Asphalt mixture modification with a plastomeric compound containing recycled plastic: laboratory and field investigation

Fabrizio Cardone ⓘ · **Sara Spadoni** ⓘ · **Gilda Ferrotti** ⓘ · **Francesco Canestrari** ⓘ

Abstract The use of recycled plastic in asphalt pavements represents a sustainable and economic choice which, if correctly designed, could significantly improve the resistance against the typical distresses of flexible pavements. For this reason, this paper aims at evaluating the mechanical properties of two asphalt mixtures modified with two plastomeric compounds through the dry method, by comparing their results with those obtained for a reference asphalt mixture modified with Styrene–Butadiene–Styrene (SBS) polymers. One of the compounds consisted of plastomeric polymers, whereas the other was made of recycled plastic and graphene. The experimental program included laboratory tests on shear gyratory compacted specimens and cores extracted from a real-scale field trial. The results showed that stiffness, fatigue and rutting resistance of the two polymeric compound modified mixtures were comparable to those of the reference mixture. Finally, a Falling Weight Deflectometer (FWD) campaign, performed in the field after one year of service life of the pavement, showed a reduced structural response of the sections constructed with compound modified mixtures with respect to the reference one because of compaction issues and possible interlayer de-bonding effects.

1 Introduction

Nowadays, the use of polymer modified bituminous materials is a well-known practice which is widely employed with excellent results in pavement engineering. The polymers used for the modification of asphalt pavement materials can be broadly divided in elastomers (such as styrene–butadiene–styrene SBS and styrene-butadiene-rubber SBR copolymers) and plastomers (such as ethylene vinyl acetate EVA, high-/low-density polyethylene HDPE/LDPE, polypropylene PP, polyethylene PE, polyethylene terephthalate PET and polyvinyl chloride PVC). These polymers are ad-hoc engineered materials with the aim of improving specific characteristics of the bituminous mixtures to withstand the typical distresses experienced by the pavements during their in-service life [1–5]. The

F. Cardone · S. Spadoni (✉) · G. Ferrotti · F. Canestrari
Department of Civil and Building Engineering and
Architecture (DICEA), Università Politecnica delle
Marche, Via Brecce Bianche, 60131 Ancona, Italy
e-mail: s.spadoni@pm.univpm.it

F. Cardone
e-mail: f.cardone@univpm.it

G. Ferrotti
e-mail: g.ferrotti@univpm.it

F. Canestrari
e-mail: f.canestrari@univpm.it

polymer modification is usually performed by adopting the wet method, which consists in adding, blending and completely dispersing the polymer into the bitumen prior to the production of bituminous mixture [6, 7]. The wet method has the advantage to control the properties of the binder, even though handling efforts are needed at the asphalt plant when the polymer modified bitumen is stored inside tanks prior the mixing in order to avoid the phase separation [8–10]. Due to the necessity of a complete dispersion of the polymer into the bitumen, the wet method can be properly employed for polymers (e.g. SBS and EVA) which have a relatively low melting point [8–12].

Conversely, the polymeric compounds made of hard and rigid plastics, having a higher melting point, can be added through the dry method, which consists on adding and mixing the compounds with hot aggregates and bitumen directly in the asphalt plant, at temperatures ranging from 150 to 170 °C [6, 8]. Basically, the dry method is a prompter process which also requires less costs and energy than the modification with the wet method because no equipment and operations for the storage of modified bitumen is needed at the asphalt plant [7, 13, 14]. On the other hand, the dry method implies lower control of the bituminous mixture properties in comparison with the wet method. Several types of polymeric compounds can be used for dry modification of asphalt mixtures. In this sense, the recycled plastics are more and more often used for asphalt pavement applications. Indeed, the production of recycled polymers from waste plastics (i.e. substantially plastomeric product made up of various types of recycled plastics) for engineering applications is a viable technical challenge. Due to the high quantities of waste plastics generated every day worldwide, finding new sustainable and economic ways to recycle waste plastics in long-term constructions is one of the main and dutiful goals [15]. Pavement engineering represents a sector where the recycled plastics can be efficiently used in many ways, such as aggregate substitute [16–18], filler and asphalt binder modifier [15, 18, 19]. At first, the complexity of the waste plastic and its heterogeneity in chemical and physical composition are the major aspects to be studied. An in-depth critical review was conducted by Wu and Montalvo [8], summarizing the effects of different types of recycled plastics on bituminous mixture performance. Generally, the waste plastics can be added through the dry method, because the plastics could work as fine solid particle in the aggregate skeleton of the bituminous mixture contributing to the global mechanical response. It has been shown that plastic compounds could increase the stiffness, viscosity, thermal susceptibility, permanent deformation resistance and fatigue resistance of asphalt mixtures [13, 20–23, 25–27]. On the other hand, controversial results about the performance of asphalt mixture containing some types of plastic [8], such as the penalisation of the workability due to the presence of waste plastics [21, 23], the gap in understanding the long-term performance and the lack of proper guidelines and technical standards [15], could limit the use of waste plastics in bituminous mixtures.

To expand a conscious use of plastic waste and promote its application on the road pavements ensuring life cycle environmental and economic sustainability implications [19], the objective of this paper focuses on the mechanical characterization of two asphalt mixtures modified through the dry method with two plastomeric compounds. Specifically, the two compounds are in plant processed materials having similar basic composition (polyethylene PE and polypropylene PP), but one of them is obtained from recycled plastics with the addition of graphene. Furthermore, a reference asphalt mixture modified with SBS through the wet method was selected for comparison purposes. The investigation included testing campaigns on both laboratory prepared specimens and cores extracted from a dedicated full-scale field trial. The field trial was also subjected to Falling Weight Deflectometer (FWD) tests before the construction of the bituminous courses and after one year of pavement in-service life.

2 Materials and methods

2.1 Asphalt mixtures

In this study two compounds were investigated, the first is a blend of plastomeric polymers (coded as P), and the second is made of rigid recycled plastics and graphene (coded as G). Both compounds are supplied in form of hard pellets with a diameter less than 5 mm. D'Angelo et al. [28] conducted an in-depth chemical and rheological characterisation of both compounds, showing that, despite the G is made of recycled plastic,
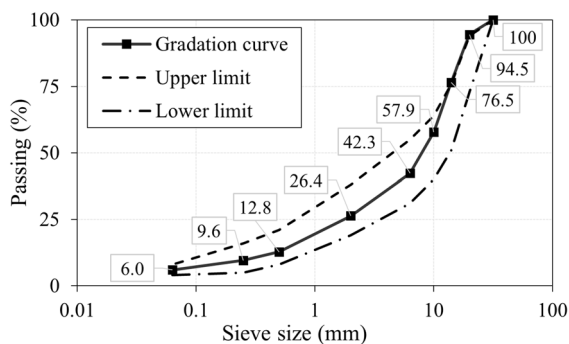
both basically consist of PE and PP, with the addition of graphene in the G compound, which should be able to improve the performance of the mixture because of the formed graphene networks [29, 30]. In the same study [28], the differential thermal profiles of P and G showed the presence of two endothermic peaks placed at 127 and 161 °C, and 141 and 167 °C respectively, due to the melting of the polymer crystalline parts. Since the higher melting temperatures of the plastics are very close to the temperatures typically used in production, lay-down and compaction of asphalt mixtures (i.e. 160–170 °C), potential effects on the mixture workability are expected.

A reference SBS modified mixture, widely employed for construction and maintenance activities in Italian motorways, was selected to be compared with two mixtures modified with the above-mentioned plastomeric compounds (P and G) by means of the dry method. All the three mixtures were produced at the asphalt plant.

A typical dense-graded curve for base courses (Fig. 1) was selected as design gradation for all the mixtures. The gradation had a nominal maximum aggregate size of 20 mm, and it was composed of limestone virgin aggregate and 30% (by aggregate mass) of reclaimed asphalt (RA). The total binder content is equal to 4.3% by aggregate weight for all the mixtures, regardless of the presence of compounds.

The reference mixture (coded as H) was produced with a SBS polymer modified bitumen (3.8% by bitumen weight) with a penetration grade of 56 dmm and a softening point of 71.9 °C. The other two mixtures (coded as PC and GC, depending on the compound employed) were produced by using a 50/70 pen grade bitumen and adding the compounds (5.2% of the total binder weight) through the dry process.

The plain 50/70 bitumen had a penetration value of 52 dmm and a softening point equal to 48.9 °C, according to [31] and [32] respectively.

The production with the dry process of the compound modified mixtures was executed in the asphalt plant at 170 °C. The RA was incorporated to the pre-heated virgin aggregates through the RA conveyor. The same RA conveyor was used to introduce the plastomeric compounds, so that they stayed away from the direct contact with the burner flame of the drum. Finally, the bitumen was added and mixed with the hot aggregate blend containing compounds.

2.2 Laboratory prepared specimens

After the mixing at the asphalt plant, loose mixtures were immediately compacted at 160 °C by using a gyratory compactor (EN 12,697–31:2019 [33]) to obtain 150 mm diameter cylindrical specimens with a final height of 150 mm and a target air void content equal to 6.0%. Figure 2 summarizes the average number of gyrations needed for the compaction of the mixtures showing that the PC and GC materials are characterized by a lower workability (i.e. higher number of gyrations) with respect to the reference one (H). This finding can be likely related to the presence of plastics within the mixtures PC and GC (due to their melting point very close to the compaction temperature) which required higher energy effort for compacting the specimens at the same target height.

After compaction, each gyratory specimen was cored in order to obtain 100 mm diameter specimens,

Fig. 1 Design gradation curve
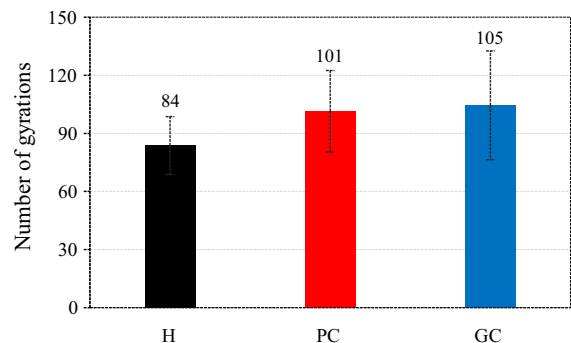
Fig. 2 Number of gyrations needed for the compaction (error bars represents the standard deviation)

which were subsequently cut at specific heights, suitable for testing characterization.

2.3 Field specimens

The investigation also included the construction and the monitoring of a full-scale field trial laid along the A12 Italian motorway, with the same asphalt mixtures used for the laboratory specimen preparation. Specifically, the field trial consisted in three 200 m long test sections, including two sections constructed with the mixtures modified with the polymeric compounds (PC and GC) and a reference test section constructed with the SBS modified mixture (H).

Figure 3 shows the pavement layers consisting of an open graded wearing course (coded as OG) with thickness of 4 cm and two base courses (superior and inferior) with thickness of 10 and 15 cm, hereafter named as "field_sup" and "field_inf", respectively. Both base courses of each section were made with the same mixture and constructed in sequence within one morning, meaning that the field_sup course was compacted on the field_inf course while this last one had not yet completely cool down. As a consequence, it is likely that the field_inf course was subjected to a sort of additional compaction effort, which could make it characterized by an air void content lower than that of the field_sup course. For each section, all the bituminous courses were built on a granular foundation with a nominal thickness of 35 cm, as shown by an exploratory pit.
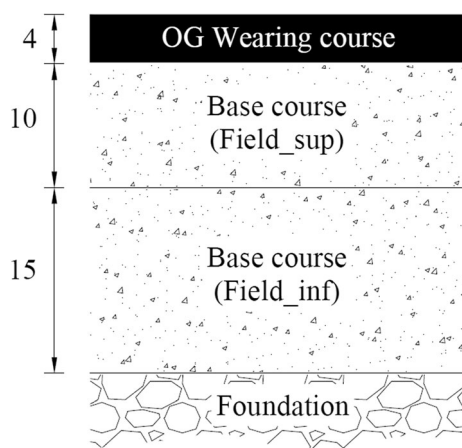
Fig. 3 Pavement layers of the test field

Six months after the construction, 100 mm diameter samples were cored from the field and, after removing the OG wearing course, trimmed to specific heights suitable for testing characterization.

2.4 Experimental program

The experimental research involved both laboratory and field investigations. The testing program was carried out on laboratory produced specimens and cores from the test field for evaluating the mechanical behaviour of the three mixtures in terms of stiffness properties (indirect tensile stiffness modulus ITSM and dynamic modulus), fatigue (indirect tensile fatigue test ITFT) and rutting resistance (triaxial cyclic compression test TCCT). It is worth pointing out that the specimens from the test field were cored from both the field_sup and the field_inf course (Fig. 3). Figure 4 shows a summary of the laboratory testing program and the testing temperatures.

The experimental program regarding the field investigation also included two FWD campaigns at an interval of one year. Specifically, the first series of FWD tests was carried out directly on the foundation before the construction of the asphalt mixture courses with the aim of evaluating the bearing capacity of the underlying unbound layers (i.e. foundation and subgrade). The second FWD series was carried out on the pavement after one year of service life under actual traffic loading in order to evaluate the different structural response of the three bituminous mixtures.

2.5 Test methods

2.5.1 Indirect tensile stiffness modulus (ITSM)

The ITSM were determined according to EN 12,697–26 [34] by means of a servo-pneumatic machine. The standard defines a pulse load, with rise-time of 124 ms and pulse repetition period of 3.0 s, to be applied on the specimens in order to achieve the target horizontal deformation of 5 ± 2 μm. The ITSM can be calculated as follows:

$$\text{ITSM} = \frac{F_{max}(v + 0.273)}{t \cdot d_{max}} \quad (1)$$

where F_{max} is the maximum value of the pulse load, t is thickness of the specimen, v is the Poisson's ratio assumed equal to 0.35 and d_{max} is the target horizontal
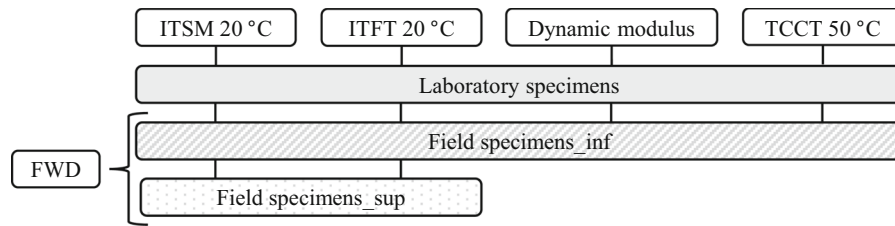
Fig. 4 Experimental program

deformation. The tests were carried out at 20 °C on 100 mm diameter specimens with a nominal height of 60 mm, which were previously conditioned for at least four hours at test temperature. Six replicates were performed for each mixture.

2.5.2 Dynamic modulus test

Dynamic complex modulus was measured to evaluate the stiffness of the mixtures over a wide range of temperature and loading frequency. Dynamic modulus tests (AASHTO T 378 [35]) were performed at four temperatures (5, 20, 35 and 50 °C) and 6 frequencies (20, 10, 5, 1, 0.5 and 0.1 Hz) by means of Universal Testing Machine (UTM) in compression mode. For each configuration (i.e. loading frequency and temperature), the tests were carried out in control strain mode. The axial load was applied at the top and the bottom of the specimen, and the axial deformations were measured in the central part of the specimen, through three LVDTs placed 120 degrees apart. Specifically, the specimen was subjected to a controlled sinusoidal (haversine) compressive stress which was in turn selected in order to obtain a target strain level equal to 50με. For each loading frequency and temperature, the dynamic modulus was calculated as the ratio between the resulting axial stress and the target axial strain amplitudes. Based on the time–temperature superposition principle, the experimental data were shifted along the frequency axis through the shift factors determined with the Williams-Landel-Ferry (WLF) formulation [36], which allow the determination of the master curves at 20 °C.

The tests were carried out on 100 mm diameter specimens having a nominal height of 150 mm for laboratory specimens and 120 mm for the field cores. Two replicates were tested for each mixture.

2.5.3 Indirect tensile fatigue test

The fatigue resistance of the mixtures was evaluated by means of the indirect tensile fatigue test (ITFT), carried out through a servo-pneumatic machine according to EN 12,697–24 Annex E [37]. The test was performed under controlled-stress mode by applying repeated haversine load with 0.1 s loading time and 0.4 s rest time. The stress levels were selected in order to have initial horizontal strains ranging between 70 and 400με, with the aim of obtaining a fatigue life between 10^3 and 10^6 cycles. During the test, the number of loading cycles applied on the specimen was recorded until the complete fracture of the specimen occurred (failure). Test data were analysed in terms of fatigue curve as an indicator of fatigue response of the material. Specifically, in a bi-logarithmic plane, the relation between the initial horizontal strain $\varepsilon_{h,0}$ and the number of cycles at failure N_f was expressed by a linear relation:

$$\log N_f = a - b \cdot \log \varepsilon_{h,0} \qquad (2)$$

where a and b are material parameters, and $\varepsilon_{h,0}$ was measured at the 100th load cycle. The tests were carried out at 20 °C on the same specimens prior subjected to ITSM tests. Before testing, the specimen was conditioned for four hours in the climatic chamber at the test temperature. A total of six repetitions for each material and each field course (field_sup and field_inf) were tested in order to depict the fatigue curve as an indicator of the fatigue response of the material.

2.5.4 Triaxial cyclic compression test

The resistance to permanent deformation was evaluated by means of triaxial cyclic compression test (TCCT) according to EN 12,697–25 (test method B) [38]. Specifically, a cylindrical specimen was placed

between two parallel loading platens in a triaxial chamber and subjected to a confining pressure of 50 kPa and a superposed cyclic axial block-pulse stress of 200 kPa for 10,000 loading cycles at test temperature of 50 °C (EN 13,108–20 [39]). The pulse duration was 1 s with 1 s rest period. During the test, the cumulative axial strain of the test specimens was measured and depicted as a function of the number of load cycles to obtain the creep curve.

Finally, the slope B_1 of the quasi-linear second stage of the creep curve was calculated, and the creep rate f_c was determined and selected to evaluate the permanent deformation behaviour of the mixtures:

$$f_c = B_1 \cdot 10^4 \tag{3}$$

The tests were carried out on 100 mm diameter specimens having a nominal height of 120 mm, and two replicates were performed for each mixture.

2.5.5 Falling weight deflectometer (FWD) campaign

The structural properties of the granular and bituminous courses of the test field pavements were evaluated by means of in-situ FWD testing. The FWD equipment used was configured with nine geophones placed at 0, 200, 300, 400, 500, 600, 700, 800, 1500 mm from the centre of the 300 mm loading plate. The stiffness moduli of the pavement layers were computed through the back-calculation method, using BACAN software. The pavement was assimilated to a three-layers elastic structure. The first layer included the asphalt mixtures, i.e. the 4 cm open-graded wearing course and the 10 + 15 cm base courses (Fig. 3). The second layer represented the 35 cm granular foundation and the third layer corresponded to the subgrade, which was modelled with infinite thickness. For the back-calculation of the FWD data obtained before the construction of the bituminous courses, the pavement was assimilated to a structure made of two layers (i.e. foundation and subgrade).

3 Results and analysis

3.1 Indirect tensile stiffness modulus

The mean values of the ITSM measured at 20 °C on both laboratory specimens and field cores along with the corresponding average air void contents are shown in Fig. 5. Laboratory specimens showed significantly higher ITSM as compared to the cores, regardless of type of asphalt mixtures. This result can be due to the different volumetric properties between laboratory specimens and cores. Indeed, the field cores were characterized by a higher air voids content with respect to the laboratory specimens, resulting in lower ITSM values. In the field_inf course, the higher stiffness modulus of the reference mixture with respect to the compound modified mixtures was justified by the lower air voids content of the specimens H (i.e. 2.8%) as compared to specimens PC and GC (i.e. 5.1 and 4.8%, respectively). This difference in air voids of about 2% can be due to the different additional compaction undergone by the reference mixture H with respect to the PC and GC mixtures. In fact, the superior base layer was built over the inferior one consecutively when the latter was still warm. Consequently, the H mixture of the inferior base course experienced a higher compaction effort (resulting in a better packing), differently to PC and GC mixtures whose workability was reduced by the presence of plastomeric compounds (P and G). As explained in a previous study [28], both compounds are responsible for a more rigid network within the PC and GC mixtures because of laydown and compaction temperatures were close or slightly lower than their melting point.
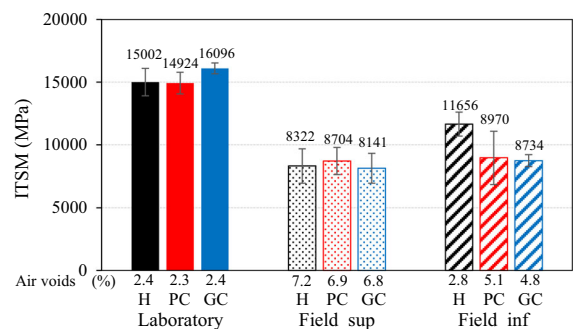
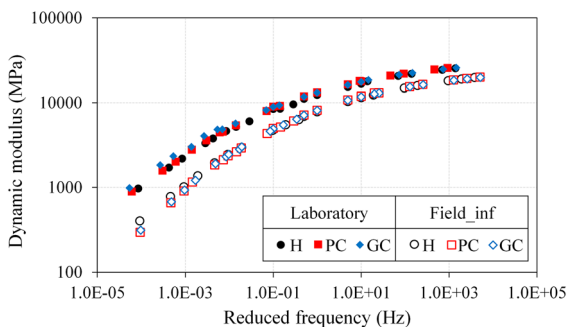**Fig. 5** ITSM tests results (error bars represent the standard deviation)

3.2 Dynamic modulus

Dynamic modulus data in terms of master curves are shown in Fig. 6. As for both laboratory specimens and field cores, the dynamic modulus curves overlapped, highlighting that the three mixtures are characterized by similar stiffness properties throughout the range of the investigated frequencies and temperatures. However, the laboratory mixtures were stiffer than the corresponding field mixtures. Also in this case, the reason is mostly ascribable to the different volumetric properties of the specimens due to the compaction method experienced (laboratory vs. field). Indeed, the volumetric analysis showed that the laboratory specimens were characterized by 2% lower air voids content as compared to the field cores. Overall, the analysis of dynamic modulus master curves confirms the ITSM results, highlighting that the type of compound did not affect the stiffness of the modified mixtures, which in turn was comparable to the reference SBS modified mixture.

Finally, the shift factors of all the specimens calculated according to WLF model are shown in Fig. 7. In general, from the analysis of both laboratory and field mixtures, it can be observed that the shift factors calculated for the three mixtures and the corresponding trends were very close, highlighting that the plastomeric compounds gave to the mixtures a thermal susceptibility comparable to that of the SBS polymers.

3.3 Fatigue resistance

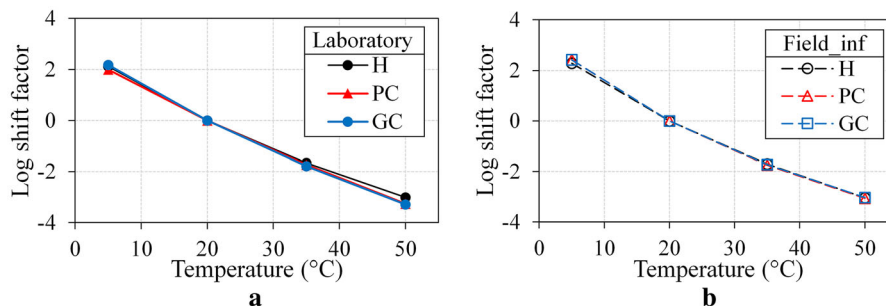The fatigue curves of laboratory and field mixtures are shown in Fig. 8, whereas the fitting parameters of the linear relation (Eq. 2) and the strain corresponding to 10^6 cycles (ε_6) [37] are reported in Table 1. The fatigue curves of the field mixtures (Fig. 8b) include the experimental data of both field_sup and field_inf courses as the materials used in the two courses is the same in each section.

Comparing the performance of the laboratory produced mixtures (Fig. 8a), both compound-modified mixtures showed an improved fatigue response with respect to the reference H mixture in terms of a higher ε_6 value. This outcome was not confirmed by results gathered from the field cores, where H mixture showed the best performance in terms of higher ε_6 value combined to a lower sensitivity to the strain level with respect the mixtures GC and PC which showed a similar fatigue response (Fig. 8b). The difference between laboratory and field behaviour can be due to the effects related to the field construction activities. The fatigue response of specimens obtained under controlled laboratory conditions and characterized by similar volumetric properties (regardless of the compaction energy applied – Fig. 2), is expected to be directly related to the intrinsic mixture composition. As for the field conditions, even though a proper attention has been paid during the construction activities, the fatigue response of the mixtures was necessarily affected by the material workability, which penalized the compound modified mixtures. In addition, it can be observed that the field specimens always showed a higher fatigue life than the laboratory ones. This is likely due to the higher stiffness (Fig. 5) characterizing the laboratory specimens, which might have induced a more brittle behaviour resulting in a premature fatigue failure.

3.4 Rutting resistance

The results of the calculated creep rate f_c from the creep curves are shown in Fig. 9, where the average air voids content of the specimens is reported as well. The figure shows that field_inf cores were characterized by a lower rutting resistance as compared to the laboratory specimens. However, it is important to highlight that the higher creep rate values in the field condition were likely due to the higher air void content and worst aggregate packing compared to that of shear gyratory compacted specimens, which made the mixtures more prone to rutting at high temperature. Moreover, the PC mixture showed the best performance in both

Fig. 6 Dynamic modulus master curves at the reference temperature of 20 °C

Fig. 7 Shift factors of laboratory specimens **a** and field cores **b**

Fig. 8 Fatigue curves of **a** laboratory produced specimens and **b** of field cores
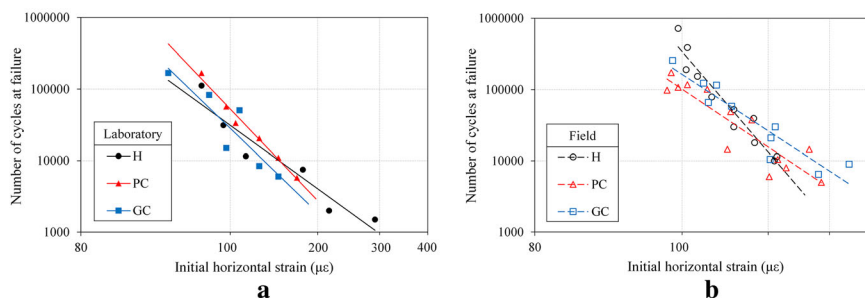
Table 1 Parameters of the experimental fatigue curves

	b		a		R^2	ε_6
	Average value	Standard deviation	Average value	Standard deviation		
Laboratory_H	− 5.034	0.780	15.589	1.800	0.91	80
Laboratory_PC	− 7.274	0.475	20.753	1.066	0.98	107
Laboratory_GC	− 6.713	1.582	19.249	3.489	0.82	94
Field_H	− 8.017	0.742	23.203	1.704	0.93	140
Field_PC	− 4.611	0.655	15.169	1.519	0.82	97
Field_GC	− 4.504	0.605	15.140	1.420	0.87	107

laboratory and field condition, with a creep rate 25% lower than the reference one, confirming that the stiffening contribution of plastics enhances the permanent deformation resistance of the mixture. Contrarily, the GC mixture showed controversial results, because the expected good laboratory performance was not confirmed in field. However, this result finds support in many research works which obtained similar controversial conclusions from different rutting tests performed on bituminous mixtures modified with plastics [21, 24, 40, 41], underlining the crucial role of the homogeneity of the specimen and test

conditions, such as the initial stress and the confinement and the loading conditions (duration and intensity of load cycles and rest period) on the rutting response.

3.5 FWD test results

As for the analysis of FWD measurements, each test section (H, PC and GC) was considered as a distinct homogeneous section. Specifically, for each test section the measured basins were considered to calculate the average basin, assumed as representative
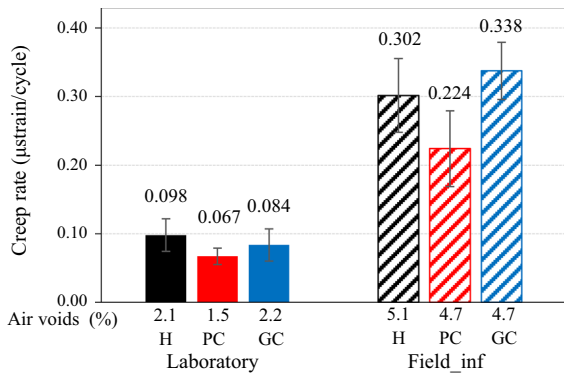
Fig. 9 Creep rate results at 50 °C (error bars represent the standard deviation)

of the section. After that, the stiffness moduli of the layers were back-calculated with BACAN software. The stiffness values of the unbound granular courses (i.e. foundation and subgrade) obtained from the back-calculation are shown in Fig. 10a, where FWD (1) indicates the results from the campaign performed before the construction of the bituminous courses and FWD (2) indicates those calculated after one year of in-service life of the pavement. The results show very good correspondence between the two campaigns, highlighting comparable moduli for each test section, especially for the foundation course. However, a slightly higher stiffness was registered for the foundation course for the H mixture test section.

The stiffness modulus values of the bituminous courses for each test section, obtained from the back-calculation (named FWD (2)) and referred to a temperature of 20 °C, are shown in Fig. 10b. It is worth pointing out that the moduli of the bituminous

courses are slightly underestimated due to the presence of the open graded (OG) wearing course characterized by lower stiffness with respect to the dense-graded base courses. For comparison purpose, in the same Fig. 10b, the dynamic modulus data measured at the frequency of 20 Hz (the same reference frequency of FWD test) on the cores of field_inf course are reported. It can be observed that the dynamic moduli of the cores were very similar for all the mixtures, whereas in the FWD (2) campaign, a higher modulus was obtained from H section as compared to PC and GC ones. It is important to underline in this regard that the stiffness obtained from the back-calculation represents the response of the entire bituminous system and thus also depends on the bonding conditions among the single bituminous courses forming the system itself. Thus, the lower stiffness of both sections built with compound modified mixtures (PC and GC) can be likely ascribable to the de-bonding effects occurred at the interface of the two base courses, as observed during the drilling of the PC and GC cores, whose field_sup and field_inf courses appeared detached from each other. This de-bonding effect can be due to the high melting temperature of P and G compound which could likely cause a loss in adhesion between the two courses during the construction, not ensuring a proper interlocking which is also responsible for guaranteeing a suitable adhesion level within the system.

Fig. 10 Stiffness moduli from back-calculation of **a** unbound courses and **b** bituminous courses
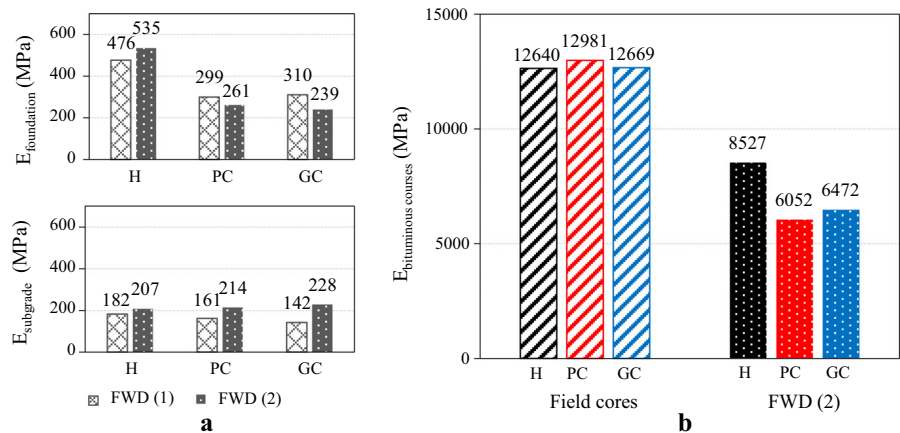
4 Conclusions

The objective of this research was to evaluate the mechanical response of two mixtures, one modified with plastomeric polymers (PC) and the other one modified with rigid recycled plastics and graphene (GC), through the dry method. Moreover, a reference SBS modified mixture (H) was considered for comparison purpose. The mechanical characterization was performed through a laboratory investigation in terms of stiffness properties, fatigue characteristics and rutting behaviour by testing gyratory compacted specimens and cores extracted from a dedicated full-scale field trial built with the same bituminous mixtures. In addition, the structural properties of the field trial were monitored by performing FWD testing after one year of in-service life. Based on the experimental results, the main conclusions can be summarized as follows:

- The stiffness and the thermal susceptibility of the plastomeric compound modified mixtures were comparable to those of the reference SBS mixture, highlighting that the difference in stiffness between laboratory specimens and field cores is mainly related to their volumetric properties;
- The plastomeric compound modified mixtures showed a similar fatigue resistance, contrarily to the reference one, which highlighted a different sensitivity to the applied strain level depending on the compaction condition (laboratory or field). However, the lower fatigue response in laboratory was likely due to a more brittle behaviour caused by the higher stiffness of the mixtures;
- The plastomeric compound mixtures showed better rutting response, especially in the case of PC mixtures which ensured the highest rutting resistance;
- FWD testing, performed on a dedicated full-scale field trial, showed a reduced structural response of the sections constructed with compound modified mixtures as compared to the reference one. This finding can be likely due to the de-bonding effects imputable to a penalized interlocking between the courses of the PC and GC sections, related to the thermal properties of the two polymeric compounds.

Overall considered, it can be stated that the use of plastomeric compounds to modify bituminous mixtures represents a valid technical solution because they ensure comparable performance with respect to a conventional SBS modified mixture, along with the advantage of producing modified bituminous mixtures according to a more cost-effective and sustainable process (i.e. dry method). Moreover, the similar performance showed by the two mixtures modified with plastomeric compounds encourages the use of recycled plastic for more sustainable pavement applications. However, it is worth pointing out that the use of this technology can entail operational drawbacks especially related to a penalized workability of the compound modified mixtures, which in turn can cause a reduction of the pavement efficiency due to potential de-bonding effects. Moreover, the peculiar thermal properties (i.e. high melting point) of the compounds can hinder the applicability of warm technologies along with the use of high RA amount within mixture.

Author contributions Conceptualization: Francesco Canestrari; Methodology: Fabrizio Cardone, Gilda Ferrotti; Formal analysis and investigation: Fabrizio Cardone, Gilda Ferrotti, Sara Spadoni; Writing—original draft preparation: Sara Spadoni; Writing—review and editing: Fabrizio Cardone, Gilda Ferrotti; Supervision: Francesco Canestrari.

Data availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of 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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