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A complete study on an asphalt concrete modified with graphene and recycled hard-plastics: A case study

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ABSTRACT

To date, many asphalt modifiers have been introduced and tested in the road pavement industry aiming at improving the properties of asphalt concrete and consequently its service life. In this context, also considering the environmental and circular economy principles, recently waste plastics, as a source of plastomeric polymers, have gotten more attention. This paper presents a complete case study on an asphalt pavement containing an asphalt concrete modifier composed of recycled hard plastics and graphene nanoplatelets that is compared with its counterpart made of SBS Polymer-modified Bitumen (PmB). The study aimed at providing a complete knowledge on a real-scale job and practical issues using such modifier that has not been well-reported within the current literature. This paper is divided into I) mix design and pre-qualification, 2) post-production tests, and 3) two years of monitoring of the trial section. Based on the results, the mixtures modified with recycled-plastic additives showed higher stiffness and tenacity and as expected though, a higher resistance to permanent deformation in line with the literature. As far as the fatigue is concerned, a similar fatigue endurance was observed for both of the studied asphalt concretes. In addition, the pavement condition survey carried out by pavement experts did not reveal any distress or failure for both of the executed pavements.

1. Introduction

1.1. *State-of-the-knowledge*

Increasing awareness regarding environmental criteria besides uncounted benefits of circular economy has urged the road engineers to use recycled materials from different resources in the pavement layers. These materials could be used either as alternative fillers [1,2] or modifiers enhancing the mechanical and performance properties. In this context, recycled plastics of different types have been one of the most used materials in asphalt pavements, globally. In addition, worldwide plastic pollution has motivated the researchers to study the feasibility of recycled-waste plastics for being used in asphalt concretes. In fact, these investigations, in most cases were driven by the urgency of reducing the plastic wastes. As a consequence, to date, many research works have been carried out showing different types of recycled plastics as promising asphalt concrete/binder modifiers. According to the latest global surveys and investigations [3,4], it can be concluded that the type of the plastic and the method of the use (dry or wet method) have a huge

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influence on the properties of the final asphalt concrete. However, regardless of these parameters, the increment of the tenacity and modulushas been common when recycled-waste plastics was used [5,6]. This characteristics not only enables a higher resistance to permanent deformation, suitable for heavy-duty asphalt pavements, but also well-suits for the pavements of hot climate regions [7]. In fact, it has been always a challenge when both heavy-traffic loads meets harsh hot climates. If a pavement is expected to be served for weighted, heavy truckloads with high tire pressures, then the use of mixtures/materials resistant to heavy loads is necessary to withstand the burden and to guarantee the pavement's structure [8].

However, from the technical point of view, a careful equilibrium of asphalt concrete properties is always required to alleviate one type of asphalt pavement distress without aggravating others i.e. the use of an asphalt modifier technology to increase the resistance to rutting without aggravating fatigue and thermal cracking susceptibility and vice versa [9]. In fact, the type and level of modification highly depends on the design criteria and climatic characteristics. With respect to cracking susceptibility of recycled-plastics modified asphalt concretes, several research works have shown that despite the increased stiffness, they comply with the specifications' limits on low-temperature cracking performance[10]. In a research work, three different recycled plastic additives were studied via the dry method producing 10 mm Stone Mastic Asphalt (SMA). According to the results, in spite of the higher stiffness and resistance to permanent deformation, the low-temperature fracture resistance of the recycled-plastic modified SMA was also superior, when compared to the reference SMA [11]. A similar conclusion has been made in another research, where waste packaging polyethylene was used for bituminous binder modification [12]. However, it should be considered that not all of the recycled plastics are the same and consequently enables the same performance. Technically, the formulation of any polymeric compound to be used in asphalt binder/concrete is fundamental and should be considered when derived from recycled plastics,. Naturally, not all polymers can be used for the construction of flexible pavements. In fact, for example, the use of the "plast mix" (mix of several waste plastics) has not met great success in various countries around the world [13].

Besides polymers, in recent years, nanotechnology has also shown promising achievements in bitumen and asphalt modification. Nano rubber, nano silica, different kinds of nano clays, and nano graphene are the majority of the nano materials investigated and projected in the asphalt industry. It has been shown that using Nano clay as the second modifier in SBS polymer-modified bituminous binders can improve the storage stability and the aging resistance of polymer-modified asphalts binders [14]. In addition, different types of nano carbon, including Carbon Nano Tubes (CNTs), Graphene Oxides (GOs), and Graphite Nano Platelets (GNPs) are other technologies, which showed advantages in asphalt modification. Among these nano materials, it has been shown that nano graphene provides outstanding resistance to cold-temperature mechanical properties of asphalt concrete [15]. Recent studies have proven that a moderate addition of GNPs to asphalt binder could lead to about a 130 % increment in its flexural properties. Researchers at the University of Minnesota also found that the addition of graphene nano platelets significantly reduces the compaction effort required to prepare asphalt concretes [16]. In addition, compared to CNTs, in which a homogeneous dispersion of it into the modified material is considered a big challenge [17] it is much easier to disperse the GNPs into asphalt binders.

1.2. Objectives

Despite the huge research works carried out on the recycled-plastic modified asphalt binders and concretes, still, the technology is not well-recognized. This, on one hand, could be due to the variety of waste plastics introduced to the asphalt industry and on another hand the uncertainty on its durability and performance under real conditions. Furthermore, still, the many refineries that are not technically ready to realize the technology applying wet method. Bearing in mind these obstacles, the present study, aimed at investigating comprehensively the mechanical and performance properties of asphalt concretes modified with a recycled-hard-plastic asphalt modifier, which also contains graphene nanoplatelets and is introduced via dry method. The application of dry method facilitates the introduction of plastics into asphalt mixtures, which due to the challenges of compatibility and stability cannot be mixed using wet method. The authors believed that Pre- and post-production lab tests in addition to the periodical monitoring of a test track executed in the ring-road of the city of Bergamo, Italy, provide insights into the potentials of other sustainable additives compared with SBS PmBs that are characterised by higher fatigue endurance due to the elastic nature of SBS copolymers.

2. Materials

Two asphalt binders were used in this work: a PmB 45/80–65 (with high-content of SBS) and a 50/70 paving-grade neat asphalt binder. It is worth mentioning that the mixtures were first optimized for the mixture containing the SBS PmB and then the same Job Mix Formulas (JMF) were used for producing the same asphalt mixture but containing a Graphene-enhanced Recycled Plastic (GRP) asphalt modifier and 50/70 asphalt binder. Accordingly, the Optimum Bitumen Contents (OBC) following Marshall method, were 4.3 % and 5.4 % (for the Base/binder and surface course respectively).

Considering the objectives of this work, the asphalt mixtures were modified by applying two different methods for the different asphalt modifiers of this study:

I. Dry method; the GRP modifier was added directly to the hot aggregates before adding the bitumen and filler. The dosage was determined during the mix design procedure and it was 6 % on mass of the bitumen. The choice of the dosage was according to the producer's recommendations and previous studies in the literature.
II. Wet method; the bitumen was previously modified with SBS and used to produce the asphalt mixture.

The innovative part of this study was the addition of graphene to recycled-hard-plastic for asphalt concrete modification., The additive, shown in Fig. 1, is expected to enhance some of the mechanical properties of asphalt mixtures. Technically, the immense specific surface area of the nano graphene is extended throughout the binder and results in asphalt reinforcement. This additive has been developed to cope with severe rutting distress of flexible pavements either in hot climates and/or those subjected to heavy-duty traffic. However, thanks to its recycled- plastic base, it is also considered a sustainable solution for asphalt modification with low environmental impact. The applied processing method in this technology allows to recycle hard plastics, which to date are normally destined to waste-to-energy plants.

The aggregate distribution curves shown in Fig. 2 were set according to Italian specifications (Comune di Bergamo) containing 10 % and 20 % of Reclaimed Asphalt Pavement (RAP) by mass of the aggregates for the surface (wearing) course and the base/binder course, respectively. Naturally, in the mix design these OBCs include also the aged asphalt binder of the RAP. As it can be seen both the surface and the base/binder course were of dense-graded asphalt concretes.

3. Methods

Bearing in mind the targets of this applied study, the testing and quality control programme was divided into two main sections of lab-scale experimental works (pre- and post-production) and in-situ inspections and monitoring.

As mentioned earlier, during the pre-qualification lab tests, the mixes were produced following the dry method procedure. Accordingly, the modifier was added to the hot aggregates at 180 ± 5 °C. Then the mix was maintained in the oven for some minutes (approx. 45 min) to let the granules become soft before adding the hot bitumen at 160 °C. On the contrary, as a wet method, for the production of the SBS PmB mix, the PmB was heated and added directly to the hot aggregates. Nevertheless, both mixtures were produced and compacted at the same temperature. Fig. 3 demonstrates the steps followed during the applied dry and wet methods production of the mixtures in the lab.

However, it is worth mentioning that during the post-production phase, the collected asphalt samples from the job site were re-heated at 160 °C and compacted at 155 ± 2 °C. It is noteworthy that except for the permanent deformation test, for the pre- and post-production tests the specimens were manufactured applying N_3 (N_{max}) gyration number that was required based on the Italian specifications. In this sense, while the gyratory-compacted specimens contained plus 2 % air voids, the slabs for resistance to rutting test were compacted at 4 % air voids content. The manufactured specimens were subjected to the following tests according to the European standard testing methods:

- Indirect Tensile Strength (ITS) 12697–23 at 25 °C EN;
- Indirect Tensile Stiffness Modulus (ITSM) EN 12697–26 IT-CY at 5, 20, 40 °C;
- resistance to permanent deformation, Wheel Tracking Device (WTD) EN 12697–22 at 60 °C;
- and resistance to Fatigue, Indirect Tensile Fatigue Tests (ITFT) EN 12697–22 at 20 °C.

Finally, the monitoring of the test track was carried by three pavement experts. For this target, the presence of visible cracks, edge deteriorations, and rutting were controlled for two executive years exactly after the pavement installation. Further details are explained in the following related sections.

4. Results and analysis

4.1. Tensile strength

In literature, the Indirect Tensile Strength (ITS) has been often used for assessing the level of the tenacity of the asphalt concrete. ITS value is the maximum calculated tensile stress applied to a cylindrical specimen loaded diametrically until breakage occurs at the test temperature and displacement speed. The ITS was calculated at 25 °C, as per the EN 12697–23 European standard, using the Eq. (1):

$$ITS = \frac{2P}{\pi DH} \tag{1}$$

Fig. 1. The Graphene-enhanced recycled plastic(GRP) asphalt modifier.

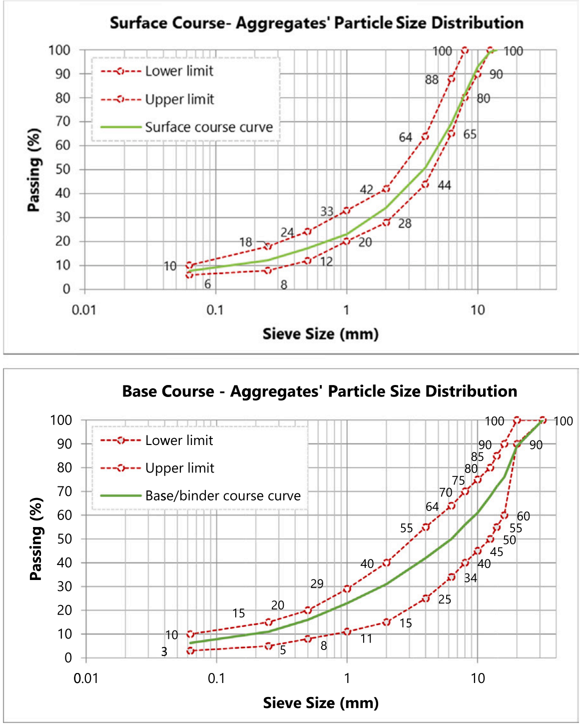

Fig. 2. The grading bands and aggregates' particle distribution.

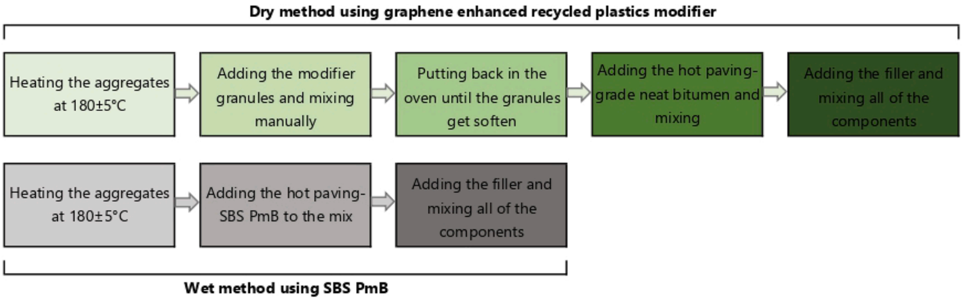

Fig. 3. Dry method vs. Wet method applied during mixture production in the lab.

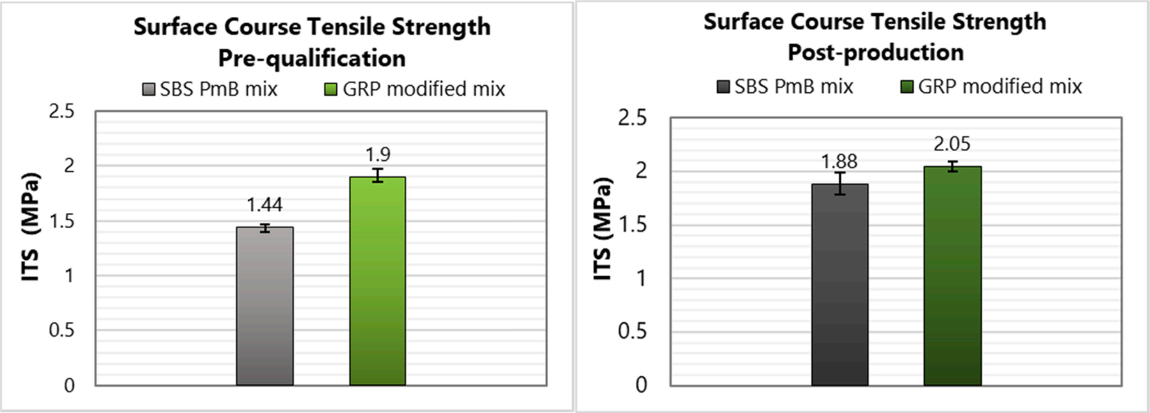

Fig. 4. Pre-and post-production Indirect Tensile Strength (ITS) of the surface course.

Where ITS is the indirect tensile strength (GPa), P is the peak load (kN), D is the diameter of the specimen (mm), and H is the height of the specimen (mm).

Figs. 4 and 5 show the ITS test's results in MPa for the surface course and base/binder course, respectively. Accordingly, the following highlights can be drawn by analysing the obtained results.

- The same trend was observed for both pre-qualification tests' results and post-production control results for both the mixtures. For both mixtures, during the pre-qualification phase, the mixture made of SBS PmB showed lower ITS vales compared to the mixture containing recycled-plastic modifier. This on one hand could show the validity of the obtained results and from another hand shows the accuracy of the mixture produced in the plant.
- For both surface and base/binder course, the mixture containing recycled-plastic modifier showed either equal or higher values compared to the mixture made of PmB.
- No significant difference was recorded between the values of the surface and base/binder course. This could be either due to the very similar void content or proportion of the binder content.
- In both pre-qualification tests' results and post-production control tests' results, very similar results were obtained for the asphalt mixture containing recycled plastic modifier. This, on one hand, certifies the homogeneity of the mixture produced via the dry method and from another hand shows the conformity of the procedure followed in the laboratory to what was followed during the production in the asphalt plant.

4.2. *Stiffness*

The stiffness modulus was tested using an indirect tensile load configuration accordaning to EN 12697–26 annex C, IT-CY. The test was conducted under deformation control mode. The deformations at each temperature were selected considering the recommended values of the reference standard (table C.2). The test was conducted at three different levels of temperatures of 5, 20, and 40 °C, representing low, medium, and high temperature conditions, consequently, 4.0, 7.5, and 14 μm were the considered deformations, respectively.

The ITSM was calculated using Eq. (2):

$$ITSM = \frac{F \times (\nu + 0.27)}{z \times h} \tag{2}$$

Where F is the peak value of the applied vertical load (N), z is the amplitude of the horizontal deformation obtained during the load cycle (mm), h is the mean thickness of the specimen (mm), and ν is Poisson's ratio (assumed to be 0.35).

According to the results shown in Figs. 6 and 7, for both of surface and base/binder course the asphalt mixture containing ~~using~~ the recycled-plastic asphalt modifier showed a higher stiffness modulus compared to the mixtures made of SBS PmB. The same has been observed in the literature and in the authors' another study, where the same recycled-plastic asphalt modifier was compared with a mixture made of different grade of SBS PmB [18]. However, considering the type of the road and the climatic condition of this project, the pavement's properties at medium to high temperatures were more concerned affecting the service life of the pavement. In addition, the stiffness of bituminous mixtures is a key parameter for the analysis and rational structural design of flexible pavements [19]. Bearing in mind these facts, in this project, with achieved remarkable moduli, higher service life is expected and the mixture technically could be more resistant to permanent deformation.

From another point of view, it should be taken into account that depending on a project's specifications, reducing the stiffness moduli is always possible by changing the asphalt binder that is used with the recycled-plastic asphalt modifier. In case, due to the climatic condition, the pavement structure, or materials, an asphalt mixture with lower stiffness is required, a softer asphalt binder i.e.

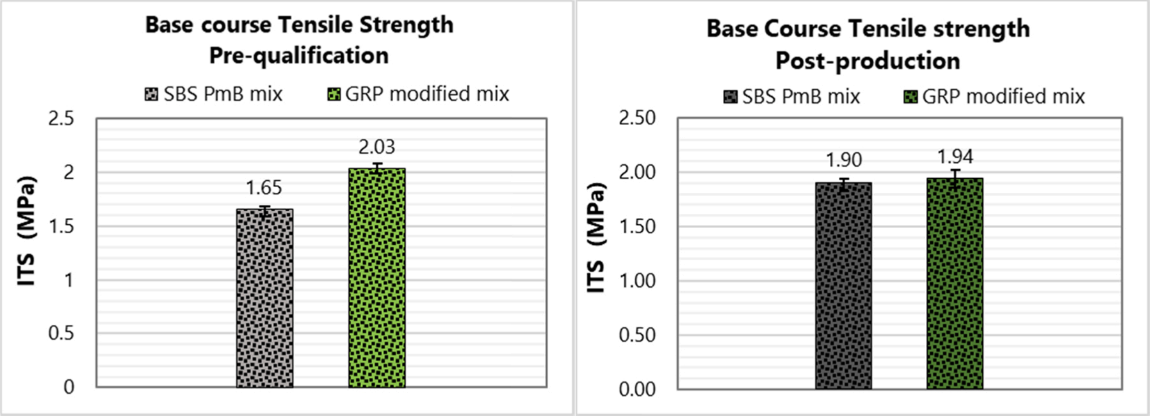

Fig. 5. Pre-and post-production Indirect Tensile Strength (ITS) of the base/binder course.

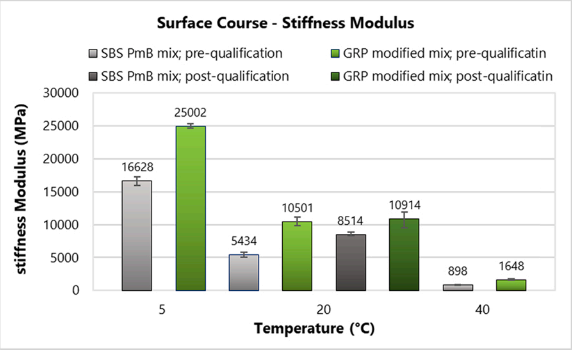

Fig. 6. Pre-and post-production Indirect Tensile Stiffness Moduli (ITSM) of the surface course.

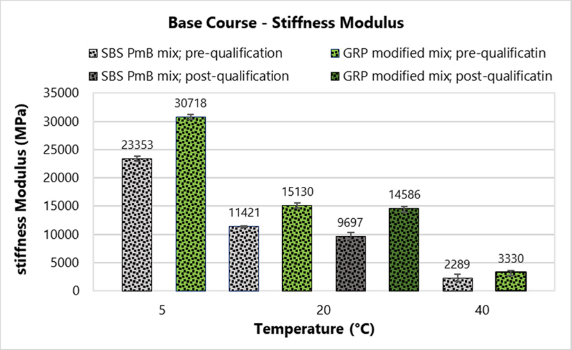

Fig. 7. Pre-and post-production Indirect Tensile Stiffness Moduli (ITSM) of the base/binder course.

70/100 could be used.

4.3. Resistance to permanent deformation

The susceptibility of the asphalt mixtures to permanent deformation was assessed by means of Wheel Tracking Device (WTD) at temperature of 60 °C. The test was carried out according to procedure B of EN 12697–22 standard. For this purpose, the collected materials from the job site were re-heated and compacted with a roller compactor to 4 % air voids.

As it can be seen in Table 1, the resistance to permanent deformation of the mixtures is almost the same for the tested mixtures. This shows the feasibility of asphalt concrete modification via dry. Based on the test results, both mixtures complied with the required values of the technical specifications of the municipality of Bergamo, which were Wheel-Tracking Slope $WTS_{air0.1}$ and $WTS_{air1.0}$ for the surface course and binder course, respectively. From another point of view, many literatures have shown that the introduction of recycled plastics in asphalt mixtures enhances the resistance to permanent deformation by increasing the stiffness properties.

4.4. Resistance to fatigue

Fatigue cracking is one of the most common distresses of asphalt pavements, particularly in locations with dominant medium to low temperatures. Fatigue cracking eventually results in degradation of the bond between asphalt mixture materials and consequently its structure. Technically, two phases of the degradation process are recognized during fatigue cracking. The first phase that results in the

Table 1
Wheel tracking resistance to rutting test results.

Mix	Surface course			Base/binder course		
	Rut depth (mm)	Proportional rut depth (%)	Wheel-tracking slope (mm/10^3)	Rut depth (mm)	Proportional rut depth (%)	Wheel-tracking slope (mm/10^3)
SBS PmB mix	1.92	3.87	0.07	2.60	2.89	0.09
GRP modified mix	1.91	3.82	0.07	2.50	2.87	0.09

degradation of the pavement is known as uniform damage distribution throughout the material. This phase is manifested by the initiation and propagation of a network of 'micro-cracks, which leads to lower rigidity (stiffness modulus). Instead, the latter phase starts with the coalescence of these 'micro-cracks and the appearance of 'macro-cracks', which propagate within the structure of the material [20].

In this study, the fatigue performance of the asphalt mixtures under repeated load was evaluated by means of Indirect Tensile Fatigue Test (ITFT) based on EN 12697–24 – annex E. Accordingly, a haversine load was applied considering 0.1 s loading time and 0.4 s rest time at the test temperature of 20 °C. Technically, the choice of ITFT and stress-control mode was due to the overall thickness of the asphalt pavement layer in this project, which could be considered as a thick asphalt layer. It is worth mentioning that different literatures have considered different values, however, generally, an asphalt layer thicker than 130–160 mm is considered as a thick asphalt layer [21,22]. This is in fact a determinant factor since literature has shown that the thick asphalt layers are susceptible to top-down fatigue cracking [23].

Figs. 8 and 9 show the fatigue plots drawn up by the post-production test's results. As it can be seen almost the same trend was obtained for both surface and base/binder course. According to the strain vs. Number of cycles (N_f) fatigue plots, both mixtures showed relatively similar fatigue endurance. In fact, a very similar initial strain related to 1 million cycles ($_{\varepsilon 6}$) was obtained for the surface and base/binder course. It is noteworthy that the low ε_6 values obtained in this study, was due to the characteristics (volumetrics) of the tested specimens. As it was mentioned in the section methods, the test specimens were compacted at $N_{3(max)}$ to comply with the local specification. Naturally, low air void compacted specimens resulted in high modulus and lower strains.

Considering that ITFT test is carried out under stress control mode, the stress vs Number of cycles to failure (N_f) fatigue plots were also elaborated that enables the fatigue performance analysis from a different perspective. Considering these fatigue plots, the same trend of strain vs. the number of cycles to failure was observed, which was also in line with other recorded characteristics of the mixtures. This has been shown in several previous similar studies [18,24,25].

5. Trial section profile and monitoring

The test track of this case study was a section of the northern ring road of the city Bergamo (SS470), northern Italy. Due to its location, the highway collects and directs the traffic stream to the southern ring road and A4 motorway towards Milan and Brescia. As shown in Fig. 10, it consisted of 4 sections: 1) 40–50 mm surface course containing SBS PmB; 2) 40–50 mm surface course containing the graphene and waste-hard-plastic asphalt modifier; 3) 40–50 mm surface course containing on an 80–100 mm base/binder course both containing the graphene and waste-hard-plastic asphalt modifier; and 4) 40–50 mm surface course containing on an 80–100 mm base/binder course both containing SBS PmB. Obviously, during the job the old pavement was milled up to 150 mm and removed and the surface was covered with a tack coat bitumen emulsion before installing the new layers.

The periodical pavement inspection and monitoring were carried out to evaluate the pavement surface condition and to identify the presence of early-age pavement damage. Fig. 11 shows a section of the installed pavement made of the GRW modifier and 50/70 asphalt binder. The pavement experts' inspection was carried out after the first and second year of pavement's installation and this will continue to provide a real picture of the test section under realistic climate and traffic service. According to the precise controls, no pavement distress was observed. In addition to the visible distresses, the rut depth was also controlled. The measurement of rut depths is best carried out using a standard straight edge and a calibrated wedge. On the basis of its general use and its ease of handling and transportation, a 2-meter straight edge is the most practical. According to the assessments carried out, thanks to the mixture's high modulus and its resistance to permanent deformation, no rutting was observed during the monitoring investigations.

6. Conclusions

This paper represents a complete case study, where a full-depth asphalt pavement containing an asphalt modifier composed of waste hard-plastics and nanoplatelets of graphene is compared with the same asphalt but made of SBS polymer-modified bitumen (PmB). The main objective of this investigation was to verify the performance and mechanical properties both in the laboratory and in-situ under realistic conditions. From the analysis of the obtained tests' results, execution experience, and 2 years of monitoring, the following conclusion can be drawn:

- In line with the existing literature on the waste-plastic modified asphalts, the asphalt containing the graphene and waste-hard-plastic (GWP) asphalt modifier showed increased stiffness and strength. This has been achieved both with pre- and post-production tests.
- As it could be expected by considering especially the post-production stiffness and strength values, both of the tested mixtures exhibited very similar resistance to permanent deformation. This has also been recorded in many previous researches on the waste-plastic modified asphalts, discussed earlier in the section literature review of this paper.
- According to the test results of this study, the fatigue life of the asphalt containing recycled-plastic asphalt modifier was greater or comparable compared to the same mixture made of SBS PmB. However, the authors believe that the type of waste plastics, selected for the production of the asphalt modifier, plays a key role.
- During the production of the modified asphalt by applying dry method, neither logistic issue nor compaction difficulties were observed. In fact, the post-production tests' results were in line with those of the pre-qualification phase showing the dry-method as a more sustainable eco-friendly technology, which requires less energy.

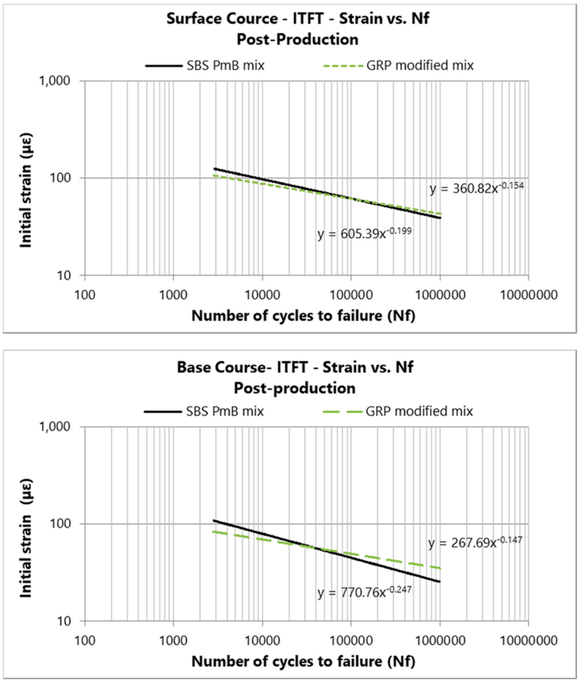

Fig. 8. Strain vs. Number of cycles to failure (N_f) fatigue life plots of the test mixtures.

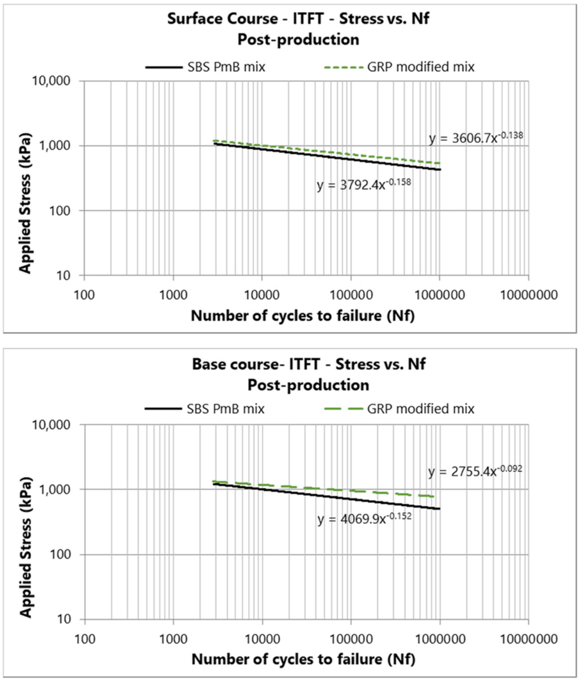

Fig. 9. Stress vs. Number of cycles to failure (N_f) fatigue life plots of the test mixtures.

- Two years of monitoring by means of experts' visual inspection and rut depth control showed no distress (visible cracks), disintegration, or permanent deformation. This could prove the viability of recycled-waste plastics as a sustainable asphalt modifier that allows both environmental reservation and circular economy.

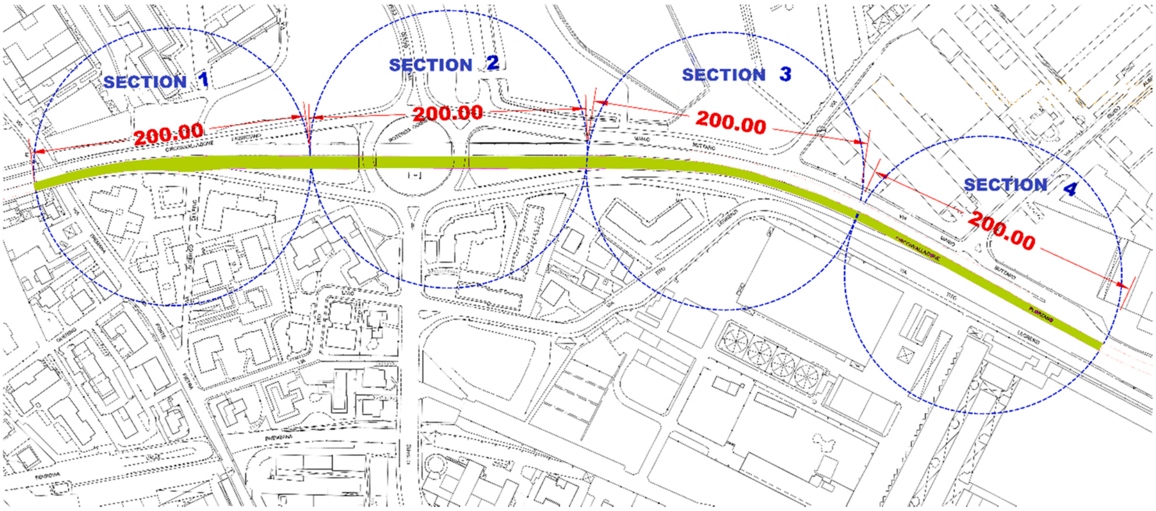

Fig. 10. The test track sketch.

Fig. 11. July 2022 pavement monitoring; the third year after its construction.

7. Future scopes

While this paper covered many bugs within recycled plastic asphalt concretes, still there are some aspects that was not studied and should be considered in the future studies. Low-temperature performance of plastomeric modified mixtures is still under sceptics that shall be studied more especially for the pavements in the cold climate regions. In addition, since the type of the mixtures was limited by the project's specifications, investigating the influence of the types of the asphalt concrete e.g., SMA and testing considering different climatic condition are recommended.

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

No data was used for the research described in the article.

Acknowledgment

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