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Mix design validation through performance-related analysis of in plant asphalt mixtures containing high RAP content

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Abstract

Producing new asphalt mixtures with high content of Reclaimed Asphalt Pavement (RAP) is a major challenge in road construction for economic and environmental reasons. Although many laboratory studies addressed this issue, concerns related to the number of variables involved in the plant production process still limit hot recycling, especially when Styrene–Butadiene–Styrene (SBS) modified bitumens are used. In this sense, plant produced mixtures should be directly investigated to obtain reliable performance evaluations.

Given this background, the paper proposes the mechanical characterization of dense-graded mixtures with 40% RAP produced at the asphalt plant as part of rehabilitation activities of an in-service motorway. The Bailey Method was applied to optimize the mix design. Mixtures were prepared by using two polymer modified bitumens (with high and low SBS polymer content) and selected RAP fractions composed only of asphalt layers including SBS modified bitumen itself. An additional mixture prepared according to the current practice for binder layers of motorway pavements was produced for comparison purposes.

Advanced laboratory tests allowed the determination of the main material properties (i.e. compactability, cracking and rutting aptitude, indirect tensile strength, fatigue and self-healing). Results showed that mixtures with 40% RAP had performance comparable or even enhanced than the reference mixture especially when prepared with low modified bitumens. Consequently, this study shows that an accurate mix design and the selection of adequate bitumens overcome the potential drawbacks related to the use of high RAP percentage given the possibility to produce suitable recycled mixtures.

Keywords: Hot recycling; Compactability; Polymer modified bitumen; SBS; RAP; Mechanical properties

1. Introduction

Over the last decade, in many different manufacturing fields the increasing costs of energy and natural resources as well as the need to preserve raw materials led toward the implementation of green technologies and environmentally-friendly productions. In this context, recycling represents an efficient solution to increase cost and energy savings and has gained growing acceptance also in the case of pavement industry [1,2]. In fact, since pavements are generally composed by aggregate and bitumen (no-renewable and expensive resources) the re-use of a certain amount of *Reclaimed Asphalt Pavement* (RAP) coming from the demolition of old flexible pavements allows the concurrent exploitation of its bituminous and aggregate component, with significant benefits in terms of environment and costs.

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Among various recycling procedures currently available, the hot recycling process is widely recognized as the one which ensures better performance, but at the expense of the limited amount of RAP incorporated, usually up to 20–30% [1]. Although over the last years many laboratory studies have focused on the optimization of hot recycling procedures [3–6] to increase the RAP content allowed for the production of new bituminous mixtures, many doubts and concerns still exist when mixtures are produced in plants. In fact, mixtures prepared in large scale productions usually do not perform as well as mixtures optimized in laboratory [1] since several variables related to the production process, not adequately reproducible in laboratory, significantly compromise mixture performance. Potential detrimental effects are mainly related to RAP stockpile conditions and RAP temperature when mixed with other virgin aggregate fractions. In fact, the presence of an external thin film of aged bitumen makes it impossible to treat RAP as a virgin aggregate, forcing modifications to the production process. RAP aggregates are added into the mixer directly at ambient temperature or processed in a leased drum at low temperature in order to avoid excessive aging of reclaimed bitumen and consequent increased pollutant emissions (unavoidable if RAP comes into contact with the burner flame of the virgin aggregates drum) [7]. However, this working temperature level does not allow the complete drying of RAP aggregates, which often retain a high percentage of water that negatively alters the interactions with other material components and, consequently, overall mixture performance. Clearly, such an issue becomes even more significant when large amounts of RAP are added to virgin aggregates making it difficult to achieve satisfactory performance despite previous laboratory mix design optimization. On the other hand, the presence of higher amounts of reclaimed aggregates pre-coated by a thin film of bitumen (RAP) could result as helpful to compensate the abovementioned drawbacks as well as other potential issues related to the stiffening contribution given by the aged reclaimed bitumen [8,9].

As a consequence, the performance assessment of in plant produced recycled mixtures is essential to verify and, eventually, properly adapt the mix design previously optimized in the laboratory. Such a validation can demonstrate the feasibility of successfully producing hot recycled mixtures with high RAP contents without compromising material performance. It constitutes a fundamental step for a further increase in the maximum amount of RAP currently allowed for new bituminous mixtures.

Given this background, the paper describes the performance evaluation of dense graded hot recycled mixtures produced in a central double drum plant as part of rehabilitation and maintenance activities of an in-service Italian motorway segment. The mixtures were prepared with 40% RAP following the mix design previously optimized through a specific laboratory study based on the Bailey Method [6]. Two bitumens, high and low SBS (Styrene–Butadiene–Styrene) polymer modified, were employed in order to evaluate bitumen grade effects on mixture performance when combined with a high amount of RAP. The experimental investigation included a wide set of laboratory tests aimed at defining the main properties required for flexible pavements (e.g. compactability, stiffness, cracking and rutting resistance, indirect tensile strength, fatigue and self-healing behavior).

2. Objectives

The main objective of this research study was to validate on a large scale in plant production the effectiveness of the mix design previously implemented through laboratory tests for hot recycled mixtures incorporating a high amount of RAP. The extensive mechanical characterization carried out also intended to evaluate the feasibility of common in plant production processes when higher amounts of reclaimed aggregates are added to the mixtures compared to standard production. Such an evaluation constitutes an essential step toward the potential increase of the maximum amount of RAP currently approved by the technical standards for the production of new bituminous mixtures. Finally, the use of bitumens with different amounts of polymer modifier for preparing the studied mixtures provided a further comparison useful to identify the best materials combination in terms of performance.

3. Experimental program

3.1. Materials

Three full scale experimental sections were constructed along a stretch of an in-service Italian motorway as part of maintenance and rehabilitation activities.

In each section, a binder layer with a thickness of 80 mm was built using hot recycled mixtures prepared in a double drum central production plant.

In the first section, the binder layer was built using a mixture (coded as *REF_situ*) with a Nominal Maximum Aggregate Size (NMAS) equal to 20 mm. The aggregate grading curve combined virgin limestone aggregates (i.e. 24% of 10/20, 26% of 8/16, 24% of 0/4 mm and 1% of filler by total aggregate weight) and 25% by total aggregate weight of unfractioned RAP (i.e. 0/16 mm) which contains 5.08% b RAP aggregate weight of SBS polymer modified bitumen. This mixture, used as reference for comparison purposes, was prepared according to the Italian technical specification for motorway binder layers and was selected since it represents the one currently employed for maintenance and rehabilitation activities. Complying with the practice commonly adopted for Italian motorways, the mixture had a total bitumen content (virgin bitumen + reclaimed bitumen from RAP) equal to 4.8% by total aggregate weight. The virgin bitumen was a high polymer modified bitumen (coded as "hard" bitumen *H*) which includes 3.8% of SBS by bitumen weight.

In the two adjacent sections binder mixtures were both realized according to the mix design previously optimized through a specific laboratory study [6]. Similarly to the reference mixture, they were characterized by a NMAS equal to 20 mm including the same virgin limestone aggregates but 40% RAP by total aggregate weight. The latter was previously fractioned in two sizes (i.e. 0/8 mm and 8/16 mm) in order to minimize the variability often related to RAP sources which can significantly affect aggregate gradation and, consequently, material performance. The aggregate grading curve was designed on the basis of the Bailey Method prescriptions for recycled mixtures [10] with the aim to enhance aggregate packing and volumetric properties, potentially negatively affected by the higher content of stiff aged bitumen released by RAP. Technical specification requirements for the grading envelope of Italian motorway binder layers were a further parameter considered for the optimization of the aggregate gradation.

Due to the higher amount of RAP included than the reference mixture, the Optimum Bitumen Content (OBC) of the 40% RAP mixtures was found to be equal to 5.2% by aggregate weight. In this sense, it is worth noting that the calculation of the total bitumen content includes the virgin bitumen and all the bitumen within the RAP. However, not all the aged bitumen coating RAP aggregates is released during the mixing process [4,11,12]. Only a part of RAP bitumen reactivates and contributes to the effective working bitumen of recycled mixtures. As a consequence, larger RAP amounts imply higher total bitumen content. In fact, the increase in RAP amount causes an increase in the relative percentage of inactive bitumen (referred to as "*black rock*"), which must be accounted for in the calculation of the total bitumen content required to achieve the same effective working bitumen (WB) of mixtures prepared with only virgin aggregates or lower amount of RAP. To this aim, each RAP aggregate fraction underwent a solvent extraction to determine the aged bitumen content needed to calculate the proper amount of virgin bitumen. The two bitumen percentages were equal to 5.97% and 4.73% by RAP aggregate weight for RAP 0/8 and 8/16 mm, respectively. In particular, mixtures without RAP for Italian motorway binder layers are prepared with a total bitumen content of 4.5% by aggregate weight to ensure optimum performance. A previous specific research [12] based on performance-related analyses demonstrated that the RAP bitumen reactivation of the same mixtures investigated in this study was equal to 70%. Therefore, the optimum bitumen content and the Virgin Bitumen (VB) amount needed to guarantee the same performance (i.e. same working bitumen) of a virgin mixture (i.e. 4.5%) can be calculated as follows:

- Active RAP bitumen $(RAP_{AB}) = 0.7 \cdot (5.97 \cdot 25 + 4.73 \cdot 15)/100 = 1.54\%$
- Inactive RAP bitumen $(RAP_{IB}) = (1 - 0.7) \cdot (5.97 \cdot 25 + 4.73 \cdot 15)/100 = 0.66\%$
- Total RAP bitumen $(RAP_{tot}) = RAP_{AB} + RAP_{IB} = 1.54\% + 0.66\% = 2.20\%$
- $OBC = WB + RAP_{IB} = 4.5\% + 0.66\% = 5.20\%$
- $VB = OBC - RAP_{tot} = 5.20\% - 2.20\% = 3.00\%$

considering the abovementioned degree of reactivation (i.e. 70%), as well as the percentage of bitumen for each RAP fraction (i.e. 5.97% and 4.73% for RAP 8/16 and RAP 0/8 mm, respectively) and the corresponding amount of each RAP fraction in the mixture (i.e. 25% of RAP 0/8 and 15% of RAP 8/16 mm).

Two Styrene–Butadiene–Styrene (SBS) modified bitumens were employed for preparing each 40% RAP mixture: one mixture (coded as *5.2%H_situ*) was manufactured with the same high modified bitumen (*H*) used for the reference mixture. Such a bitumen was selected since it is the one commonly employed for the production of Italian motorway asphalt mixes. For the second one (coded as *5.2% S_situ*) a low modified bitumen (coded as "soft" bitumen *S* and including 1.8% of SBS polymer by bitumen weight) was adopted with the aim to investigate benefits and drawbacks coming from the combination of a lower grade bitumen with the stiff aged bitumen released by RAP aggregates.

The main basic properties of the virgin bitumens used in this investigation as well as the aged bitumen reclaimed from RAP aggregates are reported in Table 1. Table 2 summarizes the aggregate gradation of each plant produced mixture determined after solvent extraction (i.e. "Plant") along with the laboratory mix design (i.e. "Design") and the grading envelope limits prescribed by the Italian technical specifications for binder layers.

3.2. Testing

During in plant productions, a certain amount of each mixture was taken in quantity sufficient for laboratory compaction of all samples necessary to achieve a comprehensive experimental picture of mixtures behavior.

Cylindrical specimens with a diameter of 150 mm were prepared in laboratory at 160 °C by means of a Superpave Gyratory Compactor (SGC). They were compacted immediately after the in plant production in order to avoid further aging due to re-heating. Their air voids content, set equal to 3.5% to comply with the prescribed limit range (3–5%), was afterward verified by measuring maximum and bulk density (EN 12697-05 procedure C and EN 12697-06 procedure B respectively). The volumetric analysis was integrated with the calculation of the Compaction Energy Index (CEI) determined as suggested by Mahmoud and Bahia [13] to evaluate the compactability of each mixture.

Each gyratory specimen was subsequently cored and cut in order to prepare samples of adequate dimensions for carrying out performance-based laboratory tests related to the main distresses that flexible pavements can suffer during their in-service life.

Table 1
Basic characteristics of the virgin bitumens and the aged bitumen reclaimed from RAP.

Characteristic	Standard	Unit	Soft	Hard	Reclaimed bitumen
SBS polymer content by weight	–	%	1.8	3.8	3.8
Penetration [25 °C; 100 g; 5 s]	EN 1426	dmm	60	54	15
Ring and ball softening point	EN 1427	°C	66	71	75
Dynamic viscosity @ 135 °C	ASTM D4402	Pa·s	1.15	1.24	5.45
Mass loss after RTFOT	EN 12607-1	%	0.08	0.05	–
Penetration after RTFOT	EN 1426	0.1 mm	37	27	–
Ring and ball softening point after RTFOT	EN 1427	°C	73	77	–

Table 2
Mixtures composition and grading envelope.

Sieve (mm)	Passing (%)							
	REF_situ		*5.2%H_situ*		*5.2%S_situ*		*Grading envelope*	
	Design	Plant	Design	Plant	Design	Plant	Max	Min
31.5	100	100	100	100	100	100	100	100
20	92.4	93.3	92.3	95.4	92.3	94.6	98	85
14	80.9	72.7	79.4	74.8	79.4	73.5	87	70
10	69	59.4	64.8	63.1	64.8	61.1	78	58
6.3	–	50.8	–	48.6	–	47.9	66	46
2	28.7	28.6	26.9	27.2	26.9	26.8	38	25
0.5	14.1	12.8	12.9	13.7	12.9	12.3	21	11
0.25	9.4	9.6	9.4	9.4	9.4	9.2	17	7
0.063	5.2	6.3	4.8	6.8	4.8	5.8	8	4
Total bitumen (%)	4.8	5.0	5.2	5.2	5.2	5.1	6.0	4.5

The experimental investigation involved cyclic uniaxial compression tests for measuring the complex modulus (E^*) and the phase angle (δ) in accordance with the American standard AASHTO TP 79-09. Specimens were subjected to sinusoidal load waves in controlled strain mode (setting 30 με as target strain level) at six frequencies (i.e. 0.1, 0.3, 1, 3, 10, 20 Hz) and five temperatures (i.e. 10, 20, 30, 40, 50 °C). According to EN 12697-26, stiffness properties were also evaluated in indirect tensile configuration at 20 °C through Indirect Tensile Stiffness Modulus (ITSM) tests.

The cracking propagation resistance was evaluated by performing Semi-Circular Bending (SCB) tests (EN 12697-44) at a temperature of 10 °C with a constant vertical deformation rate equal to 5 mm/min. In order to gain a better understanding of the cracking aptitude of each mixture, cyclic Indirect Tensile Fatigue Tests (ITFT) were also performed according to the British standard BS DD ABF. The test, carried out at 20 °C in control stress mode for a minimum of three stress levels and applying a loading characterized by a rise-time of 124 ms, was considered completed when the sample achieved the full fracture.

The same test configuration (indirect tensile test), in control strain mode and with the insertion of multiple rest periods at 20 °C, was used to assess the self-healing capability. The test protocol was specifically optimized for asphalt mixtures on the basis of previous studies mainly focused on bitumens and mastics [14,15]. The load was applied in vertical direction and the corresponding horizontal deformation was continuously monitored through deformation transducers, so allowing the calculation of the stiffness modulus ($|E^*|$) and its variation over time. Loading phases were alternated by rest periods of two hours inserted at a specified damage level (i.e. 20% reduction of the initial complex modulus). The rest period's duration was optimized to allow an adequate recovery of material properties. The loading pulse had a haversine form with a rise time of 124 ms followed by a rest time of 1252 ms. The latter was selected as it guarantees the complete recovery of the delayed elasticity eventually generated during loading applications.

Additionally, cyclic triaxial compression tests were performed according to EN 12697-25 (Method B) to evaluate the resistance to permanent deformations. Tests were carried out at 40 °C by applying a confining pressure of 50 kPa and a cyclic block pulse load of 200 kPa.

Finally, the Indirect Tensile Strength (ITS) was measured following the European standard EN 12697-23 in order to verify the observance of the limits prescribed by technical specifications for binder layers.

It is worth noting that all SGC samples were characterized by a diameter of 150 mm and higher heights than requested for the specific type of test in order to achieve improved material homogeneity and lower scale effects. Then, each sample was cored (to obtain a diameter of 100 mm), whereas the upper and the lower parts were cut to avoid lack of uniformity along the specimen height (see Table 3 for details on specimen dimensions).

Table 3
Experimental program: test replicates and sample dimensions.

Mixture	CEI	Complex modulus	ITS	ITSM	SCB	ITFT	Self-healing	Permanent deformation
REF_situ	6	3	4	6	4	6	3	2
5.2%H_situ	6	3	4	6	4	6	3	2
5.2%S_situ	6	3	4	6	4	6	3	2
Sample dimension (D·H; mm)	150·100–170	100·150	100·63.5	100·50	150·75	100·50	100·50	100·80

In particular, three SGC specimens were used for evaluating the complex modulus according to AASHTO TP79. Afterward, the same specimens were cut to obtain samples with adequate dimensions for performing ITSM, ITFT and self-healing tests. A fourth SGC specimen was cut to obtain four samples useful for the evaluation of the cracking propagation resistance through SCB tests. Two SGC specimens were used for obtaining a total of four samples for the evaluation of the Indirect Tensile Strength. Finally, other two SGC specimens were cored and used exclusively for the permanent deformation analysis through the cyclic triaxial compression test.

Table 3 summarizes the overall experimental program specifying for each type of test sample dimensions and number of replicates carried out.

4. Results and discussion

4.1. Compactability and volumetric properties

The air void content was used as main parameter to evaluate the volumetric properties of the investigated mixtures. Italian technical specifications prescribe an air voids range between 3% and 5% for binder layers after a number of gyrations N_{des} equal to 120.

The compactability aptitude of each mixture was assessed on the basis of the Compaction Energy Index (CEI) as proposed by Mahmoud and Bahia [13]. This parameter is calculated as the area under the densification curve (derived from the gyratory compactor data) from the 8th gyration to the number of gyrations corresponding to 92% of the maximum theoretical density. The CEI is linked to the work required to achieve a pre-fixed density after in situ roller compaction. Therefore, the lower the CEI, the higher the workability of the mixture. Air voids and CEI values were calculated as average of all specimens compacted in laboratory. Moreover, a statistical analysis based on on-way ANOVA tests at 95% confidence level was run (Table 4). This further evaluation resulted helpful to identify the statistical significance of the results in order to gain a better understanding and adequately ranking material behaviors.

Table 4
ANOVA statistical analysis for CEI values.

Compared mixtures	*p*-value	Significant?
REF_situ/5.2%H_situ	0.001	YES
REF_situ/5.2%S_situ	0.001	YES
5.2%H_situ/5.2%S_situ	0.808	NO
REF_situ/REF_LAB	0.118	NO
5.2%H_situ/5.2%H_LAB	0.621	NO
5.2%S_situ/5.2%S_LAB	0.470	NO

Results in terms of air voids and CEI are reported for the three investigated mixtures in Fig. 1 along with the error bars represented as standard deviation. The same figure also summarizes the results previously achieved in terms of volumetric properties for the corresponding laboratory produced mixtures.

All mixtures were able to achieve the desired air void's target, showing values between 3.5 and 4% in accordance with technical standard requirements. In terms of compactability, the reference mixture was characterized by the worst aptitude regardless of the production method (in plant or laboratory produced) as demonstrated by the highest CEI values. On the contrary, mixtures prepared with 40% RAP were both able to achieve good workability, not significantly affected by the type of virgin modified bitumen used (S and H). In fact, the statistical analysis shown in Table 4 confirms a significant difference between the reference and the two 40% RAP mixtures (p-values lower than 0.05), whereas it does not identify a noticeable variance between *5.2%H_situ* and *5.2%S_situ*.

Such a finding was unforeseen since higher amounts of RAP were expected to provide lower workability mainly due to the proportional higher percentage of stiff aged bitumen released by RAP aggregates and the variability often related to RAP sources. Hence, the optimization of the aggregate gradation through the Bailey Method and the RAP fractioning in two sizes can be considered an effective method to achieve a better control of the aggregate gradation and balance potential negative effects related to higher amounts of stiff aged bitumen.

Moreover, the statistical analysis points out that the results collected for each mixture prepared in laboratory were not significantly different from the data obtained for the corresponding mixtures prepared at the asphalt plant. Such an outcome, along with the aggregate gradations reported in Table 2 which shows similar trends for laboratory and in plant produced mixtures, suggests that the mix design optimized through the laboratory study was successfully reproduced in large scale plant production, preserving the overall mixture composition as well as its volumetric and compactability properties.

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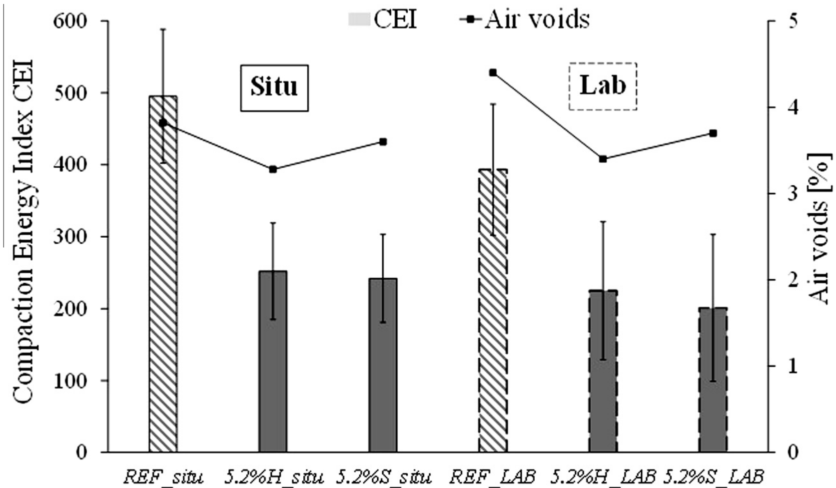


Fig. 1. Air voids and Compaction Energy Index results.

4.2. Stiffness properties

One fundamental concern related to the use of large amounts of milled material is related to the stiffening effect provided by the aged bitumen released by RAP aggregates when they come into contact with the pre-heated virgin aggregates during the mixing process. Bearing in mind that stiffness properties directly affect overall mixture behavior both at high and low temperatures, it is important to evaluate the materials in a broad range of test conditions. In this sense, all mixtures were investigated in terms of stiffness at different temperatures and frequencies by using two different test configurations with the aim to identify a reliable ranking of the materials.

First, cyclic uniaxial compression tests were performed as specified in Section 3.2.

Results are depicted in Fig. 2 in terms of storage (E_1) and loss (E_2) modulus (i.e. Cole-Cole diagram). As expected due to the presence of aged polymer modified bitumens, which do not respect the Time-Temperature Superposition Principle [16], for each investigated mixture the impossibility to fit the data with a unique continuous line suggests that these materials cannot be considered as thermo-rheologically simple. However, considering only the norm of the complex modulus E^*, the Partial Time-Temperature Superposition Principle can be applied [17]. As a consequence, the master curve of the complex modulus norm $|E^*|$ was determined for each mixture as average of two replicates at a temperature of 20 °C by modeling the data through a four-parameter sigmoidal function [18] with free variation of the shift factors (Fig. 3).

Considering the comparison between the mixtures prepared with the same kind of bitumen *H* (*5.2%H_situ Vs REF_situ*), results in Fig. 3 show that the 15% increase in RAP percentage caused a significant stiffening effect within the whole temperature/frequency range investigated. Such a finding is attributable to the proportional higher presence of aged bitumen which underwent all short and long term oxidation phenomena. On the contrary, the use of a low modified virgin bitumen S was found able to effectively counterbalance the presence of higher RAP content without lowering too excessively stiffness properties, as demonstrated by the similarity of the master curve trend between the reference mixture and the mixture *5.2%S_situ*. On the basis of these results, it is reasonable to predict benefits in terms of fracture properties for mixtures prepared with bitumen *S* compared to mixtures with bitumen *H*, as confirmed by the results discussed in Section 4.3.

With the aim to deeply investigate the thermo-dependent behavior of mixtures, the shift factors obtained to construct the master curves were depicted as a function of temperature. As shown in Fig. 4, the regression curve representing the reference mixture was characterized by a slope value slightly lower than 40% RAP mixtures, hence indicating lower thermo-dependency.

The results achieved through the cyclic uniaxial compression test were confirmed by the data measured in indirect tensile configuration. As shown in Fig. 5, the complex modulus norm measured at 20 °C and 2 Hz were consistent with the average Indirect Tensile Stiffness Modulus calculated at the same temperature and corresponding rise-time, hence supporting the remarks derived by the complex modulus analysis and further validating laboratory measurements.

Moreover, a statistical analysis based on one-way ANOVA tests at 95% confidence level was carried out to prove the significance of the above discussed observations.

The *p*-values obtained for each material comparison in terms of ITSM are summarized in the table included in Fig. 5 and confirmed the significant difference between the mixture prepared with bitumen *H* and 40% RAP with respect to both the reference mixture and the mixture prepared with bitumen *S* which, on the contrary, did not exhibited remarkable variation between each other.

Finally, in plant produced mixtures were compared with the corresponding laboratory produced mixtures (Fig. 6).

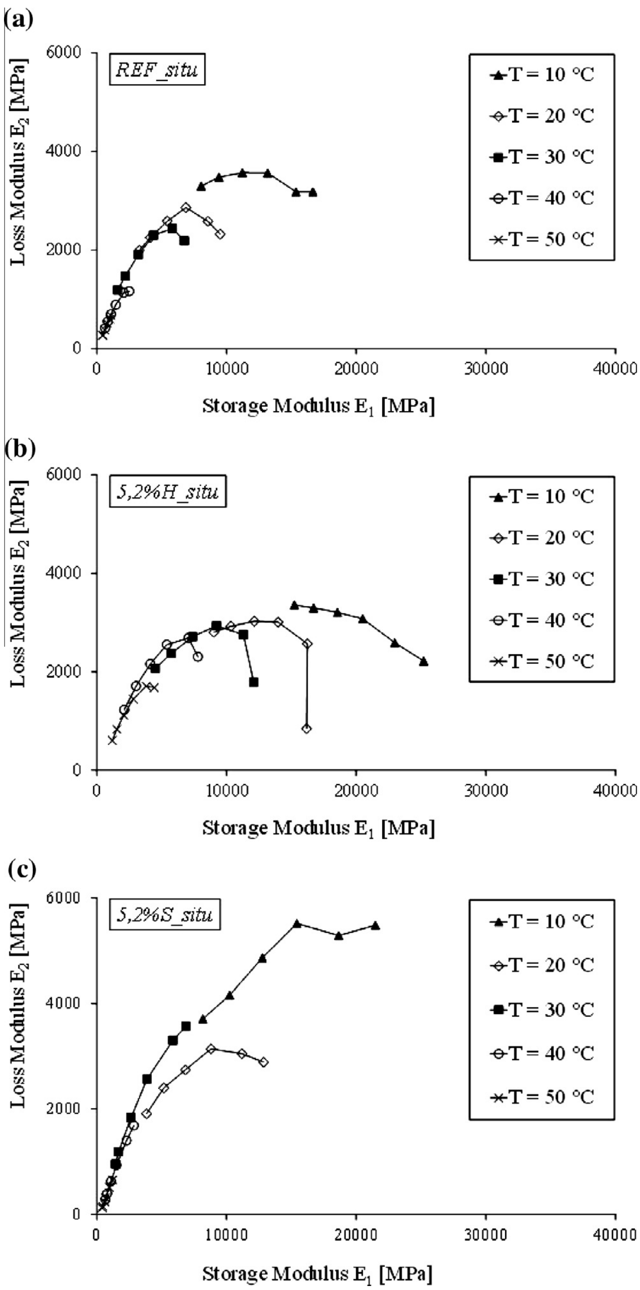


Fig. 2. Cole-Cole diagrams: (a) mixture REF_situ; (b) mixture 5.2% H_situ; (c) mixture *5.2%S_situ*.

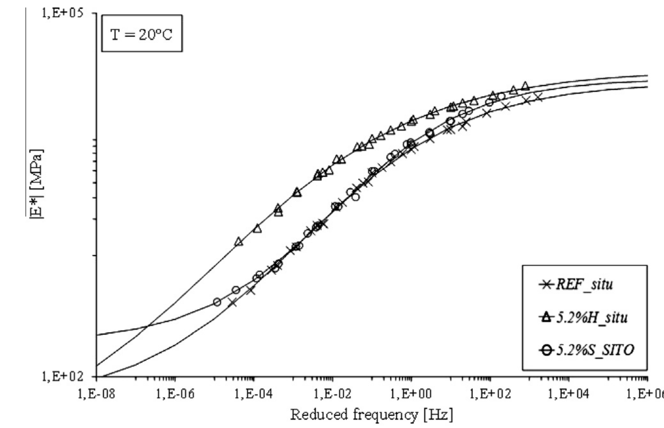


Fig. 3. $|E^*|$ master curves at 20 °C within the temperature range investigated.

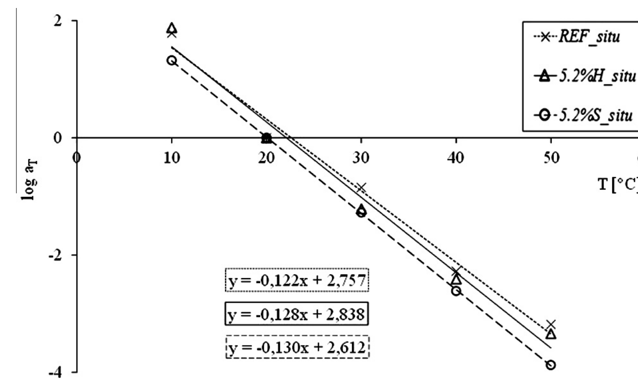


Fig. 4. Shift factors *Vs* temperature.

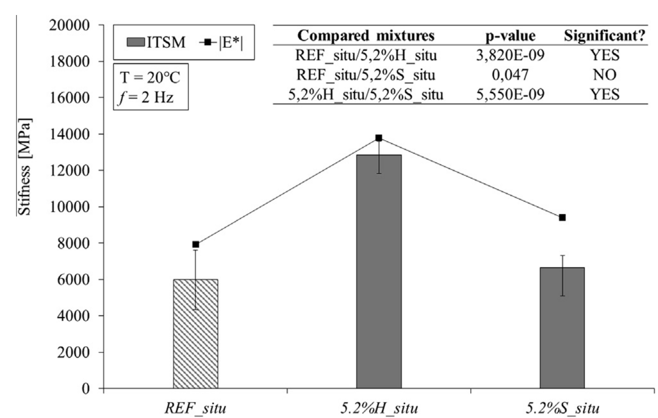


Fig. 5. $|E^*|$ and ITSM @ 20 °C and 2 Hz (124 ms rise time for ITSM) with the standard deviation error bars.

It is worth noting that, although the ranking of the materials is exactly the same regardless of the production process considered (in plant or laboratory), all in plant mixtures resulted to be less stiff than the corresponding laboratory mixtures.

Such a tendency can be related to the more severe oxidation process undergone by laboratory produced mixtures. In fact, in order to simulate the oxidation phenomena generated during transportation and lay-down (i.e. short term aging), the materials prepared in laboratory were kept 1 h at the compaction temperature (i.e. 160 °C) in a force draft oven. However, it must be considered the different production scale: in laboratory only the material for compacting one or few samples was concurrently produced. Thus, all the aggregate surface coated by bitumen was subjected to high temperatures inside the oven. For operational reasons, after in plant production this further heating time was not taken into account.

On the basis of such a finding, subsequent similar investigations have considered this evident effect applying 1 h in

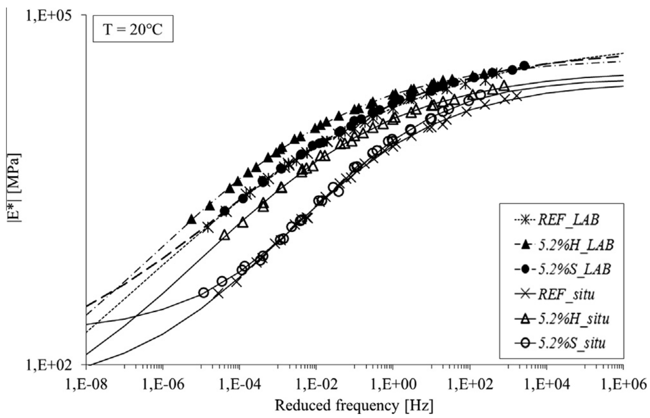


Fig. 6. $|E^*|$ master curves at 20 °C: comparison between laboratory and in plant produced mixtures.

a force draft oven also to in plant produced mixtures before laboratory compaction.

4.3. Fracture properties

One major risk related to high amounts of RAP aggregates, caused by the presence of stiff oxidized bitumen, is the production of too brittle materials with negative impacts in terms of cracking formation and propagation resistance. Therefore, evaluating the fracture properties of recycled mixtures is essential in order to properly judge the effective material behavior. In this sense, two different mechanical tests were used in the present study to address the issue.

First, Semi-Circular Bending tests were performed according to EN 12697-44 to evaluate the cracking propagation resistance at intermediate temperature (i.e. 10 °C) in terms of fracture toughness K and fracture energy G.

According to EN 12697-44, the fracture toughness K, which is a function of the maximum stress at failure and is mainly related to the cracking initiation resistance, was determined using the following equation:

$$K = \sigma_{max} \cdot f\left(\frac{a}{W}\right) \tag{1}$$

where the fracture toughness K is measured in (N/mm$^{1.5}$), σ_{max} is the maximum stress at failure (N/mm^2), a is the notch depth (mm), W is the specimen height (mm) and $f\left(\frac{a}{W}\right)$ is a geometric factor.

The total fracture energy G, which represents the work required to increase the fractured surface until complete failure, was calculated as the area under the load-displacement curve normalized with respect to the area of ligament [8,19,20] as follows:

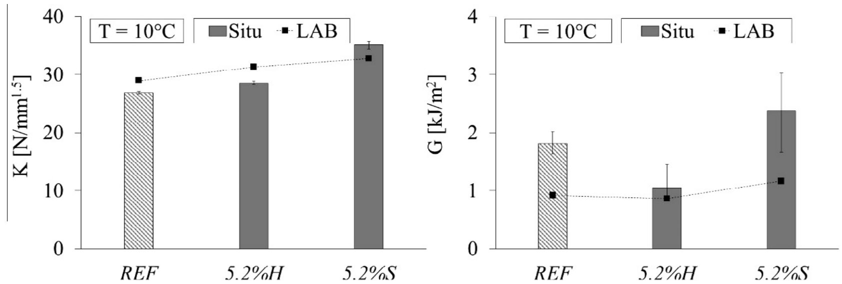
$$G = \frac{\int Fds}{t \cdot (W - a)} \tag{2}$$

where the total fracture energy G is measured in kJ/m^2, $\int Fds$ is the area under the load-displacement curve, t is the specimen thickness (mm) and the product $t \times (W - a)$ represents the area of ligament.

Results, as average of four replicates, are depicted in Fig. 7 along with the corresponding error bars expressed in terms of standard deviation. In the same figure, the data of the corresponding laboratory produced mixtures are also reported and the results of the one-way ANOVA analysis carried out for evaluating the statistical significance of the results summarized.

In terms of fracture toughness K no significant difference was found between the investigated mixtures, as well as between laboratory and in plant produced materials. Therefore, the higher presence of RAP and the in plant production did not cause any detrimental effect on cracking initiation resistance. This finding was in accordance with a specific previous study focused on low temperature cracking resistance [21]. It demonstrated that higher percentage of bitumen delays the crack initiation and allows a more uniform and gradual stress distribution during cooling before the crack formation, as verified by observing lower values of the coefficients of contraction for mixtures with higher bitumen content. Bearing in mind that 40% RAP mixtures had a total bitumen content higher than the reference mixture (i.e. 5.2% *Vs* 4.8%), this aspect can counterbalance the detrimental effect of higher amount of RAP in terms of cracking initiation, as demonstrated by similar K values. On the contrary, different responses resulted in terms of fracture energy G, demonstrating that the cracking propagation resistance is affected by a higher amount of RAP and virgin modified bitumen type. In fact, the mixture prepared with 40% RAP and the low modified bitumen *S* ensured optimum cracking performance (i.e. higher fracture energy) comparable and even enhanced with respect to the reference material, whereas the mixture prepared with 40% RAP and the high modified bitumen *H* demonstrated less ductility (i.e. lower fracture energy), significantly different than the other two mixtures. Such a finding demonstrates that the use of a softer bitumen combined with high RAP contents can considerably enhance fracture properties. Consistently with the stiffness behavior detected for the mixture prepared with bitumen *S* (see Section 4.2), it appears clear that a low modified virgin bitumen, along with the implementation of the Bailey Method and the fractioning of RAP in two sizes, can successfully counterbalance potential detrimental effects of higher amount of RAP making the mixture more ductile and less prone to crack.

Moreover, it is interesting to note that all in plant produced mixtures showed significantly different values of fracture energy than the corresponding laboratory mixtures. Such a result is in accordance with the observation drawn in terms of stiffness properties. As previously explained, also in this case the difference detected can be attributed to the more severe aging process undergone by the laboratory produced mixtures which, giving rise to stiffening effects, had consequences also in terms of fracture propagation resistance making the mixtures more brittle.



Compared mixtures	p-value	Significant?
REF_situ/5,2%H_situ	0,226	NO
REF_situ/5,2%S_situ	0,192	NO
5,2%H_situ/5,2%S_situ	0,313	NO
REF_situ/REF_LAB	0,354	NO
5,2%H_situ/5,2%H_LAB	0,053	NO
5,2%S_situ/5,2%S_LAB	0,987	NO

Compared mixtures	p-value	Significant?
REF_situ/5,2%H_situ	0,003	YES
REF_situ/5,2%S_situ	0,073	NO
5,2%H_situ/5,2%S_situ	0,005	YES
REF_situ/REF_LAB	2,0E-04	YES
5,2%H_situ/5,2%H_LAB	0,0256	YES
5,2%S_situ/5,2%S_LAB	0,009	YES

Fig. 7. Semi-Circular Bending test results: fracture toughness K and fracture energy G.

In order to validate SCB test results and obtain a more reliable picture of fracture materials behavior, cyclic indirect tension tests were also performed at 20 °C. The number of loading cycles to failure N_f as function of the initial horizontal strain ε_x (calculated according to BS DD ABF) provides a measure of the material fracture resistance. In particular, the horizontal deformation corresponding to a fixed number of loading cycles equal to 10^6 ($\varepsilon_{x,N_f=10^6}$ representative of typical loading for medium-traffic flexible pavements) was considered as significant parameter to evaluate the long term response of each mixture and to rank materials in terms of fracture resistance.

Results are depicted in a bi-logarithmic plane (Fig. 8) as linear regression of test data for both in plant and laboratory mixtures. Mixture *5.2%H_situ* was characterized by the lowest cracking resistance consistently with its higher stiffness detected through compression and indirect tensile tests. On the contrary, the mixture prepared with 40% RAP and bitumen *S* (*5.2%S_situ*), which was characterized by stiffness properties comparable with the reference mixture, ensured the best response in terms of fracture resistance, as demonstrated by the highest value $\varepsilon_{x,N_f=10^6}$ and the lowest slope of the regression line in Fig. 8. Apparently, fracture properties of recycled mixtures are directly related to stiffness properties: the higher the stiffness, the lower the fracture resistance. As a consequence, the inclusion of higher amounts of RAP without changing the type of virgin bitumen caused an increase in stiffness as well as in brittleness resulting in worst cracking resistance. However, the adoption of an adequate virgin bitumen able to tune the overall behavior in terms of stiffness and ductility is able to successfully counterbalance these negative effects.

Also in this case, the mixtures prepared in laboratory were characterized by lower fracture resistance than the corresponding in plant produced mixtures (Fig. 8), confirming the more severe aging process hypothesized for the former, responsible for higher stiffness and brittleness.

Repeated indirect tension test results were in perfect agreement with SCB findings as shown in Fig. 9 where a very good correlation between fracture energy G and $\varepsilon_{x,N_f=10^6}$ can be observed considering both laboratory and in plant produced mixtures, hence further confirming the

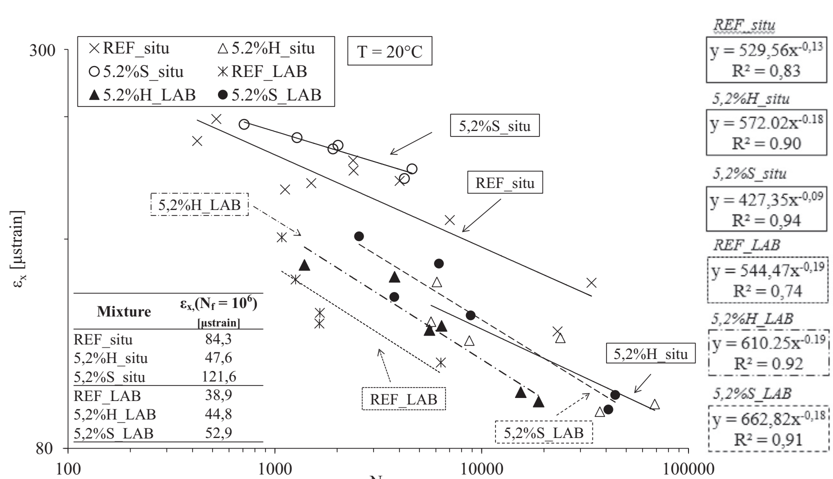


Fig. 8. Strain *Vs* loading cycles relationship.

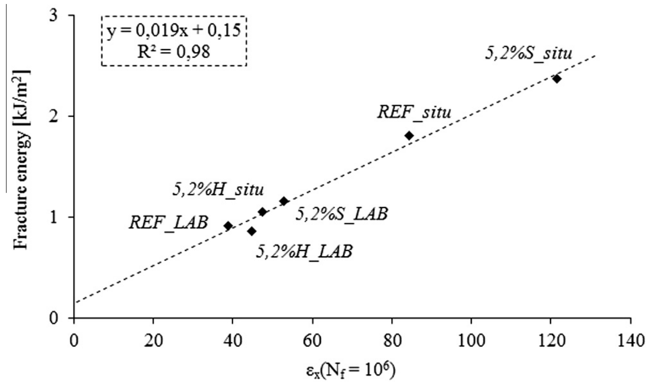


Fig. 9. Correlation between SCB and ITFT data.

reliability of test procedures and laboratory practices adopted to evaluate recycled mixtures.

4.4. Self-healing potential

In order to get a comprehensive picture of the effects due to higher RAP contents, the in plant produced mixtures investigated in this study were analyzed also in terms of self-healing capability, a property which strongly affects fatigue performance. Although self-healing is mainly related to bitumen, viscoelastic and thermo-dependent binding component of asphalt mixtures, the interactions between bitumen and aggregate particles can significantly alter this aptitude. Therefore, it is important to investigate directly mixtures in terms of self-healing potential.

This issue represents a cutting-edge analysis, so far addressed by few research studies [22–24]. Therefore, no consolidated and standardized test procedures are currently available. In order to bridge this gap, the present research adopted the same test protocol and data elaboration method previously implemented for bitumens and successfully adopted also for mastics [14,15], providing the necessary adjustment to make the procedures suitable for mixtures.

According to the test procedure specified in Section 3.2, a repeated indirect tension test configuration in controlled strain mode was adopted by applying a vertical cyclic loading alternated with multiple rest periods (for a minimum of six) of 120 min each (duration that allowed adequate recovery of material properties). The horizontal deformation of the specimen was monitored through specific transducers during both loading and rest phases.

The damage accumulation in the specimen during the load application was measured by calculating the gradual decrease in the stiffness modulus norm $|E^*|$, whereas the self-healing capability was assessed using the stiffness modulus recovery that occurs during rest periods. Each rest period was inserted when a specified damage level was reached (i.e. 20% reduction of the initial stiffness modulus).

The same loading frequency applied during ITF test was adopted: the haversine loading pulse had a rise-time of 124 ms followed by a rest time of 1252 ms. The latter guaranteed enough time to completely recover the delayed elasticity eventually generated during load applications, which does not effectively contribute to the self-healing potential of the material.

The so acquired test data were analyzed with the same approach adopted for bitumens and mastics [14,15] which allows separate identification of self-healing and thixotropic components, as follows briefly summarized for the understanding of the parameters used to evaluate the self-healing capability.

After an initial drop in the stiffness modulus, mainly attributable to thixotropy [25,26], typical test results show a quasi linear reduction which identifies the macroscopic progressive damage accumulation within the specimen [27]. After the insertion of the rest period, that allows a significant recovery in material properties, the successive reloading induces a corresponding damage accumulation having a trend similar to the initial loading stage. However, as the number of rest periods inserted increases, the complex modulus reduction recorded during the subsequent loading phase becomes faster. This is attributed to the reduced recovery of the loss modulus during each rest period as the number of rest increases. In fact, as the damage progresses in the material, its self-healing capability proportionally reduces. As a consequence, when the material has completely exhausted its self-healing capability after a sufficient number of rest periods, the loading cycles to reach the target damage level (i.e. 80% of initial complex modulus) become constant. Hence, when the material has exploited its self-healing potential, the insertion of other rest periods does not provide any further benefits. The constant number of loading cycles achieved after several rest periods can be attributed to other phenomena such as thixotropy or steric hardening that, contrary to the self-healing capability, continue to act even once the material has reached complete failure. Such phenomena, intrinsic properties of the mixture, are completely reversible and represent fictitious contributions to the overall fatigue resistance.

As already mentioned, what was experimentally observed was consistent with the findings of previous studies conducted on bitumens and mastics [14,15]. Therefore, the same analytical model was adopted in this study. The model parameter used to quantify the self-healing potential and the overall fatigue endurance limit considering multiple rest periods are summarized as follows:

- N_0: number of loading cycles necessary in the first loading phase to achieve the selected damage level (i.e. 20% reduction of the initial complex modulus);
- ΔN_i: number of loading cycles recovered after each "i-th" rest period necessary to re-achieve the selected damage level (i.e. 20% reduction of the initial complex modulus), assumed as sum of two components (i.e. $\Delta N_H(i)$ self-healing contribution and $\Delta N_\infty(i)$ thixotropy contribution);

– N_{fat}: effective total number of cycles before failure resisted by the material after the insertion of infinite rest periods, inclusive of self-healing contribution;
– N_{fH}: cumulative self-healing capability (sum of each i-th self-healing contribution $\Delta N_H(i)$). The higher this value, the higher the self-healing potential of the material;
– n_{95}: number of rest periods necessary to reach the 95% of N_{fH}. The higher this value, the higher the capability of the mixture to maintain over time its self-healing potential. This parameter is believed to be mainly related to the chemical structure of the bituminous phase.

Further details on test procedures and data analysis are specified elsewhere [14,15].

Results are summarized in Table 5 as average of three replicates for each investigated mixture. In the same table, results previously collected on the corresponding laboratory produced mixtures are also reported for comparison purposes. A one-way ANOVA test at a confidence level of 95% was performed to evaluate the statistical significance of the results (Table 6).

On the basis of the analytical model adopted, the evaluation of the self-healing capability mainly depends on the parameters n_{95} and N_{fH}. The value N_0 is related to the classical concept of fatigue without considering the self-healing capability, whereas the parameter N_{fat} indicates the overall fatigue endurance limit when multiple rest periods are considered.

It is worth nothing that the 40% RAP mixtures were characterized by enhanced self-healing potential than the reference mixture as testified by the significantly higher N_{fH} value regardless of the type of virgin bitumen used. The same trend was found for the initial number of loading cycles before the target complex modulus reduction (N_0) and the overall fatigue endurance limit determined considering the self-healing ability (N_{fat}). On the contrary, the differences recorded for the parameter n_{95} are statistically insignificant, demonstrating that the investigated mixtures maintain their self-healing potential for a similar service life.

The abovementioned findings represent a further confirmation that the grading curve optimization through the Bailey Method and the RAP fractioning in two sizes were effective tools for optimizing overall mixtures performance.

Moreover, bearing in mind that self-healing depends on two main mechanisms (cohesive self-healing occurring within the bituminous phase; adhesive self-healing occurring at the bitumen-aggregate interface) [22,28], other aspects contribute to improve self-healing performance of 40% RAP mixtures as explained hereafter:

– the expected enhanced adhesion at the interface bitumen-aggregate due to higher amounts of aggregates particles pre-coated by a thin film of bitumen (RAP) that, even if aged, is able to provide better interactions with the virgin bitumen improving adhesive self-healing;
– the analysis of the bituminous phase [14] showed higher self-healing performance for the high modified bitumen *H*. Moreover, the same analysis showed that the higher the aged bitumen amount (due to higher presence of RAP), the higher the cohesive self-healing capability. Such behavior can be attributed to the aging effects on the chemical structure of bitumen and polymer: oxidation phenomena cause the formation of shorter polymer chains due to SBS disruption of the butadiene block [29]. Shorter polymer chains could allow a better interdiffusion within the bituminous phase. Since interdiffusion is the main mechanism responsible for cohesive self-healing development, it is assumed that bitumens with higher content of aged bitumen, and consequently higher amount of short polymer chains, are more prone to self-heal, as demonstrated by the results collected on the investigated mixtures.

Moreover, the statistical analysis shows that the performance of in plant produced mixtures are perfectly in accordance with the results obtained for laboratory produced mixtures, hence indicating that large scale in plant productions did not alter overall mixtures properties.

Table 5
Self-healing model parameters.

Mixture	N_0	N_{fat}	N_{fH}	n_{95}
REF_situ	91	179	88	9
5.2%H_situ	217	631	414	7
5.2%S_situ	205	561	356	8
REF_LAB	78	168	90	9
5.2%H_LAB	205	602	396	10
5.2%S_LAB	185	536	351	6

4.5. Permanent deformation resistance

According to EN 12697-25, cyclic triaxial compression tests were performed to evaluate the rutting susceptibility of the investigated mixtures. As indicated in the European standard, the creep rate f_c was used as parameter to define the permanent deformation resistance. The creep rate is calculated as the slope of the (quasi) linear part of the least square linear fit of the creep curve which relates the cumulative axial strain and the number of load cycles. Hence, the lower the creep rate, the lower the tendency to accumulate permanent deformation.

Results, as average of a minimum of two replicates, are summarized in Table 7 along with the data previously recorded for laboratory produced mixtures and the results of the one-way ANOVA test run at a 95% confidence level to evaluate the statistical significance of the acquired data.

Regarding in plant mixtures, contrary to what was expected on the basis of stiffness properties, it is interesting to note that the mixture with 40% RAP and the low modified bitumen *S* ensured the best rutting resistance, showing a creep rate comparable with the reference mixture. On the contrary, the mixture *5.2%H_situ* was characterized by a

Table 6
Statistical significance of self-healing model parameters.

Parameter N_0			Parameter N_{fH}		
Compared mixtures	*p*-value	Significant?	Compared mixtures	*p*-value	Significant?
REF_situ/5.2%H_situ	0.068	YES	REF_situ/5.2%H_situ	0.001	YES
REF_situ/5.2%S_situ	0.005	YES	REF_situ/5.2%S_situ	0.001	YES
5.2%H_situ/5.2%S_situ	0.835	NO	5.2%H_situ/5.2%S_situ	0.224	NO
REF_situ/REF_LAB	0.560	NO	REF_situ/REF_LAB	0.951	NO
5.2%H_situ/5.2%H_LAB	0.884	NO	5.2%H_situ/5.2%H_LAB	0.878	NO
5.2%S_situ/5.2%S_LAB	0.563	NO	5.2%S_situ/5.2%S_LAB	0.937	NO
Parameter N_{fat}			Parameter n_{95}		
Compared mixtures	*p*-value	Significant?	Compared mixtures	*p*-value	Significant?
REF_situ/5.2%H_situ	0.006	YES	REF_situ/5.2%H_situ	0.676	NO
REF_situ/5.2%S_situ	0.001	YES	REF_situ/5.2%S_situ	0.764	NO
5.2%H_situ/5.2%S_situ	0.464	NO	5.2%H_situ/5.2%S_situ	0.794	NO
REF_situ/REF_LAB	0.862	NO	REF_situ/REF_LAB	0.539	NO
5.2%H_situ/5.2%H_LAB	0.876	NO	5.2%H_situ/5.2%H_LAB	0.389	NO
5.2%S_situ/5.2%S_LAB	0.682	NO	5.2%S_situ/5.2%S_LAB	0.471	NO

Table 7
Creep rate values and statistical analysis results.

Mixture	Creep rate f_c [µstrains/10^2 cicli]	Compared mixtures	*p*-value	Significant?
REF_situ	7.47	REF_situ/5.2%H_situ	0.014	YES
5.2%H_situ	11.99	REF_situ/5.2%S_situ	0.914	NO
5.2%S_situ	7.39	5.2%H_situ/5.2%S_situ	0.010	YES
REF_LAB	7.10	REF_situ/REF_LAB	0.811	NO
5.2%H_LAB	2.26	5.2%H_situ/5.2%H_LAB	0.001	YES
5.2%S_LAB	4.31	5.2%S_situ/5.2%S_LAB	0.212	NO

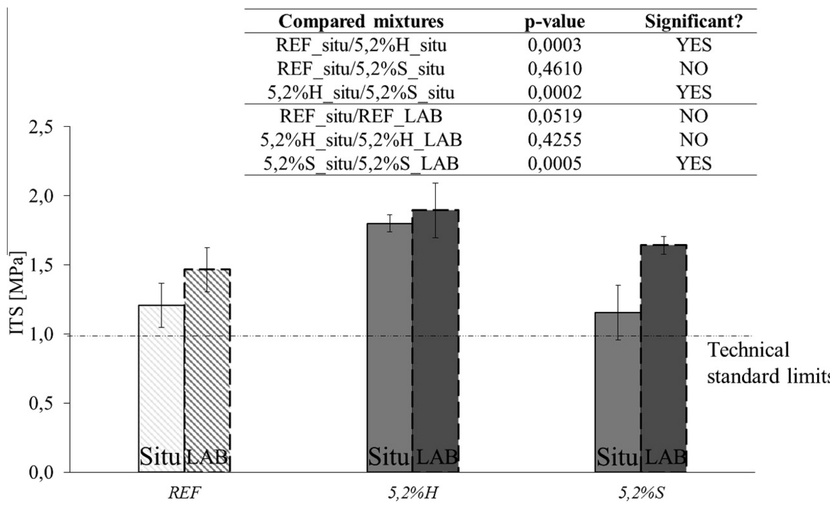
significantly higher creep rate value, although the higher stiffness modulus recorded.

The enhanced compactability (as confirmed by the CEI analysis shown in Section 4.1) of the mixture *5.2%S_situ*, obtained through the Bailey method and the RAP fractioning in two sizes, could have prevented higher accumulation of permanent deformation, major risk related to the use of a softer virgin bitumen. At the same time, the comparison between the *REF_situ* and *5.2%H_situ* mixtures highlighted that, at equal type of virgin bitumen (i.e. *H*), higher amounts of total bitumen (virgin bitumen + aged bitumen released by RAP; 4.8% for the reference mixture *Vs* 5.2% for *5.2%H_situ*) played a negative role in terms of rutting despite higher stiffness and improved compactability. This finding confirms that the higher the bitumen content, the lower the rutting resistance.

Such behavior was not detected for the mixture prepared with the low modified bitumen *S*. Although also this mixture was prepared with higher bitumen content than the reference one, the soft modified bitumen probably acted as "lubricant", so helping to reach an improved aggregate packing. Such a finding was demonstrated by previous studies based on a specific image analysis which judged the aggregate packing [21]. Through a recently developed software based on imaging processors algorithms, two main parameters were calculated by processing 2-dimensional images of mixtures sections: the proximity zone length and the number of contact points between aggregate particles. The higher these values, the better the interlocking between aggregates and, in turn, the lower the rutting susceptibility. The image analysis showed that the 40% RAP mixture prepared with the low modified bitumen S was able to achieve higher interlocking and an improved aggregate packing (i.e. higher number of contact points and higher proximity zone length) than the reference mixture and the 40% RAP mixture prepared with the high modified bitumen *H* [21]. Such a finding explain the better performance in terms of rutting compared to the other two mixtures. Thus, the improved internal skeleton was able to overcome the higher rutting susceptibility associated to softer bitumen and higher bitumen content so explaining the better performance of *5.2%S_situ* mixture in terms of rutting.

4.6. Indirect tensile strength test

The Indirect Tensile test was performed with the double purpose to verify the requirements prescribed by the technical specifications for Italian motorway binder layers and to obtain a further parameter able to detect the influence of bitumen type on recycled mixtures response. According to the European standard EN 12697-23, the following equation was used to calculate the Indirect Tensile Strength (ITS):



Compared mixtures	p-value	Significant?
REF_situ/5,2%H_situ	0,0003	YES
REF_situ/5,2%S_situ	0,4610	NO
5,2%H_situ/5,2%S_situ	0,0002	YES
REF_situ/REF_LAB	0,0519	NO
5,2%H_situ/5,2%H_LAB	0,4255	NO
5,2%S_situ/5,2%S_LAB	0,0005	YES

Fig. 10. Indirect Tensile Strength results.

$$ITS = \frac{2 \cdot P_{max}}{\pi \cdot t \cdot d} \qquad (3)$$

where the Indirect Tensile Strength is measured in MPa, P_{max} is the maximum load [N], t is the height of the sample [mm] and d is the specimen diameter [mm].

Fig. 10 shows the results obtained as average of four replicates (along with the error bars expressed as standard deviation) for the investigated mixtures directly in comparison with the data recorded for the corresponding laboratory produced mixtures.

All materials showed results higher than the limit (0.95 MPa) prescribed by the technical standards. In particular, the reference mixture and the mixture prepared with the low modified bitumen *S* showed comparable results, whereas the mixture produced with the high modified bitumen *H* had ITS values significantly higher than the other mixtures, confirming the same trend already achieved with the laboratory produced mixtures. Therefore, the stiffening effect caused by the presence of higher RAP content is detectable also in terms of ITS and is amplified by the combination with a high modified bitumen. However, the results achieved by using a softer virgin bitumen further demonstrates the importance of the bituminous component on the stiffening response of a mixture especially to compensate the stiffening contribution provided by RAP aggregates.

5. Conclusions

The experimental study described in this paper focused on the mechanical characterization of hot plant recycled asphalt mixtures produced for maintenance and rehabilitation activities in a motorway stretch. The investigation addressed both volumetric and mechanical properties of two dense graded mixtures prepared with 40% RAP (fractioned in two sizes) and two different virgin polymer modified bitumens (low and high modified). A third mixture, prepared with 25% of unfractioned RAP in accordance with the current practice for binder layers, was used as reference for comparison purposes. The study aimed at validating the mix design previously implemented through a specific laboratory study (based on the application of the Bailey method) by verifying the performance of mixtures prepared directly at the asphalt plant in large scale productions. The main final goal was to evaluate the feasibility of in plant productions when large amounts of RAP are included and assess the reliability of laboratory studies to predict "real-scale" mixture performance.

The experimental program included a broad set of laboratory tests which allowed the identification of compactability and volumetric properties, stiffness, rutting and fatigue resistance, as well as self-healing potential.

Based on the results collected, the main following conclusions can be drawn:

– although the larger presence of stiff aged bitumen, the 40% RAP mixtures exhibited volumetric properties within the limit range provided by the technical standards and similar to the reference mixture. Additionally, higher amount of RAP did not cause difficulties in terms of compactability. Contrary to what was expected, compactability was higher for the 40% RAP mixtures;
– due to the presence of aged and polymer modified bitumens, the investigated mixtures did not behave as thermo-rheologically simple materials. However, the master curves of the complex modulus norm were determined through the Partial Time-Temperature Superposition Principle. As expected, due to the presence of higher RAP content, the 40% RAP mixture prepared with the high modified bitumen *H* showed stiffness values significantly higher than the reference. On the contrary, the lower stiffness moduli detected for the 40% RAP mixture prepared with the low modified bitumen *S* demonstrated that the use of a softer bitumen can successfully counterbalance the stiffening effect caused by

higher amounts of RAP without negatively altering overall stiffness properties (comparable with the reference mixture);
- the previous finding had direct consequences on fracture properties, which are strictly related to mixture stiffness. In fact, in accordance with the complex modulus master curves trend, the 40% RAP mixture prepared with bitumen *S* showed the best performance in terms of ductility and fatigue resistance, contrary to the mixture with 40% RAP and bitumen *H* which was characterized by the worst cracking and fatigue aptitude;
- the 40% RAP mixtures demonstrated better self-healing capabilities than the reference mixture regardless of the virgin bitumen used thanks to the chemical interaction between aged and virgin SBS polymer modified bitumens. Also the improved adhesion at the bitumen-aggregate interface due to the higher presence of particles coated by a thin film of aged bitumen helped to develop improved self-healing potential;
- also in terms of rutting, the mixture prepared with the low modified bitumen *S* was characterized by optimum performance, due to the improved aggregate packing achieved thanks to the enhanced workability.

Finally, the comparison between the results collected for in plant and laboratory produced mixtures allowed the validation of the mix design specifically implemented in laboratory. Laboratory and in plant mixtures were identical in terms of raw materials and mix design, and they were subjected to the same mechanical characterization. Generally, optimum correlation was found between laboratory and in plant mixtures performance, so demonstrating the suitability of the adopted laboratory practices to simulate real plant conditions. The analysis performed to evaluate the statistical significance of in plant and laboratory mixtures results demonstrated the reliability of the mix design optimized in laboratory and the feasibility of large scale in plant productions.

It can be concluded that the overall findings of this experimental investigation demonstrated the possibility to produce mixtures including high amount of RAP (up to 40%) characterized by optimum performance with regard to the main distresses typical of flexible pavements. The research points out the necessity to appropriately optimize the aggregate gradation with specific laboratory studies and suggests to carefully evaluate the selection of the most appropriate virgin bitumen, primarily recommending the use of a low modified bitumen when high amount of RAP are included.

In particular, the Bailey method and the RAP fractioning in two sizes were effective tools to optimize the mix design and counterbalance potential drawbacks due to the inclusion of high RAP content, hence guaranteeing good performance both at high and low service temperatures.

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