposed mixing procedure for the dry process can allow for maximizing the effect of polymer addition.

4.2. Stiffness modulus

Assuming the great number of observations made for the evaluation of this complex parameter (50 measurements for each asphalt mixture at each test temperature), all the measures were filtered to remove anomalous values by adopting the 3σ method (3 standard deviation method); so the control charts was adopted as statistical process control tool to ascertain the state of control of the procedures adopted (Fig. 4) [44,45]. As results, it is possible to observe how the from the analysis of data distribution in the three regions (μ ± σ; μ ± 2σ and μ ± 3σ) for measurements conducted at 10 °C and 20 °C (in Fig. 4**a** are shown as example the results provided by HMA$_{PMB}$ solutions at 20 °C) do not present values that overcome the ± 3σ limits and there almost the 80% of observed value are equal distributed between the first (μ ± σ) and the second region (μ ± 2σ), while only the 20% of the measured values are located in third region (μ ± 3σ). Otherwise, the measures conducted at 40 °C (Fig. 4**b, 4c and 4d**) generally return a greater dispersion of measured values than the measures conducted at lower temperatures and two values, but two points overcome the control limits: one for HMA$_{NB}$ and another one for HMA$_{PMA}$ overcome the control limits, so they were excluded from the following analysis. In detail considering the results at 40 °C (Fig. 4**b, 4c and 4d**) and the three regions mentioned



a) b) c) d)

Fig. 4. Control charts for ITSM measurements a) control chart for HMA$_{PMB}$ @20 °C; b) control chart for HMA$_{NB}$ @40 °C; c) control chart for HMA$_{PMB}$ @40 °C; d) control chart for HMA$_{PMA}$ @40 °C.

above the data are located as follow: a) 2% in region 3 (μ ± 3σ), 28% in region 2 (μ ± 2σ) and 70% in region 1 (μ ± σ) for HMA$_{\text{NB}}$ solution; b) 4% in region 3 (μ ± 3σ), 26% in region 2 (μ ± 2σ) and 70% in region 1 (μ ± σ) for HMA$_{\text{PMB}}$ solution; c) 4% in region 3 (μ ± 3σ), 14% in region 2 (μ ± 2σ) and 82% in region 1 (μ ± σ) for HMA$_{\text{PMA}}$ solution;

As it possible to observe, all the asphalt mixtures display a good homogeneity data referring to the test conducted, but at 40 °C the PMB solution is the only alternative that have no points over the limits. This differences are surely due to the higher influence of viscoelastic nature of bitumen on the deformation control during the test at higher temperatures. This conclusion is also supported by the analysis of primary materials adopted since, considering the inner structure of PMB that contains SBS polymer, it was expected a more elastic response at higher temperatures, that involves a better deformation control under repeated loads.

Considering the data resulted from the control chart analysis the resulted ITSM mean values at each temperature are shown in Table 4. From the analysis of the results provided in Table 4 it is possible to see how the standard deviation is higher at lower temperatures (10 and 20 °C) while it is lower at 40 °C. At the same time, the coefficient of variation (CV), obtained as ratio between the standard deviation and the mean, is very low for all investigated mixtures at all investigated temperatures, that indicate the homogeneity for all measured data as also confirmed by the maximum minimum and the mean residuals values indicated in Table 4. Hence, considering the mean residuals between HMA$_{\text{PMA}}$ vs HMA$_{\text{PMB,}}$ it possible to ascertain the PMA solution has a greater response in terms of ITSM at 10 and 20 °C while the PMB solution maximize its properties at 40 °C.

From the analysis of the results here provided it become useful the analysis of data distribution in Fig. 5 that shows the results related to structural behaviour of asphalt mixtures by representing the mean *ITSM* (provided as mean value of 50 measures done on each tested solution) for all investigated asphalt mixtures at 10, 20, and 40 °C. In detail the diagram has on the x-axis the measurement conducted for each mixture, while on the y-axis is reported the related ITS value which are indicated as single points for the modified solutions (HMA$_{\text{PMB}}$ and HMA$_{\text{PMB}}$) and as continuous line for HMA$_{\text{NB}}$ asphalt mixture assumed as reference value.

In detail it possible to observe that graphically in some cases there are no significant variations between the ITSM value of modified mixture than the same value related to the reference mixture. For example, the HMA$_{\text{PMB}}$ solution exhibited an at 10 and 20 °C that it does not appear considerable; in fact comparing the graphical result of Fig. 5a with the mean values shown in Table 4 it is possible to know that the increment is equal to 3.6% at 10 °C and of 6% at 20 °C. Moreover, HMA$_{\text{PMA}}$ exhibited higher *ITSM* values than HMA$_{\text{NB}}$ at all test temperatures (+11% at 10 °C, +18% at 20 °C, and + 34% at 40 °C).

On this way, to better identify how the measures values of ITSM parameter done on modified asphalt solutions are related to the same values measured on HMA$_{\text{NB}}$ asphalt solution, the performances diagrams were considered (Fig. 5b) showing on the x-axis the values of ITSM measured on HMA$_{\text{NB}}$ solution, while on the y-axis are reported the corresponding values measured on modified asphalt mixtures (HMA$_{\text{PMB}}$ and HMA$_{\text{PMA}}$). Hence, if the clouds of points are homogeneously distributed around the bisector of the first quadrant of a Cartesian reference system, the homogeneity of plotted values was ensured; so, the measured ITSM are almost the same between mixtures. Starting from these considerations, from the analysis of performance diagrams (see Fig. 5b) it is possible to ascertain that

- Three different group of data can be observed, one for each temperature investigated (10, 20 and 40 °C) so a significant difference would appear to be present between the ITSM values varying the test temperature, but analysing the diagram at each temperature it confirms that at 10 °C and 20 °C the difference between HMA$_{\text{PMB}}$ and HMA$_{\text{NB}}$ is not so considerable;
- Also in this case, in confirmation of the results provided by control chart in Fig. 4 it is possible to observe that the measures conducted at 40 °C generally returns graphically a greater dispersion of measured values can be observed than the measures conducted at lower temperatures.
- It is also relevant how both modified asphalt solutions (HMA$_{\text{PMB}}$ and HMA$_{\text{PMA}}$) display greater ITSM values at 40 °C than traditional solution, since almost all measured values lie above the bisector, as also deduced in Fig. 5;

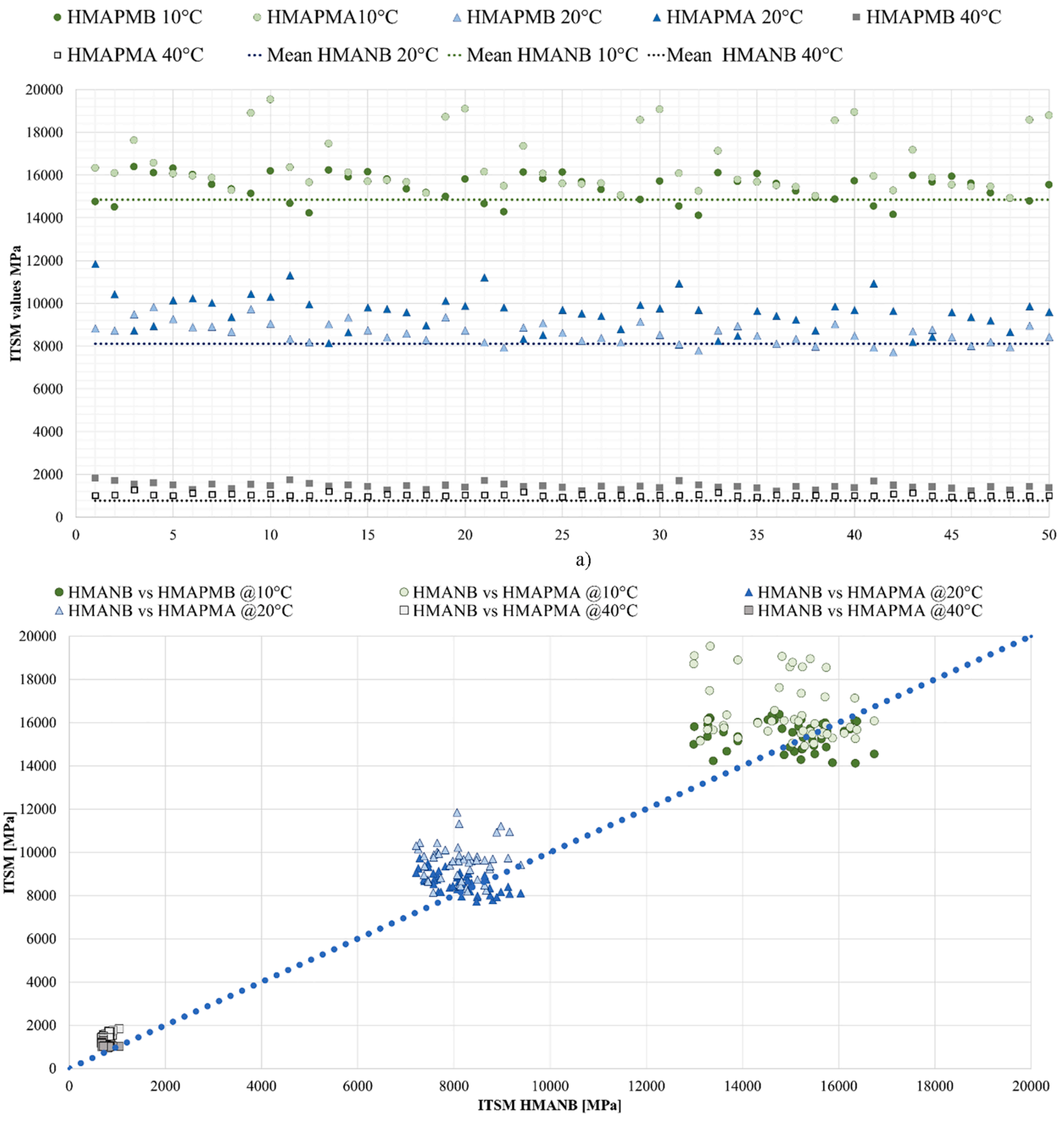
Considering these results, it is also possible to confirm that the introduction of modifiers into the asphalt mixtures both adopting dry or wet procedures help to improve their mechanical response under loads independently from the temperatures investigated also considering that no differences occur between the asphalt mixtures in terms of volumetric properties, gradation curve and bitumen content. Hence, the improvement of mechanical properties can be surely do to the modifiers adopted. In detail, it is also possible to ascertain how the modifier adopted by dry process give a more significant contribution to improve the response at 10 °C and 20 °C; while the use of SBS involve a considerable increment of stiffness at higher test temperatures.

Those results are completely in agreement with types of primary materials adopted since, considering the inner structure of PMB that contains SBS polymer, it was expected a higher and more elastic response under repeated road cycles at high temperatures than the others asphalt mixtures prepared using neat bitumen.

Considering the results provided by the performance diagram, the residual diagrams were also made (see Fig. 6) showing on the x-axis the number of measurement and on the y-axis the residual value calculated as the difference between the single ITSM value measured and the mean ITSM value of HMA$_{\text{NB}}$ asphalt solution. First, the residual diagrams (Fig. 6) confirm the results provided by the performance diagrams referring to the higher ITSM values of modified solution than traditional one, since almost all the residual values calculated for modified asphalt mixtures are positive number. In detail, the diagram of ITSM at 10 °C (Fig. 6a) displays how the measures conducted on PMA mixture return higher residual values than evaluations both made on PMB and traditional solutions. This situation, confirm the higher increment of stiffness

Table 4
Mean values of ITSM with Standard deviation.

Mixture type	Temperature	MeanMPa	Std. Dev.	Sample size	CV	Max. MPa	Min. MPa	Mean residual	HMA$_{\text{PMA}}$ vs HMA$_{\text{PMB}}$ Mean residuals
HMA$_{\text{NB}}$	10 °C	14,853	1031.74	50	0.069	16,741	12,896	0	
HMA$_{\text{PMB}}$		15,391	633.799	50	0.041	16,383	14,115	537.54	−1699.42
HMA$_{\text{PMA}}$		16,498	1334.203	50	0.081	19,534	14,928	1645.02	472.94
HMA$_{\text{NB}}$	20 °C	8120	539.57	50	0.066	9387	7213	0	
HMA$_{\text{PMB}}$		8613	491.567	50	0.057	9827	7724	493.02	−1300.75
HMA$_{\text{PMA}}$		9582	63.194	50	0.061	11,853	8136	1462.6	601.05
HMA$_{\text{NB}}$	40 °C	773	75.00	49	0.097	919	773.22		
HMA$_{\text{PMB}}$		1451	141.254	50	0.097	1216	1450.7	677.50	410.62
HMA$_{\text{PMA}}$		1040	63.194	49	0.061	1283	940	266.9	−384.82



a)

b)

Fig. 5. ITSM evaluation a) Distribution of ITSM mean results at 10, 20 and 40 °C b) Performance diagram ITSM HMA_{NB} vs ITSM of HMA_{PMB} and HMA_{PMA}.

of PMA than PMB in comparison with traditional asphalt mixtures. On the other hand, the diagram in Fig. 6b related to ITSM analysis at 20 °C shows how the residual values of both PMB and PMA solutions are lower than the same values observed for ITSM 10 °C; this condition, merge with the results provided by the graphic in Fig. 5 where it is possible to see how moving from 20 °C to 10 °C an higher increment of stiffness can be observed.

Hence, analysing the residual plot of ITSM values at 40 °C (Fig. 6c) an inversion trend can be shown referring to PMB solution, since unlike what was noted for 10 °C and 20 °C it exhibits the greater residual value than PMA and traditional mixtures which shown the lowest residual values.

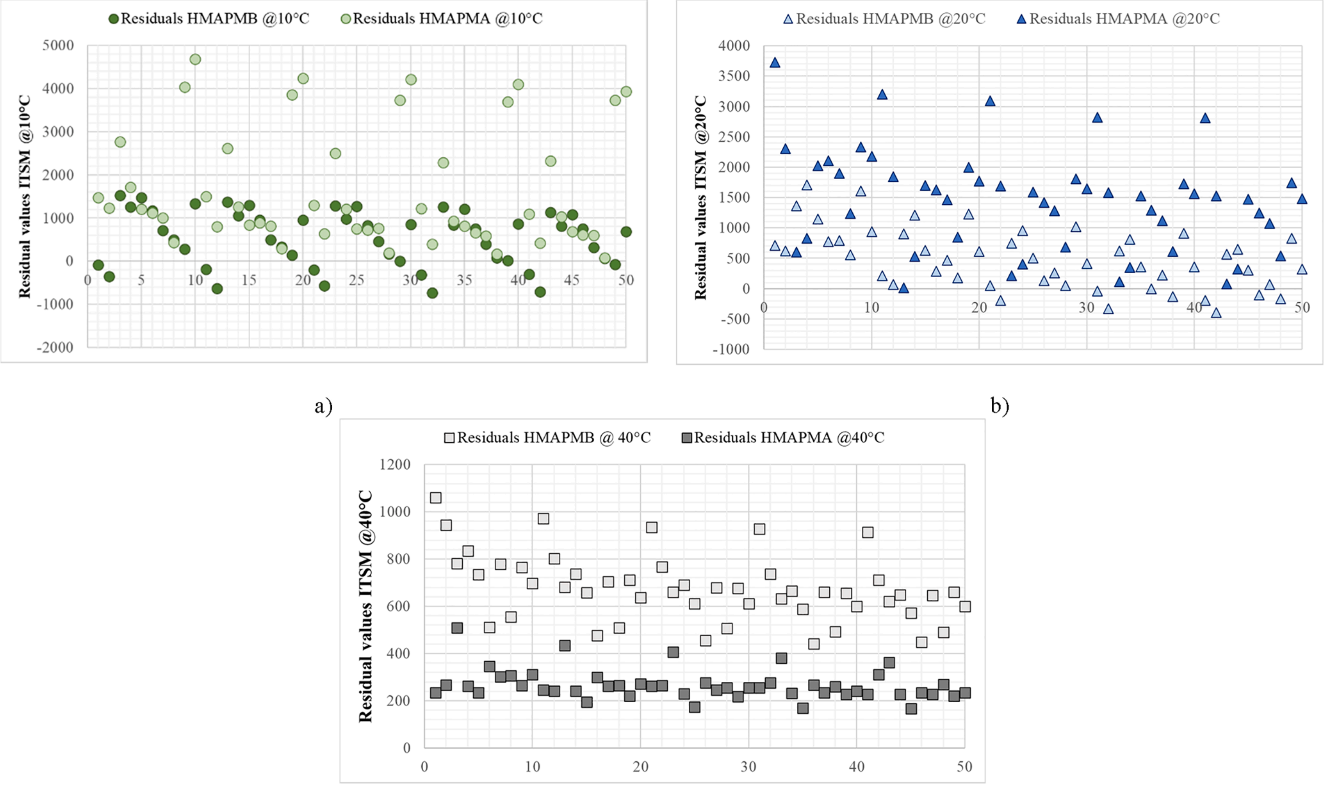
In order to confirm this analysis made on the ITSM results, an analysis of variance (ANOVA) was carried out to evaluate if the test temperature variation determined statistically significant differences on the mean value of stiffness modulus and if at the same temperature value significant statistical differences occurs between the asphalt mixtures.

Before moving to ANOVA, the normal probability distribution of ITSM values for each asphalt mixture was checked. A Lilliefors normality test based on the Kolmogorov-Smirnov (KS) test was adopted. to assure that the normal probability distribution was guarantee for all experimental data involved in the statistical analysis. For example, Fig. 7 shows the graphically results report of KS test for PMB solution at all investigated temperatures.

Assured the normal probability distribution of the data, the ANOVA test was performed on each asphalt mixture investigated with a significance level of 0.05 to test the following H_0 hypotheses: are the ITSM values evaluated at 10 °C, on HMA_{NB}, HMA_{PMB} and HMA_{PMA} statistically equal to the corresponding ITSM values evaluated at 20 °C and 40 °C?

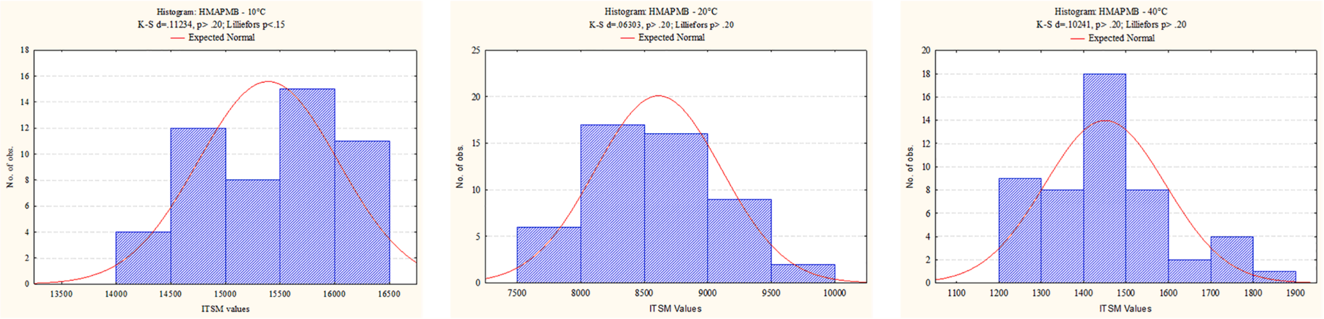
Assured the normal probability distribution of the data, the ANOVA test was performed on each asphalt mixture investigated with a significance level of 0.05 to test the following H_0 hypotheses: a) are the ITSM values evaluated at 10 °C, on HMA_{NB}, HMA_{PMB} and HMA_{PMA} statistically equal to the corresponding ITSM values evaluated at 20 °C and 40 °C?; b) are the ITSM values evaluated at 10,20 and 40 °C on HMA_{NB}, statistically equal to the corresponding ITSM values evaluated on HMA_{PMB} and HMA_{PMA} at the same temperatures?

The results of ANOVA (see Table 5) confirm all the analysis made above considering the graphics in Fig. 5 since it explains how there is a significant influence of test temperature on the stiffness modulus (in line with results provided by performance diagram in Fig. 5b), since all the investigated solution displays those statistical differences are present between the ITSM values varying the test temperatures. At the same time, it is interesting to observe in Table 5 that at 10 °C and 20 °C there



a) b) c)

Fig. 6. ITSM residuals between alternative mixtures and HMA_{NB} a) at 10 °C; b) at 20 °C and c) at 40 °C.



a) b) c)

Fig. 7. KS test results of PMB solution a) KS test results at 10 °C; b) KS test results at 20 °C; c) KS test results at 40 °C.

Table 5
ANOVA test results.

Temp.	Mixture type	Mean ITSM MPa	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
10 °C	HMA_{NB}	14852.92	****						
10 °C	HMA_{PMB}	15390.46	****						
10 °C	HMA_{PMA}	16497.94		****					
20 °C	HMA_{NB}	8119.680			****				
20 °C	HMA_{PMB}	8612.700			****				
20 °C	HMA_{PMA}	9582.300				****			
40 °C	HMA_{NB}	773.220					****		
40 °C	HMA_{PMB}	1040.120						****	
40 °C	HMA_{PMA}	1450.740							****

are no significant variations between the ITSM values of PMB solutions than traditional mixture, in confirmation of the preliminary conclusions made analysing Fig. 5. In detail, at 10 °C the ANOVA includes both HMA_{NB} and HMA_{PMB} in the homogeneous group nr. 1; while at 20 °C they are both included in Group 3. However, statistically differences can be observed between the PMA solution and the others asphalt mixtures at all investigated temperatures. In fact, has also described for Fig. 5 and Fig. 6 since it is always represented alone in the groups number 2,4,5,6,7.

4.3. Cracking resistance

Referring to the resistance to cracking phenomena, to analyse the results provided by the tests conducted, a correlation between fatigue line and Semi-Circular bending test should be done. On this way, referring to the global failure mechanism the fatigue test results in Table 6 shows that the asphalt mixtures prepared using PMB exhibit a higher fatigue line value as well as a greater crack-propagation resistance than traditional solution with neat bitumen, which is observable from the increment of 53% in terms of maximum fracture stress and of 59% in terms of fracture toughness. Moreover, for HMA_{PMA}, the highest fatigue line value (1.34E + 04 vs 1.30E + 04 of PMB and 1.01E + 04 of traditional mixture) did not correspond to the highest crack-propagation resistance value since this mixture attained the same maximum fracture stress (1.08 MPa both for PMA and PMB) and fracture toughness as HMA_{PMB} (27.98 MPa of PMA vs 28.21 of PMB).

4.4. Rutting resistance

Referring to the susceptibility of the HMA to deformation, Fig. 8 depicts that HMA_{PMB} exhibited the best mechanical properties, both in terms of the stiffness modulus which was + 88% higher than that of HMA_{NB} and + 39% higher than that of HMA_{PMA} and the rutting resistance, where it exhibited the lowest rut depth (1.86 mm vs 1.92 mm for HMA_{PMA} at 10,000 cycles and 2.00 mm for HMA_{NB} at 8000 cycles).

It is useful to see, from the analysis of Fig. 8, that there is a strongly correlation between the mechanical response of asphalt mixtures int terms of stiffness modulus at 40 °C and the related response in terms of rut depth at 60 °C. In detail, Fig. 8 displays how to an increment of stiffness modulus corresponds to proportional rut depth reduction independently from the mixture type.

4.5. Cumulative results and general discussions

This paper presents a complete characterization procedures and analysis to investigate the mechanical response of modified asphalt mixtures. In detail, three asphalt mixtures for binder layers were compared through a complete laboratory test program aimed at mechanical response towards the most important damage causes. The main findings of the conducted research study are summarized in Table 7 which underlines the mean results provided by the laboratory test program conducted to achieve the main goal of the research study

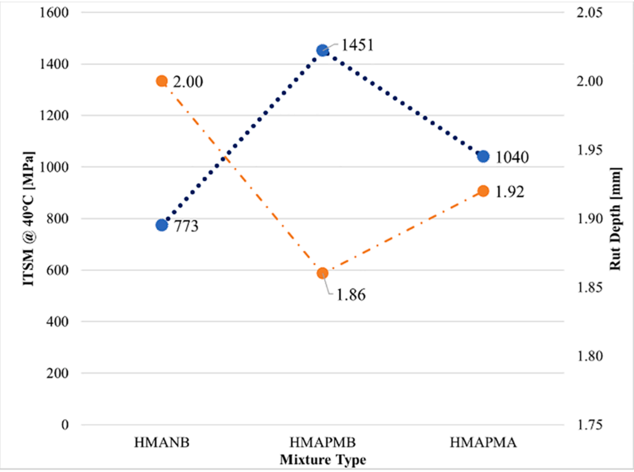


Fig. 8. Rutting resistance a) ITSM variation @40 °C b) comparison between ITSM@40 °C and rut depth.

Starting from the considerations made in previous sections it is possible to see how to determine the attitude of the asphalt mixtures to resist to the main causes of damage, the stiffness modulus plays a key role. The present research study has demonstrated how a significant variation in terms of stiffness modulus involves an equally variation on the resistance to damage.

This condition can be confirmed correlating the results explained in Fig. 5 with the results provided by rutting resistance. In fact, making a more general analysis of mechanical performances and rutting resistance properties, it is possible to observe that:

a) results obtained are completely in agreement with types of primary materials adopted since, considering the inner structure of PMB that contains SBS polymer, it was expected a higher and more elastic response under repeated road cycles at high temperatures than the others asphalt mixtures prepared using neat bitumen. This condition has been appreciated both considering the results of ITSM values that displays an increment of 88% than HMANB and + 39% higher than that of HMAPMA and the rutting resistance, where it exhibited the lowest rut depth (1.86 mm vs 1.92 mm for HMAPMA at 10,000 cycles and 2.00 mm for HMANB at 8000 cycles
b) There is a strongly correlation between the stiffness modulus at 40 °C and the rutting resistance as shown in Fig. 8

Table 6
Cracking resistance, results from fatigue and SCB tests.

General Informations				Test sample			
Test	Parameter	Temperature	Mixture	Fatique line	Mean	St. dev	CV
Fatique	Fatique line Nr. of cycles	10 °C	HMA_{NB}	1.01E + 04	1.01E + 04	706.91	0.070
Fatique	Fatique line Nr. of cycles	10 °C	HMA_{PMB}	1.30E + 04	1.27E + 04	487.02	0.038
Fatique	Fatique line Nr. of cycles	10 °C	HMA_{PMA}	1.36E + 04	1.34E + 04	442.29	0.033
SCB	fracture toughness $N/mm^{1/5}$	10 °C	HMA_{NB}	17.62	17.73	0.78	0.04
SCB	fracture toughness $N/mm^{1/5}$	10 °C	HMA_{PMB}	27.42	28.21	1.56	0.06
SCB	fracture toughness $N/mm^{1/5}$	10 °C	HMA_{PMA}	26.89	27.98	1.78	0.06
SCB	Max. Stress MPa	10 °C	HMA_{NB}	0.68	0.71	0.04	0.06
SCB	Max. Stress MPa	10 °C	HMA_{PMB}	1.01	1.08	0.06	0.06
SCB	Max. Stress MPa	10 °C	HMA_{PMA}	1.04	1.08	0.06	0.06

Table 7
Cumulative results.

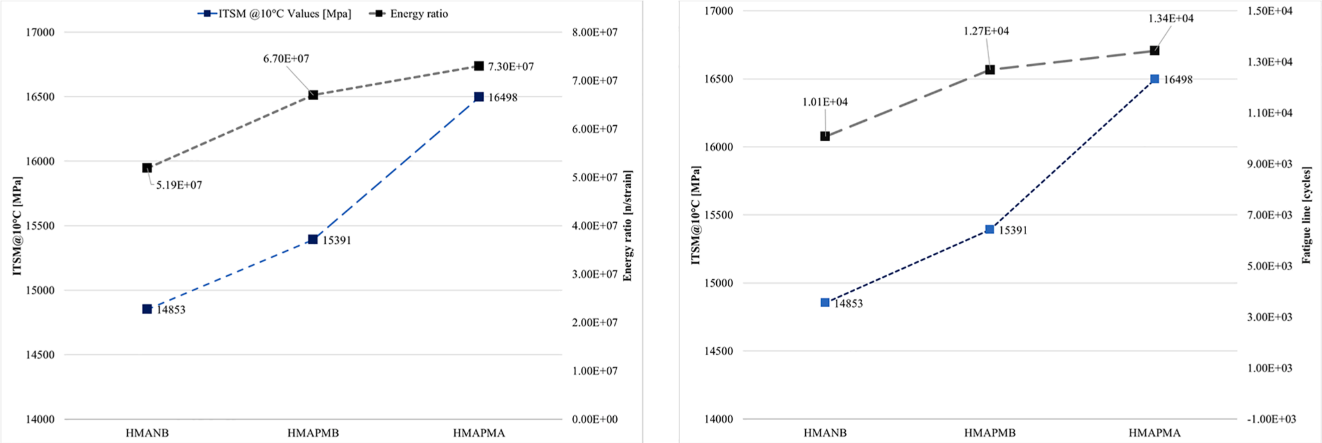
Mixture type	Test	Temperature	Standard	Response investigated	Unit	Mean	Std Dev	CV	Sample size
HMA$_{NB}$	ITS	10 °C	EN 12697–23	Moisture damage	MPa	3.37	0.53	0.158	3
HMA$_{PMB}$	ITS	10 °C	EN 12697–23	Moisture damage	MPa	2.97	0.28	0.095	3
HMA$_{PMA}$	ITS	10 °C	EN 12697–23	Moisture damage	MPa	4.45	0.39	0.088	3
HMA$_{NB}$	ITSR	15 °C	EN 12697–12	Moisture damage	%	90.91			2
HMA$_{PMB}$	ITSR	15 °C	EN 12697–13	Moisture damage	%	94.59			2
HMA$_{PMA}$	ITSR	15 °C	EN 12697–14	Moisture damage	%	98.84			2
HMA$_{NB}$	ITSM	10 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	14,853	1031.74	0.069	50
HMA$_{PMB}$	ITSM	10 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	15,391	633.799	0.041	50
HMA$_{PMA}$	ITSM	10 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	16,498	1334.203	0.081	50
HMA$_{NB}$	ITSM	20 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	8120	539.57	0.066	50
HMA$_{PMB}$	ITSM	20 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	8613	491.567	0.057	50
HMA$_{PMA}$	ITSM	20 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	9582	63.194	0.061	50
HMA$_{NB}$	ITSM	40 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	773	75.00	0.097	49
HMA$_{PMB}$	ITSM	40 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	1451	141.254	0.097	50
HMA$_{PMA}$	ITSM	40 °C	EN 12697–26 - ANNEX C	Structural behaviour	MPa	1040	63.194	0.061	49
HMA$_{NB}$	Fatigue	10 °C	EN 12697–24 - ANNEX E	Fatigue resistance	Cycles	1.01E + 04	706.91	0.07	5
HMA$_{PMB}$	Fatigue	10 °C	EN 12697–24 - ANNEX E	Fatigue resistance	Cycles	1.27E + 04	487.02	0.04	5
HMA$_{PMA}$	Fatigue	10 °C	EN 12697–24 - ANNEX E	Fatigue resistance	Cycles	1.34E + 04	442.29	0.03	5
HMA$_{NB}$	SCB	10 °C	EN 12697–44	Crack propagation	$N/mm^{1/5}$	17.73	0.78	0.04	5
HMA$_{PMB}$	SCB	10 °C	EN 12697–44	Crack propagation	$N/mm^{1/5}$	28.21	1.56	0.06	5
HMA$_{PMA}$	SCB	10 °C	EN 12697–44	Crack propagation	$N/mm^{1/5}$	27.98	1.78	0.06	5
HMA$_{NB}$	Wheel Tracker	60 °C	EN 12697–22	Rutting	mm	2.00	0.00	0.00	4
HMA$_{PMB}$	Wheel Tracker	60 °C	EN 12697–22	Rutting	mm	1.86	0.042	0.023	4
HMA$_{PMA}$	Wheel Tracker	60 °C	EN 12697–22	Rutting	mm	1.92	0.04	0.02	4

c) Referring to the HMA$_{PMA}$ solution, it is possible to see how it follows the same trend as the other two HMAs, regardless of the nature of applied load and the temperature. In any case, the increment of stiffness modulus than HMA$_{NB}$ solution, can be only related to the addition of polymeric compound because no differences are verifiable in terms of grading curve distribution and volumetric properties between the designed solutions. In detail, the PMA exhibits higher mechanical response at all investigated temperatures and for all test conducted (i.e. + +32% on ITS, +11% on ITSM at 10 °C, +18% on ITSM at 20 °C, and + 34% on ITSM at 40 °C), otherwise it exhibits a reduction of performances at higher temperature than HMA$_{PMB}$ (i.e. −39% of ITSM at 40 °C and 1.922 of rut depth vs 1.86 mm). Hence, so PMA mixture is the best choice to improve the mechanical performances at middle and low temperatures, as confirmed by the data at 10 and 20 °C, but it is non the best solution for hot operating conditions.

Otherwise, analysing the results at lower temperature, it is possible to see how considering the results of the tests conducted in the indirect tensile load configuration at 10 °C a common link between the causes of damage, mechanical performance tests, and test temperatures can be found.

On this way, it is possible to observe how the HMA$_{PMB}$ asphalt mixture reverses the trend of ITS and ITSM referring to the HMA$_{NB}$ solution. In fact, in the ITS test, HMA$_{PMB}$ exhibited poorer mechanical properties than the HMA$_{NB}$ (Fig. 4); however, based on the results obtained from the ITSM test at the same temperature, HMA$_{PMB}$ exhibited almost equal mechanical properties than the HMA$_{NB}$, since both the results provided in Fig. 5 and Table 5 (ANOVA test) confirms that no statistical differences occur. This finding was confirmed by the fatigue test results, which indicate that HMA$_{PMB}$ exhibited a slightly longer fracture line (1.27×10^4 vs 1.01×10^4, as shown in Table. 6) and energy ratio (6.70×10^7 vs 5.14×10^7, as shown in Table. 6) than HMA$_{NB}$.

Finally, another important consideration should be drawn: first, to investigate the mechanical properties of HMA$_{PMB}$ at low temperatures, 10 °C in this case, the traditional tests (i.e. ITS) are not sufficient and they may not provide accurate results, so more articulated tests are necessary (i.e. ITSM, Fatigue or SCB); moreover, moving from traditional test to dynamic tests conducted at 10 °C a strongly correlation can be found. In fact, as graphically demonstrated in Fig. 9a and Fig. 9a, an increment in the stiffness modulus corresponds to an improvement in the fatigue performance, independently from the type of HMA



a) b)

Fig. 9. Dynamic test results and comparisons. a) ITSM vs fatigue line at 10 °C, b) ITSM vs energy ratio at 10 °C.

considered.

This condition can be also related to the considerations made for higher temperatures mechanical responses, where a similar relation was described between the ITSM values and the resistance to damage phenomena.

5. Conclusions

As conclusion of an advanced test laboratory program investigation, it is possible to ascertain that

- Generally the modified asphalt mixtures exhibits higher mechanical response both in static and pseudo-static load conditions, but the significance of the improvement should be tested using adequate statistical analysis;
- The ITSM proved as a key parameter to analyse the attitude of asphalt mixtures to resist to the damage phenomena, because it is strongly related to the other parameters such as fatigue life or resistance to rutting phenomena;
- A more complex analysis of ITSM parameter is required to better understand its influence on the mechanical response of the asphalt mixtures and if different asphalt mixtures are compared a statistical analysis should be made to ascertain that statistically differences occur between them;
- To accomplish a good investigation of the low-temperature mechanical properties of modified asphalt mixture, standard tests (such as ITS) are not suitable, and more complex tests (such as ITSM and fatigue tests) are required.
- The results of the tests conducted at 10 °C in indirect tensile loading configuration demonstrate that an increment in stiffness modulus corresponds to an enhancement in fatigue performance, irrespective of the type of asphalt mixture.
- The cracking resistance of asphalt mixtures cannot be evaluated solely through fatigue tests because the crack-propagation process is necessary to determine the effective resistance capacity and, cannot be ignored.

Future research should focus on addressing- whether the use of different amounts of polymer compound can affect the final results in terms of mechanical properties. Moreover, the authors are currently continuing the investigation to improve the dataset available and to increase the database in order to extend the analyses here present to a larger scale.

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CRediT authorship contribution statement

Nunzio Viscione: Conceptualization, Methodology, Data Curation, Writing – original draft, Writing – review & editing, Visualization. **Rosa Veropalumbo:** Methodology, Formal analysis, Validation, Visualization. **Cristina Oreto:** Formal analysis, Data Curation, Writing – Review & Editing. **Salvatore Antonio Biancardo:** Formal analysis, Validation. **Francesco Abbondati:** Data curation. **Francesca Russo:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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