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Case study

Laboratory and field investigation of grouted macadam for semi-flexible pavements

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ABSTRACT

Grouted macadam (GM) made of an open-graded asphalt skeleton whose air voids are filled with a cementitious grout, is used as wearing course in semi-flexible pavements. GM stands out for its high stiffness and rutting resistance, as well as for its chemical resistant and jointless surface. Although it could satisfy all the engineering properties requested by ports, airports and industrial pavements, there are still few applications worldwide and the mechanical characteristics have rarely been investigated in depth. The main objective of this paper is to compare the stiffness, fatigue resistance and the cracking propagation resistance of GM mixtures manufactured in the field and in the laboratory. The thermal susceptibility and the ravelling resistance of laboratory specimens were also evaluated. The findings show that the stiffening contribution of the grout improves the fatigue life especially at high deformation levels. However, due to the hardening of the asphalt skeleton caused by the ageing of the bitumen, GM mixture may exhibit a brittle behaviour. Considering the validation and correspondence between laboratory and field results, the data could be useful for establish some analytical pavement design criteria.

1. Introduction

Nowadays, due to the development of the logistics industry, the heavy-load traffic demand is rapidly increasing. A promising solution for paving strategic infrastructures like airports, ports and heavy industrial areas is the semi-flexible pavement whose surface layer is built with a grouted macadam (GM) mixture. GM mixtures consists of an open-graded asphalt skeleton (25–35% air voids) filled with a high-fluidity cementitious grout, typically with total thickness up to 60 mm [1]. GM mixtures aim at combining the benefits of bituminous (e.g., jointless construction and rapid opening to traffic) and concrete pavements (e.g., high resistance to static or slow moving loads, and chemical resistance) [2]. The construction of GM wearing courses consists in a two-stage procedure, that can be completed in consecutive days. First an open-graded asphalt layer is laid and compacted using a steel roller. After cooling down, the voids of the asphalt skeleton are filled with the cementitious grout, with the help of light steel rollers or hand-operated rubber scrapers. A treatment to improve the skid resistance can also be done.

In comparison with a dense-graded asphalt concrete (AC) wearing course, GM wearing courses have higher stiffness [3–6] and lower thermal susceptibility [2,3,7]. In fact, GM mixtures partially inherit the thermo-viscoelastic behaviour from the asphalt skeleton [4]: the stiffness modulus increases with a reduction of bitumen content and with an increase of bitumen hardness, while it is little affected by the grout strength and aggregate size [1,6]. Furthermore, increasing the stiffness modulus, and therefore reducing the

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traffic-induced strain, is the main criterion for improving the fatigue life of the pavement [6]. A wide laboratory study on the fatigue properties of GM mixtures was conducted at the University of Nottingham [1,4,6–8]. The results highlighted the major role played by the strength and shrinkage properties of the cementitious grout on the fatigue performance. Moreover, it was pointed out that the conventional failure criterion used for AC mixtures (50% reduction of the initial stiffness) doesn't allow to characterise the actual fatigue behaviour of GM mixtures, which is characterised by a slower trend of stiffness decrease [1,4,8]. However, by extending the failure point until 90% reduction of the initial stiffness [6], GM mixtures show their great potential with respect to AC mixtures. This behaviour is due to a slower crack propagation stage in the asphalt skeleton because the presence of the voids-filling grout drastically reduces the weak spots where the crack can propagate [8]. On the other hand, semi-circular bending tests aimed at studying the crack-propagation resistance of GM mixtures demonstrated that their high strength may lead to a brittle failure with loss of toughness [9]. Furthermore, due to the brittle behaviour of the cementitious grout, GM mixtures may be more susceptible to traffic abrasion with respect to AC mixtures [2], even though this property seems to be affected by the compressive strength of the mixture [10].

Despite many applications and several registered patents (i.e. Salviacim©, Densiphalt©, Confalt©), the design of semi-flexible pavements is mostly based on empirical evidence because there are still few studies in the scientific literature. To fill this gap, the objective of this research was to characterise the mechanical properties of GM mixtures prepared in laboratory and sampled from in-service pavements by evaluating their stiffness, fatigue resistance, cracking propagation resistance, thermal susceptibility, and ravelling resistance. In particular, test results obtained on laboratory specimens were compared and validated by the results obtained on cores extracted from in-service pavements constructed using the same cementitious grouts.

2. Materials and methods

2.1. GM prepared in the laboratory

2.1.1. Open graded asphalt concrete

The open-graded asphalt concrete (OGAC) mixture was produced using polymer-modified bitumen (3.8% of SBS by bitumen mass) with a dosage of 5.0% by aggregate mass and adding 0.3% of additives/fibres by aggregate mass. Its nominal maximum aggregate size was 14 mm, and the filler content was 5.4% (Fig. 1).

2.1.2. Cementitious grout

Two commercial cementitious grouts supplied by the same producer were investigated in this study. The grouts, hereafter named A and B, had different density (1955 kg/m^3 for grout A and 2050 kg/m^3 for grout B), and compression strength at twenty-eight days (EN 12190 [11]) (34.6 MPa for grout A and 65 MPa for grout B). Moreover, grout B is expected to reach its strength in shorter time, allowing a faster opening to traffic.

2.1.3. Preparation of laboratory specimens

OGAC slabs with plan dimensions of 305 × 305 mm^2 and final thickness of 50 mm were compacted at 160 °C using a laboratory steel roller compactor (EN 12697–33 [12]). Based on preliminary tests, with the aim to ensure an adequate number of contact points between the aggregates and to allow the penetration of the grout, the target air void content was fixed at 23%. Before the grouting, the slabs were left to cool down for two days, otherwise the heat would have changed the water content of the grout compromising its fluidity and resistance. The quantity of water needed for the grout slurry in order to achieve the required workability and to obtain full depth penetration was determined through an experimental trial and error approach by cutting and visually inspecting for the presence of voids. The final water dosage was 31.5% by dry grout mass. The cementitious grout was poured onto the surface of the slab still into the mould (Fig. 2a). It permeated the voids primarily by gravitational flow, with the aid of a rubber applicator and a vibrating hammer to help releasing of the entrapped air. After twenty-one days of curing at room temperature, four cylindrical specimens were cored from each slab (Fig. 2b). The GM specimens were tested after a curing time of twenty-eight days.

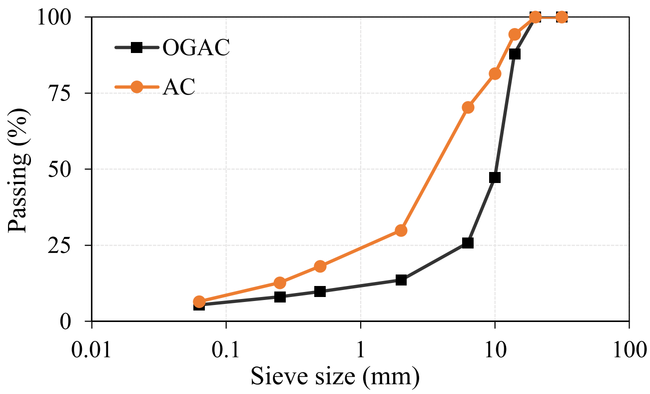

Fig. 1. Gradation curves of the open-graded asphalt concrete (OGAC) and dense-graded asphalt concrete (AC).

Fig. 2. Grouted slab into the mould (a) and cored specimen from the GM slab (b).

2.2. *GM specimens from the field*

Cylindrical samples were cored (EN 12697–27 [13]) from two in-service pavements whose GM wearing course had been made with the same cementitious grouts described above. The GM wearing courses investigated were a heavy industrial pavement in Ravenna (Italy) constructed in 2011 using grout A and the container terminal of the port of Thessaloniki (Greece) constructed in 2018 using both grouts A and B (Fig. 3). The 100 mm and 150 mm diameter cores were then trimmed to the required height of 50 mm. The obtained specimens were coded as Site R_A, Site T_A and Site T_B, which denoted the origin (R and T stand for Ravenna and Thessaloniki, respectively) and the used grout.

2.3. *Asphalt concrete*

An AC mixture for wearing courses, normally applied in high-traffic Italian pavements, was also tested for reference. The mixture was produced using polymer-modified bitumen (3.8% of SBS by bitumen mass) with a dosage of 5.2% by aggregate mass, and a nominal maximum aggregate size of 14 mm (Fig. 1).

Two series of AC specimens were prepared. The first series was prepared with the same procedure described above for the OGAC specimens i.e., compaction of slabs with final thickness of 50 mm followed by coring to a diameter of 100 mm. Their average air voids content was 6.4% (EN 12697–6 [14]). The second series was prepared following the Marshall procedure (EN 12697–30 [15]) using 50 blows/face and had a diameter of 100 mm and an average thickness of 63.5 mm. Their average air voids content was 6.1% ([14]).

Fig. 3. Samples cored from the port of Thessaloniki.

2.4. Test methods

2.4.1. Indirect tensile stiffness modulus

The stiffness of the GM and AC mixtures was investigated by measuring the indirect tensile stiffness modulus (ITSM) (Fig. 4a) (EN 12697–26 [16]). The target horizontal deformation was set to 3 μm for the AC and 5 μm for the GM mixture. The tests were carried out on specimens with a diameter of 100 mm at 5, 20, 30, 40 and 50 °C and the experimental data of ITSM at different temperatures were fitted with the sigmoidal function according to Eq. (1):

$$\log ITSM = \alpha + \frac{\beta - \alpha}{1 + \exp[\gamma + \delta \cdot T]} \tag{1}$$

where α, β, γ and δ are parameters related to the material composition. The values 10^{α} and 10^{β} represent the equilibrium and the glassy

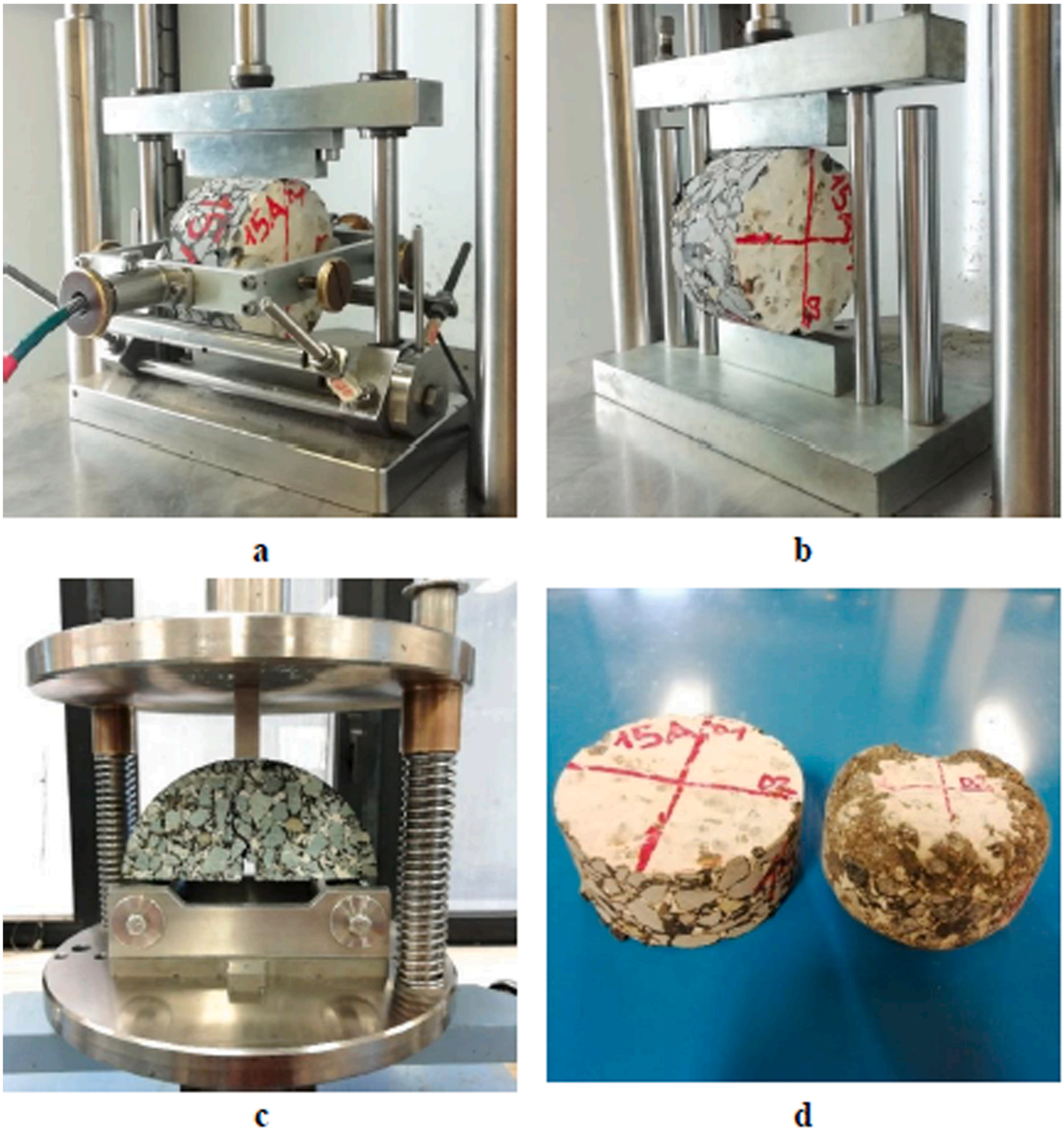

Fig. 4. Equipment of (a) ITSM, (b) ITFT and (c) SCB tests. Comparison between a GM specimen before and after Cantabro test (d).

modulus respectively, whereas $T_f = -\gamma/\delta$ is the temperature corresponding to the inflection point in a semi-logarithmic plane and δ represents the thermal susceptibility because it controls the rate at which the ITSM decreases.

2.4.2. Indirect tensile fatigue test

The fatigue resistance of the GM mixtures was investigated by means of the indirect tensile fatigue test (ITFT) (Fig. 4b) (EN 12697–24 Annex E [17]). The test was carried out at 20 °C on specimens with a diameter of 100 mm. Repeated load pulses were applied during the test with a rise-time of 124 ms and the vertical deformation was registered. The test was carried out under controlled-stress mode of loading and the stress levels were selected between 250 and 900 kPa in order to obtain a fatigue life between 10^3 and 10^6 cycles. The number of cycles corresponding to the specimen collapse was assumed as its fatigue life. In a bi-logarithmic plane, the relation between the initial horizontal deformation $\varepsilon_{h,0}$ and the number of cycles at failure N_f was expressed by a linear relation:

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

where a and b are material parameters, and $\varepsilon_{h,0}$ was calculated as follows:

$$\varepsilon_{h,0} = \frac{\sigma \cdot (1 + 3\nu)}{S} \tag{3}$$

where S is the indirect stiffness modulus value measured before starting the ITFT test and ν is the Poisson's ratio assumed equal to 0.30.

2.4.3. Semi-circular bending tests

The cracking propagation resistance of the GM mixture was investigated by means of the semi-circular bending (SCB) test (Fig. 4c) (EN 12697–44 [18]). Each 150 mm diameter specimen was cut in half and a 10 mm deep and 0.5 mm wide notch was cut in the middle of the diameter to control the crack initiation point. The semi-cylindrical specimen was placed on supports with a span of 120 mm and subjected to a vertical load applied with a constant displacement rate of 5 mm/min along the direction of the notch. The test temperature was 10 °C. During the test, a load cell and a LVDT measured the load and the vertical deflection in the middle of the specimen.

The results were expressed in terms of fracture toughness K_{IC} (Eq. (4)) [18], fracture energy G (Eq. (5)) [19] and flexibility index FI (Eq. (6)) [19].

$$K_{IC} = \sigma_{max} \cdot f\left(\frac{a}{W}\right) \tag{4}$$

where $\sigma_{max} = \frac{4.263 \cdot F_{max}}{D \cdot t}$ is the maximum supported stress, F_{max} is the peak load during the test, D and t are the diameter and the thickness of the specimen respectively, and $f\left(\frac{a}{W}\right)$ is a geometric factor [18].

$$G = \frac{\int F ds}{t \cdot (W - a)} \tag{5}$$

where $\int F ds$ is the work of fracture calculated as the area under the load versus deflection curve until a load value of 0.2 kN, $t \cdot (W - a)$ is the ligament area [20], with W and a equal to the specimen height and notch height, respectively.

$$FI = \frac{G}{|m|} \tag{6}$$

where G is the fracture energy (Eq. (5)) and m is the slope corresponding to the inflection-point of the post-peak curve, which is approximated by the sum of three exponential functions [21].

2.4.4. Cantabro tests

The ravelling resistance of the GM and AC mixtures was evaluated by means of Cantabro tests (EN 12697–17 [22]) conducted on 100 mm diameter specimens cored from each slab. However, according to the standard, Cantabro tests should be conducted on Marshall specimens. For this reason, AC specimens compacted following the Marshall procedure [15] were included in the experimental programme in order to evaluate the influence of the compaction method. It is worth pointing out that GM specimens cannot be efficiently prepared by using compacted cylindrical specimens due to uncertainties related to the grouting operations.

The specimens were conditioned at 25 °C and the percent particle loss (PL) was calculated [22].

2.5. Experimental programme

Fig. 5 shows a summary of the experimental programme and Table 1 indicates the number of repetitions for each test.

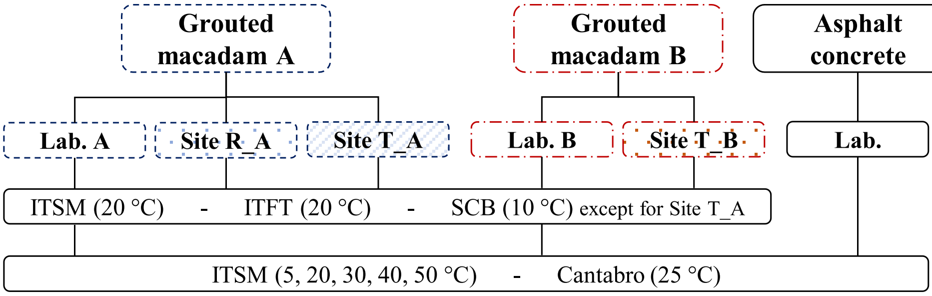

Fig. 5. Experimental programme.

Table 1
Number of repetitions for each test included in the experimental programme.

	ITSM (20 °C)	ITSM (5, 20, 30, 40, 50 °C)	ITFT (20 °C)	SCB (10 °C)	Cantabro (25 °C)
Laboratory GM, A - B	4	4	8	8	4
Laboratory AC	4	4	–	–	4
Site R_A	8	–	8	4	–
Site T_A	5	–	4	–	–
Site T_B	5	–	4	4	–

3. Results and analysis

3.1. *Stiffness modulus and thermal susceptibility*

The results of the stiffness modulus measured at 20 °C are shown in Fig. 6 using a box-plot, where the horizontal lines of the boxes represent the first, second (median) and third quartiles, and the external lines, also called whiskers, correspond to the maximum and minimum values. The average $\bar{x}$ and the standard deviation s are also reported. The average values of ITSM varied from 5000 to 12000 MPa, in agreement with the stiffness values reported in the literature [3–6]. As expected, the standard deviation was higher for field specimens where the control of the construction operations is lower with respect to laboratory. The highest ITSM values were measured on the specimens Site R_A, this underlines the crucial influence of the field origin and conditions. Moreover, it could confirm that the stiffness of GM mixtures is mainly related to the OGAC skeleton [1,6] whose bitumen was subjected to ten years of field aging. The lower laboratory ITSM values measured at twenty-eight days are due to the short curing time and to the high bitumen content in the open-graded asphalt concrete [6]. However, the higher compressive strength of grout B with respect to grout A probably led to higher ITSM values.

Fig. 7 shows the measured ITSM values of laboratory specimens with grout A and B cured for twenty-eight days, specimens with grout B cured for one year (coded as Mixture B_1y) and AC specimens. AC specimens were not tested at 50 °C due to their very low stiffness (rise-time and horizontal deformation were out the target range). For comparison, the figure also shows the thermal susceptibility results measured at 10 Hz by Cihackova et al. [3]. The model parameters in Eq. (1) were obtained by fitting the

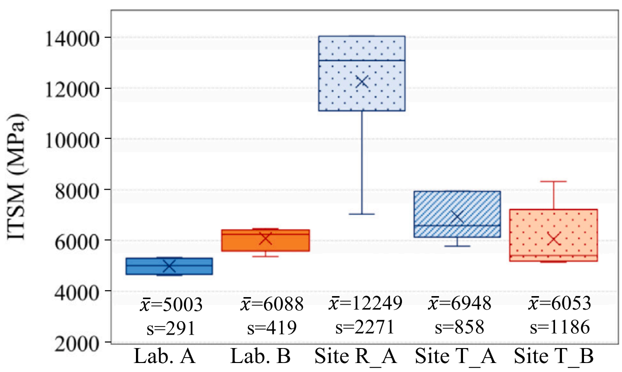

Fig. 6. Box-plot of the ITSM values of specimens prepared in laboratory and cored in situ.

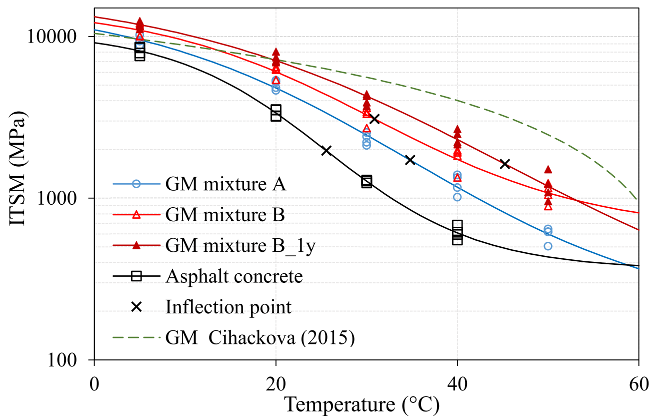

Fig. 7. Sigmoidal regression between temperature and ITSM.

Table 2
Parameters of the sigmoidal model.

	Equilibrium modulus (MPa) 10^{α}	Glassy modulus (MPa) 10^{β}	Inflection point (°C) T_f	Thermal susceptibility (-) δ	R^2
Mixture A	177	16,662	34.8	0.0659	0.99
Mixture B	619	15,378	30.9	0.0820	0.98
Mixture B_1y	132	20,027	45.2	0.0532	0.98
Asphalt Concrete	362	10,679	25.5	0.1181	0.99

experimental data and are summarised in Table 2. The high values of R^2 (i.e. 0.98–0.99) suggest that the sigmoidal function allows a good fitting of the data. For all test temperatures GM specimens were stiffer than the reference AC specimens thanks to the stiffening contribution of the grout. Moreover, GM specimens with grout B cured for 1 year were about 25% stiffer between 20 °C and 40 °C than the same mixture tested at twenty-eight days. It is probably related to the increasing strength of the grout, considering that the oxidation of the bitumen of the asphalt skeleton is limited in short term (only one year). Pointing out that a high T_f value means a lower ability of relaxing the stresses, T_f and δ values clearly highlight that the thermal susceptibility was much lower for GM mixtures than the AC mixture, even though the bitumen was polymer-modified. As a consequence, GM mixtures would show an improved bearing capacity and lower permanent deformations than AC mixtures due to their higher stiffness at high temperature.

3.2. Fatigue resistance

The results of the ITFT are shown in Fig. 8 in terms of horizontal deformation versus number of cycles at failure. The plot also shows the regression line (Eq. (2)) whereas the average value and the standard deviation of the parameters a and b are reported in Table 3. Considering the estimated initial deformation corresponding to a fatigue life of a million cycles ε_6 (Table 3) for comparison purpose, the GM specimens from Site T exhibited the best fatigue resistance. Moreover, the lower slope (a value) demonstrates that grout B enhances the performance, confirming that the grout strength (i.e. 34.6 for grout A versus 65 MPa for grout B, see Section 2.1) affected the fatigue life [1]. Laboratory specimens, tested after twenty-eight days, had the worst fatigue behaviour and the behaviour was similar for both grouts A and B. Comparing the fatigue resistance of laboratory and field specimens with grout B which had similar stiffness moduli (Fig. 6), Site T_B reached higher number of cycles at failure, suggesting that the fatigue strength of GM mixture increased during the first years of service life. This is likely due to the hardening of the grout, to the post-compaction through the traffic and to the oxidation of the asphalt skeleton.

In Fig. 9 the fatigue curves obtained in this research are compared with the fatigue curves obtained in previous studies with the same test conditions (control-stress mode, frequency of 2 Hz, 20 °C and failure criterion). Considering the small scatter, the laboratory and Site T results are plotted in single fatigue lines to simplify the comparison. For comparison purpose, the following fatigue curves were selected: GM mixtures from Oliveira [1] and Simone et al. [23], and AC mixtures from Cardone et al. [24] regarding a Hot Mix Asphalt (HMA) and a Warm Mix Asphalt (WMA) with 15% and 30% of RAP respectively. As it can be seen from Fig. 9, the lower slope of the fatigue curves of all the GM mixtures studied in this research highlights their high fatigue strength, especially at high deformation levels (> 100–150 microstrains). This result is related to the capacity of the grout to develop a remarkable adhesion with the OGAC skeleton [9] allowing the GM mixture to act as a whole against the applied load.

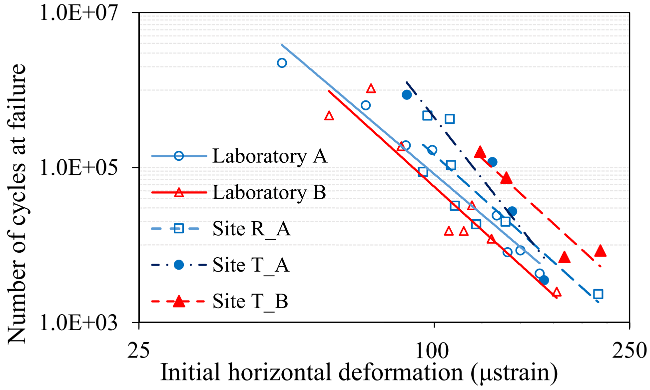

Fig. 8. Fatigue curves.

Table 3
Parameters of the experimental fatigue curves.

	b		a		R^2	ϵ_6 (μstrain)
	Average value	Standard deviation	Average value	Standard deviation		
Laboratory - Mixture A	5.366	0.420	15.648	0.850	0.96	62
Laboratory - Mixture B	5.747	0.847	16.247	1.711	0.86	61
Site R - Mixture A	5.692	1.381	16.548	2.876	0.74	71
Site T - Mixture A	8.085	1.749	21.815	3.697	0.91	90
Site T - Mixture B	5.785	1.368	17.251	3.028	0.90	88

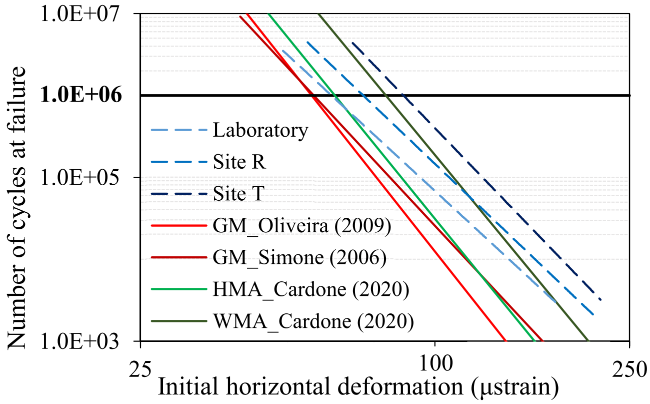

Fig. 9. Comparison between the fatigue curves of the GM mixtures investigated in this research and fatigue curves of previous studies.

3.3. Cracking propagation resistance

The results of SCB tests are shown in Fig. 10. Sample load-deflection curves are shown in Fig. 10a, whereas the fracture toughness, fracture energy and flexibility index are shown in Fig. 10b–d using box-plots. Even though somewhat higher values of K_{IC} were measured on field specimens, with respect to laboratory specimens, and on GM mixture B, with respect to GM mixture A, those differences were not statistically significant. Therefore, it is possible to conclude that the asphalt skeleton and the curing period did not have a significant effect on toughness. The flexibility index of specimens cored from Site R and Site T was lower with respect to laboratory specimens because of the high slope of the post-peak curve ($|m|$ value in Eq. (6)). The FI and fracture energy values were particularly low for Site R specimens that were tested more than ten years after construction. This outcome can be explained considering that high $|m|$ values are ascribable to the increasing of the stiffness with the ageing, which progressively causes a brittle behaviour [12]. Considering all the crack propagation indices, it can be concluded that grout B had a slightly higher than grout A performance in terms of cracking propagation.

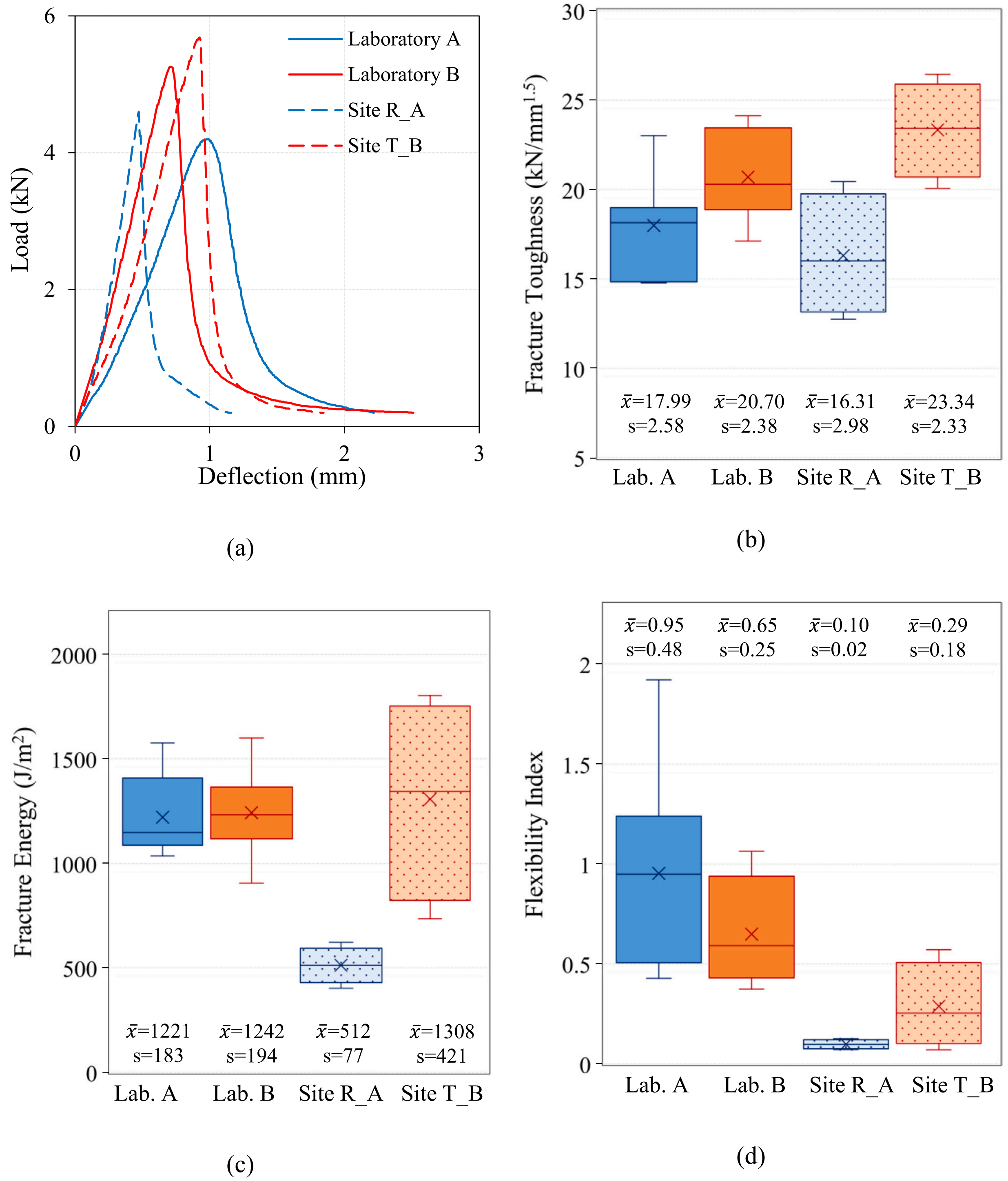

Fig. 10. Results of the SCB test: (a) sample load-deflection curves; (b) fracture toughness; (c) fracture energy and (d) flexibility index.

3.4. Ravelling resistance

The results of particle loss obtained from Cantabro tests on laboratory GM and AC specimens are shown in Fig. 11. All the mixtures had PL values lower than 12%, showing a high ravelling resistance. From a statistical point of view, given the data dispersion in terms of standard deviation, it can be assumed that GM mixtures had similar resistance, also for specimen subjected to one year of curing. The Cantabro test carried out on Marshall samples led to higher PL values with respect to the corresponding cored specimen because the

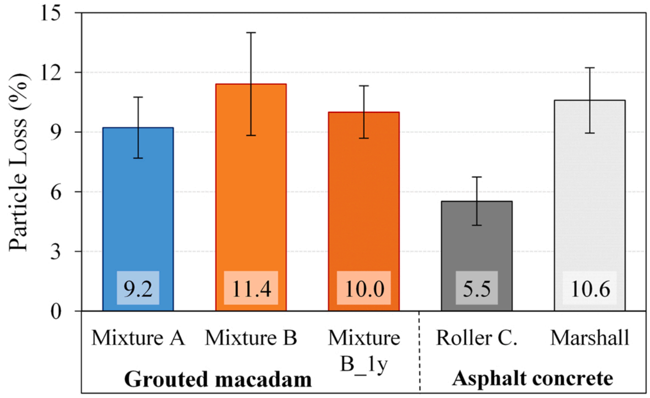

Fig. 11. Average particle loss results from Cantabro tests (error bars represents the standard deviation).

lateral surface was less dense due to the compaction in cylindrical moulds. As a consequence, the comparison between GM and AC mixtures can be done only among the cored specimen from slabs, excluding Marshall specimens. The lower PL value of the AC (Roller Compactor) specimens may be ascribable to the lower content of coarse aggregates. Considering the thermal susceptibility results (Section 3.1), it can be affirmed that the GM mixtures would be able to maintain a considerable ravelling resistance at high temperature (when the mixtures are more prone to be damaged under the action of heavy-vehicle steering wheels) outperforming AC mixture that would soften more markedly.

4. Conclusions

The objective of this research was to compare the mechanical properties of laboratory-prepared GM specimens made with two cementitious grouts with those of GM specimens sampled from in-service pavements made with the same grouts. Based on the experimental results, the following conclusions can be drawn:

- The stiffness of the GM mixtures increased during the service life, mainly due to the oxidation of the bitumen. The compressive strength of the cementitious grout also affected the stiffness, but only in the short term. Moreover, the thermal susceptibility of the tested GM mixtures was lower than a conventional AC mixture.
- The fatigue performance of the GM mixtures sampled from the field was notably higher with respect to the GM mixtures and conventional AC mixtures prepared in the laboratory, especially at high strain levels. The improvement in the fatigue resistance during service life might be ascribable to the effects of aging.
- The toughness of the GM mixtures was not significantly affected by the asphalt skeleton and the by curing period, however grout B led to a slightly higher cracking resistance than grout A.
- The GM mixtures showed a high ravelling resistance. Moreover, considering the lower thermal susceptibility of these mixtures in comparison with AC mixtures, it could be concluded that the GM mixture would maintain a high resistance also at high temperature.

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.

Data Availability

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

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