Future roads and mobility

Perpetual road pavements with a graphene-based supermodifier

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Abstract

Developing an innovative super-modifier for enhancing the performance and mechanical properties of heavy-duty asphalt pavements/those that are laid in harsh climates was the motivation of full-scale research, which discussed in this paper. Basically, the studied additive is a polymeric compound modifier containing graphene nanoplatelets for being used by applying the well-known dry method as a sustainable road paving technology. This paper represents the data obtained from the tests, which have been conducted on the specimens reproduced of the samples collected from the first trial section in September 2018, in Rome. Aiming for providing comparative study, the trial section in this practice, which included both binder and wearing course, was divided into four segments made with different mixtures. These mixtures were:1)graphene-based additive containing,2)SBS-modified,3)polymeric compound (composed of both plastomers and elastomers), additive containing, and 4)a reference mixture without any kind of additive made with 70/100 pen-graded neat bitumen. The target was validating the results that were obtained during the three-year-long lab-scale research. The testing plan consisted of Heavy Weight Deflectometer(HWD), Indirect Tensile Strength(ITS), Indirect Tensile Stiffness Modulus(ITSM), permanent deformation resistance by means of Wheel Tracking WT), and fatigue endurance by means of Indirect Tensile Fatigue Test(ITFT). According to the results (in this paper just wearing course), the mixtures containing graphene-based additive showed significantly higher stiffness, superior rutting resistance, and better fatigue endurance compared to the other mixtures, which were tested in this study. In addition to the lab-scale works, the HWD results were also showed a significantly higher estimated stiffness modulus for the mixture containing graphene-based modifier when compared to other tested mixtures. Overall, it is of utmost importance that the obtained results were almost in line with the laboratory-scale research work, which would validate the data. Key words: Performance and mechanical properties;Heavy-duty pavements;Performance and mechanical properties;Graphene nano plateles;SBS-modified;Polymeric compound;Heavy Weight Deflectometer(HWD)

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1. INTRODUCTION

The pavement life cycle is comprised of six stages: pavement design, materials' production, construction, service life, maintenance and rehabilitation, and removing/recycling due to end of life. Each stage of the life cycle provides numerous opportunities to improve the overall transportation sustainability goals. These may include such items of lowering greenhouse gas emissions, protecting the surrounding ecosystems, or improving the quality of life in the built environment [1]. However, it could be a challenge when both heavy-traffic loads and harsh climate come together. If pavements are expected to be receiving weighted, heavy truckloads with high tire pressures, then the use of mixtures resistant to heavy loads is necessary to grantee the pavement system withstand the burden [2]. In addition, we cannot escape from the fact that more and more cars will continue to be on the road, which further increases the need for heavy-duty asphalt in road pavements.

Bearing in mind the principles of sustainability to the pavement's life cycle to date, many different techniques/products have been introduced and practiced. Among them, using Reclaimed Asphalt Pavement (RAP) and different types of performance modifiers are more common. While the use of high percentage RAP containing asphalt mixture for constructing heavy-duty pavements is still under skepticism, the use of high-modulus bitumen binders and recently new asphalt modifiers adopting dry method have shown to be applicable strategies. In this respect, while the production, storage, and application of Polymer-modified Binders (PmBs) sometimes make practical difficulties and final quality concerns, the direct asphalt mixture modification (dry method) seems to be a convenient alternative with at least same properties with even more lateral benefits. The superiority of dry method, known also as Polymer-modified Asphalt (PmA) technique, mainly goes to three reasons: 1) less energy consumption for producing the material (compared to PmB production) and asphalt mixture, 2) no storage stability concerns, which is a big challenge in producing PmBs, and 3) flexible logistics that means overall the application procedure is easier and straightforward for the workers [3&4].

To date, different types of materials have been introduced and practiced for producing high-performance asphalt mixtures within PmA technology. These materials can be mainly divided into two groups of: I) composite modified fibres and II) polymeric compounds. While composite fibres are mostly used for producing Stone Mastic Asphalt (SMA) and Open Graded Friction Course (OGFC) layers, the polymeric compounds could be used for all types of asphalt mixtures and for any layer of asphalt pavements. Generally, polymeric compounds are consisted of both elastomer copolymers and plastomers, getting advantages of both types of polymers. These compounds are usually found in granular form, which provides the ease of use and logistics.

Besides asphalt polymer modification, recently Nanomaterials have shown great potential in enhancing asphalt mixture's mechanical and performance properties. Within the literature, many different Nanomaterials have been introduced but just a few of them shown capabilities of improving the asphalt mixture properties for both low and high temperatures. In this respect, mixtures containing graphene products including Graphite Nano Platelets (GNPs) and Carbon Nanotubes (CNTs) showed effectiveness in improving the resistance to low-temperature cracking as well as resistance to high-temperature permanent deformation [5&6]. Graphite Nano Platelets (GNPs) are layers of graphene stacked on top of each, other form graphite, with an interplanar spacing of 0.335 nanometers. One of the obstacles recognized for using graphene Nano products is the costs. Comparing the costs of different types of Nano graphene, GNPs are significantly more economic products than other types of graphene-based materials. This makes GNPs ideal for large-scale applications. Figure 1 shows the Nano graphene platelets appearance at room temperature and under Scanning Electron Microscope (SEM).

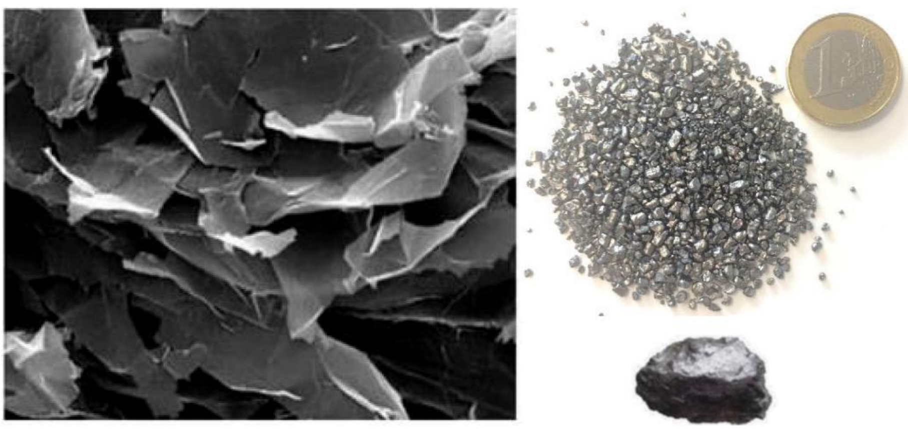

Figure 1: Graphene nanoplatelets at ambient temperature and under Scanning Electron Microscope

Considering the above-mentioned issues, a full-scale three-year-long research has been done with the main goal of exploring the mechanical and performance properties of asphalt mixtures containing a new graphene-based modifier. This paper presents the data obtained from the tests, which has been carried out on the specimens fabricated of sample mixtures collected during the laid trial sections. The data obtained from these tests validate the primary results that have been obtained by experimental works in the lab-scale research phase (were presented in the authors' earlier publications [7]). For providing a broad perspective and comparable results, 4 different trial sections were paved with four different asphalt mixtures using the same binder. These mixtures were: 1) a neat bitumen containing mixture, 2) neat bitumen+SBS containing mixture, 3) polymeric compound (using dry method) containing mixture, and 4) graphene-based modifier (using dry method) added mixture.

2. MATERIALS AND METHODS

2.1. Materials

In this work, a dense-graded binder and a wearing course were optimized using a neat 70/100 bitumen binder. Considering the principles of sustainability, both binder and wearing courses were contained 40% and 30% of RAP, respectively. For this reason, 0.2% (on the weight of RAP) of a vegetable-based rejuvenating agent was added to the mixtures. The additives and dosage of the modifiers were: 1) a polymeric compound of both elastomer copolymers and plastomers; 3% on the weight of bitumen and 2) a graphene-based super modifier; 5% on the weight of bitumen, which actually also a polymeric compound containing graphene nanoplatelets. Both additives were of Iterchimica S.r.l. products, Italy. It is worth mentioning that the graphene-enhanced super modifier has been already patented. Figure 2 shows the polymers at room temperature.

Figure 2: From left to right: SBS copolymer, polymeric compound, and Graphene-based modifier

The considered grading bands for the aggregate distribution were selected from local specifications (Capitolato Speciale d'Appalto, Rome Capitale).

2.2. Methods

2.2.1. Trial section

The trial section was a road in Rome area (Via Adreatina). Figure 3 shows the trial section segmentation based on the four different kinds of asphalt mixtures used in this study. These sections consisted of a 7 cm binder course and 3 cm wearing course. The wearing courses, which this paper represents their performances and mechanical properties, were wearing courses with a nominal maximum size of 8mm. The aggregates' particle distribution of the wearing courses have complied with an Italian local specification (Capitolato Speciale d' Appalto, Rome Capitale) shown in Table 1. Figure 4 shows the paved wearing courses segments made with different modifiers and the segment made without any type of modifier.

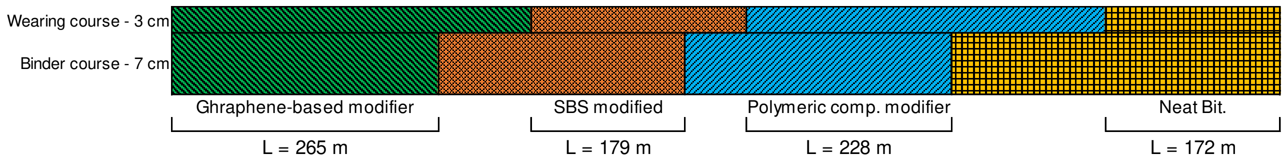

Figure 3: Trial section segments

Table 1. Applied grading curve bands for the wearing and binder course

Sieve size (mm)	Binder course		Wearing course	
	Lower limit passing (%)	Lower limit passing (%)	Upper limit passing (%)	Lower limit passing (%)
31.5	100	100	-	-
20	90	100	-	-
16	76	87	-	-
12.5	64	75	100	100
8	50	62	75	90
4	37	48	44	62
2	23	33	26	40
0.5	11	17	14	22
0.25	6	12	10	16
0.063	4	7	6	10

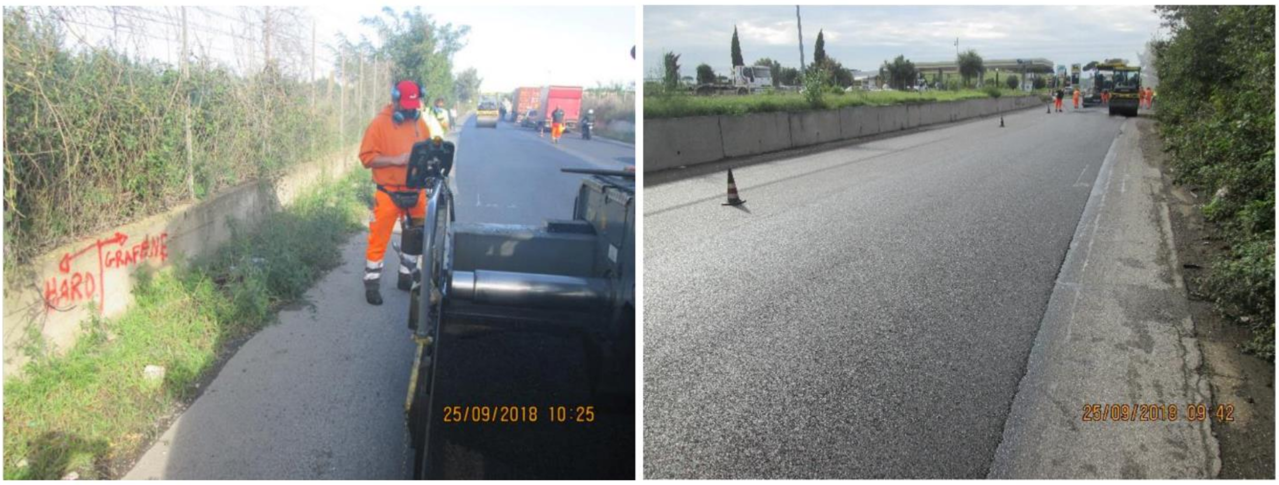

Figure 4: Trial section of Graphene-based super modifier

2.2.2. Experimental and in situ test plan

The test plan in this research was divided into two phases: 1) the in situ tests, which included Falling Weight Deflectometer (FWD) 2) Experimental tests on performance and mechanical properties of the specimens made with collected samples from the trial section. This phase consisted of Indirect Tensile Strength (ITS), Indirect Tensile Stiffness Modulus (ITSM), resistance to permanent deformation by means of Wheel Tracking test, and fatigue endurance by means of Indirect Tensile Fatigue Test (ITFT).

A Falling Weight Deflectometer (FWD) is a testing device, which is primarily used to estimate the pavement's structural capacity. The machine is usually contained with a trailer that can be towed to a location by another vehicle. The FWD is designed to impart a load pulse to the pavement's surface, which simulates the load produced by a rolling vehicle wheel [8]. The load is produced by dropping a large weight, and transmitted to the pavement through a circular load plate - typically 300 mm diameter on road. Typically, the load for road testing is about 40 kN giving about 567 kPa pressure under the load plate (50 kN / 707 kPa according to European standard). Deflection sensors (geophones; force-balance seismometers) mounted radially from the centre of the load plate measure the deformation of the pavement in response to the load. Some typical offsets are 0, 200, 300, 450, 600, 900, 1200 and 1500 mm. FWD data is most often used to calculate stiffness-related parameters of a pavement structure. The process of calculating the elastic moduli of individual layers in a multi-layer system (e.g. asphalt concrete on top of a base course on top of the subgrade) based on surface deflections is known as "back calculation". For this purpose, the initial moduli are assumed, surface deflections calculated, and then the moduli are adjusted in an iterative mode to converge on the measured deflections.

2.2.3. Specimen production

For the experimental works in this study, the specimens produced by reheating the collected samples from the trial sections and were compacted using gyratory compactor applying 100 gyrations at 150±5°C. it is worth mentioning that while the specimens used for the ITS tests was of 100 mm diameter, for the dynamic mechanical tests 150 mm was considered for the specimen production.

3. RESULTS AND ANALYSIS

3.1. Heavy Weight Deflectometer (HWD)

For the test 40 kN, 55kN and 85kN load cycles were adopted for providing a better understanding of the contribution of layers. Figure 5 shows the equipment during the test. To measure the ambient temperature, a thermometer integrated with the HWD equipment was adopted while for measuring the temperature of the bituminous layers a digital thermometer of ± 0.2° C precision was applied.

Figure 5: Applied HWD during the test

Based on the measured values of deflections and the thicknesses of the layers, through back analysis procedures and based on modelling the pavement in an elastic multilayer system, it is possible to obtain different moduli of different layers shown in Figure 6:

- the overall Stiffness modulus of the structure, "E0";
- the Stiffness modulus of the bituminous mixture, "E1";
- the Stiffness modulus of the foundation (base and subbase), "E2";
- and the Stiffness modulus of the roadbed soil, "Es".

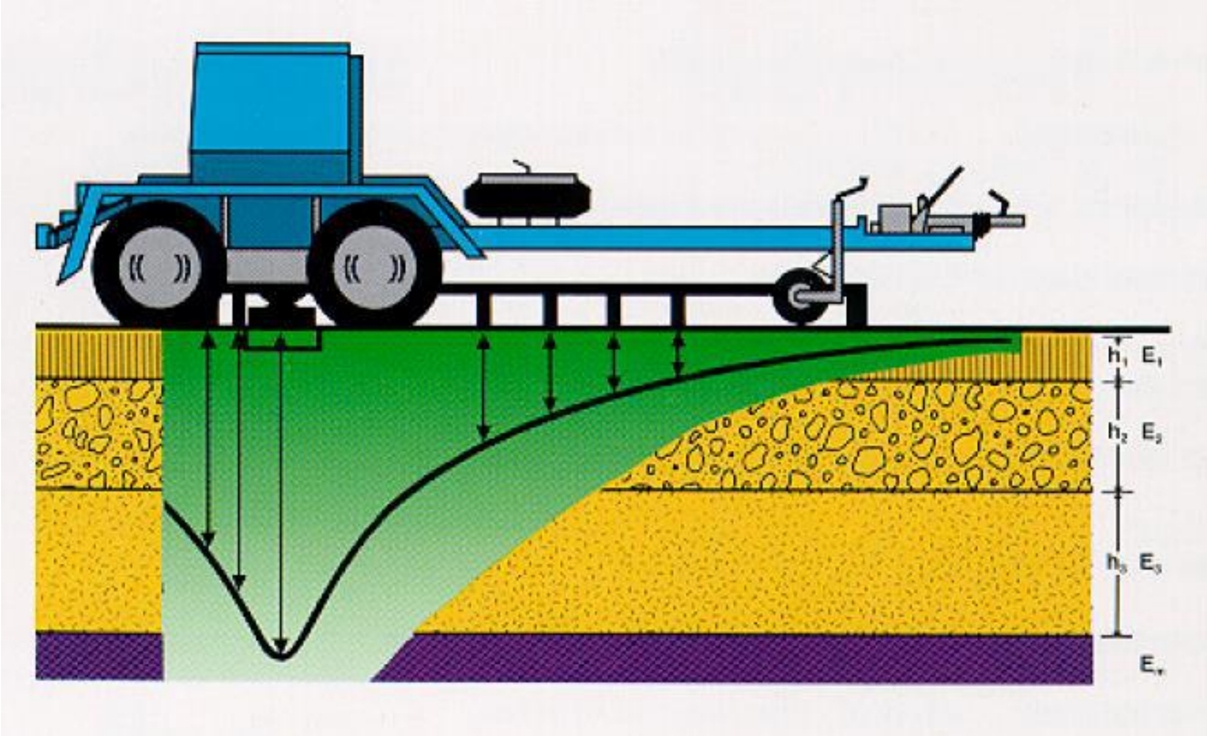

Figure 6: Pavement layer and HWD output moduli

The "ELMOD" software (a product of Dynatest International) was used for the calculations based on a back analysis procedure. Figure 7 shows the obtained values for the moduli in terms of the modulus of overall layer-E1, bituminous layer-E2, and roadbed foundation E_S. According to the results, the average estimated modulus of asphalt layer made with graphene-based modifier at 20˚C is 6424 MPa, which is almost double of the average modulus for the asphalt layer made with neat bitumen that is 3855 MPa. Comparing the mixture with two other modified mixtures showed that the stiffness modulus of the mixture containing graphene-based modifier is 20% higher (5435 MPa) than the SBS-modified mixture and 40% higher than the mixture containing polymeric compound. Overall, with comparing the results, it can be seen that the mixture containing graphene-based modifier showed superior and more convergent results compared with the other mixtures.

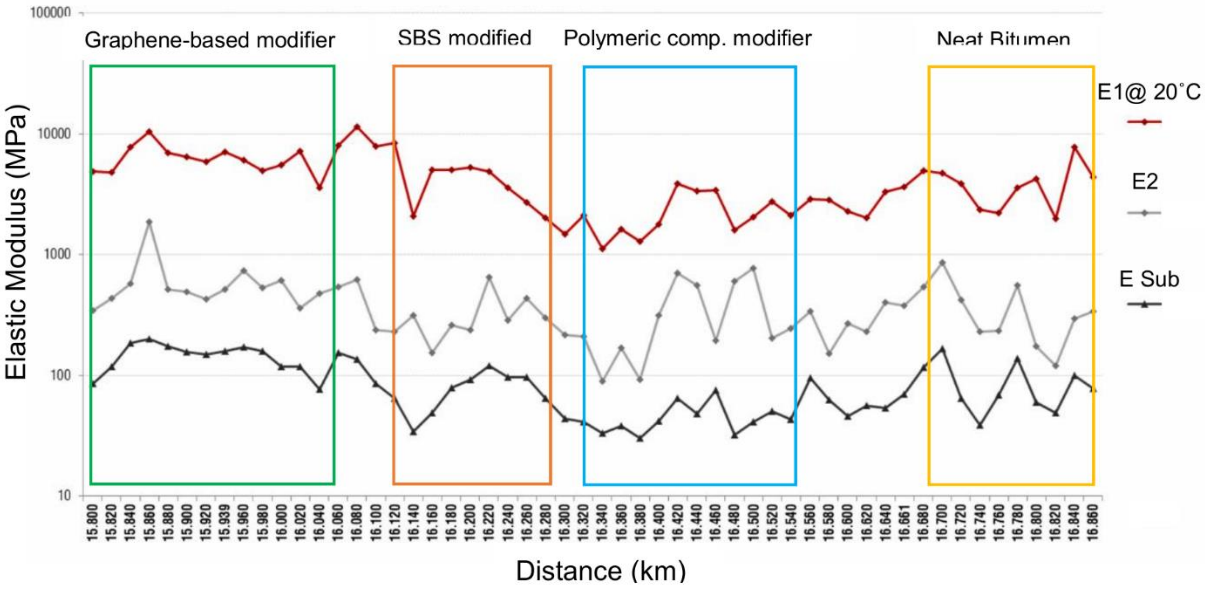

Figure 7: Elastic moduli

3.2. Indirect Tensile Strength (ITS)

In the literature, it has been shown that ITS values are also useful to estimate the resistance to fatigue and permanent deformation [9 & 10]. In the presented work, the ITS test was primarily carried out on the specimens, which have been produced by collecting samples just of the neat bitumen asphalt mixture and the asphalt mixture containing graphene-based modifier. Unfortunately, for the other two mixtures, the results are not applicable. The test was carried out according to EN 12697-23 at 25˚C. For this purpose, the collected materials from the trial sections, reheated and compacted with gyratory compactor applying 100 gyrations (N2 according to the local specifications, Capitolato Speciale d' Appalto, Rome Capitale) for producing specimens with diameter of 100 mm. It is worth mentioning that according to the most of the Italian specifications the void percentage shall be between 4 to 6% after N2 (design) gyrations. According to the test results presented in Table 2, it can be seen that the mixture containing graphene-based modifier performed better than the reference mixture showing higher ITS values. This shows the effectiveness of the graphene-based super modifier in enhancing the tensile properties of asphalt mixtures.

Table 2. Indirect Tensile Strength and volumetric parameters

Mixture	Indirect Tensile Strength (MPa)	Voids (%)	Bitumen content on the weight of Agg. (%)
Neat Bitumen	1.11	6.2	5.68
Graphene-based modifier	1.50	5.5	6.02
Comparison	+35 %	-11%	+6%

3.3. Indirect Tensile Stiffness Modulus (ITSM)

Knowledge of the "stiffness" of a bituminous mixtures is obviously a key element for the analysis and "rational" structural design of flexible pavements. Hence, "stiffness modulus" has been considered as the most appropriate parameter for the mechanical characterisation of asphalt mixes [11]. Within the literature, it has been found that the ITSM test results can be also considered as an indicator of load distribution capability of an asphalt pavement layer [12]. In addition, the test is usually conducted at different test temperature studying the thermal sensitivity of the asphalt mixes [13].

For the present work, the test was carried out following EN 12697-26 at three levels of temperatures: 5, 20, and 40˚C representing low, medium, and high-temperature conditions, respectively. It is worth mentioning that, the test has been done at frequency of 2Hz and 124±4 was the load raising time. According to the results shown in Figure 8 it can be seen that at all the test temperatures the mixture modified with graphene-based super modifier showed the highest values. The modulus of the mixture containing graphene-based modifier at 40˚C was increased by 72% compared with neat bitumen mixture and that mixture containing polymeric compound modifier, and 30% compared to the SBS modified mixture. Considering these results, a higher resistance to permanent deformation for the mixtures containing graphene-based modifier is expected.

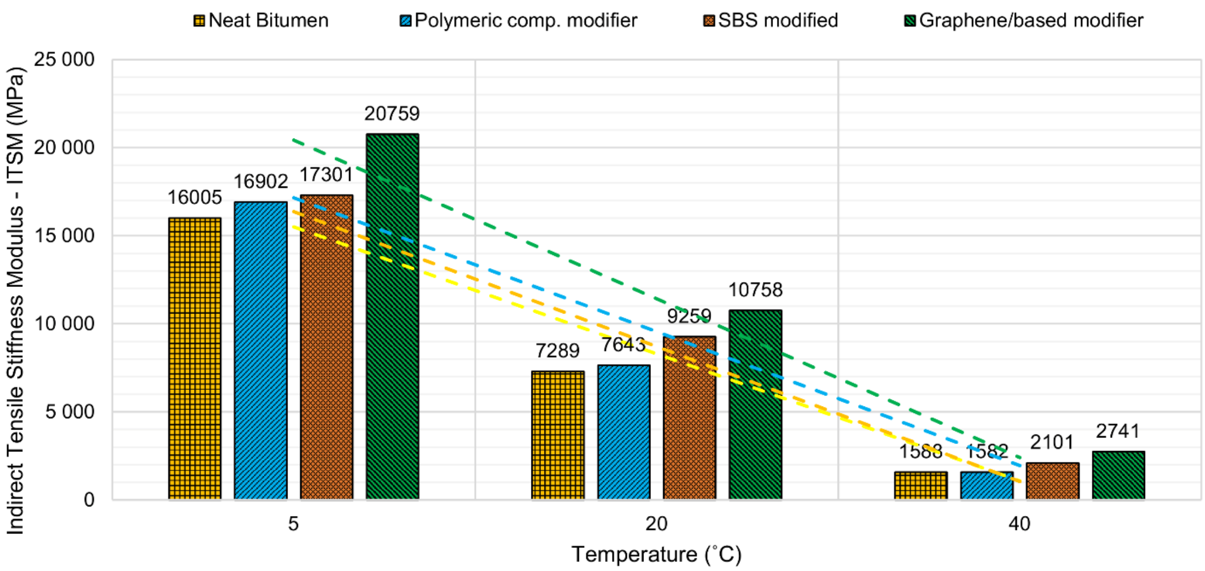

Figure 8: Indirect Tensile Stiffness Modulus (ITSM) at three levels of temperature

3.4. Resistance to Permanent Deformation

Considering the ever-increasing traffic loads and number of passes, rutting resistance has become a determinate factor for durable pavements in particular those in hot climates with average annual high temperature, where the distress gets more frequent. To date, for overcoming this problem several solutions have been introduced such as Stone Mastic Asphalt (SMA) mixtures with stone on stone skeleton and the application of modifiers/fibres for stiffening bitumen/asphalt mixtures.

In the present work, the resistance to permanent deformation of the mixtures was assessed by means of Wheel Track Device (WTD). The test was performed in accordance with European EN 12697-22 standard. For this purpose, rectangular specimens (slabs) were subjected to 30000 passes of a loaded-rubber wheel (700N vertical load) at a test temperature of 60°C. It should be mentioned that due to the high stiffness of the test mixtures at high temperature, the number of passes was increased to 30000 rather than common 10000 in most practices. For this test, the slabs (40 cm length, 30 cm width, 4 cm thickness) were prepared by using a roller compactor, applied according to EN 12697-33, at a defined geometric air voids content.

Figure 9, represents the achieved permanent deformation depth vs. the number of wheel pass. As it could be expected based on the previously obtained ITS and ITSM values, it can be seen that the graphene-based modifier improved significantly the resistance to permanent deformation compared to the reference mixture containing neat bitumen binder and also compared to other two differently modified ones. From another point of view, the recorded Proportional Rut Depth (PRD) after 30000 of passes are 3.72%, 4.27%, 4.11%, and 4.45%, which compared to the common threshold value in most of the local specifications (≤5%) shows an improvements regarding the permanent deformation resistance.

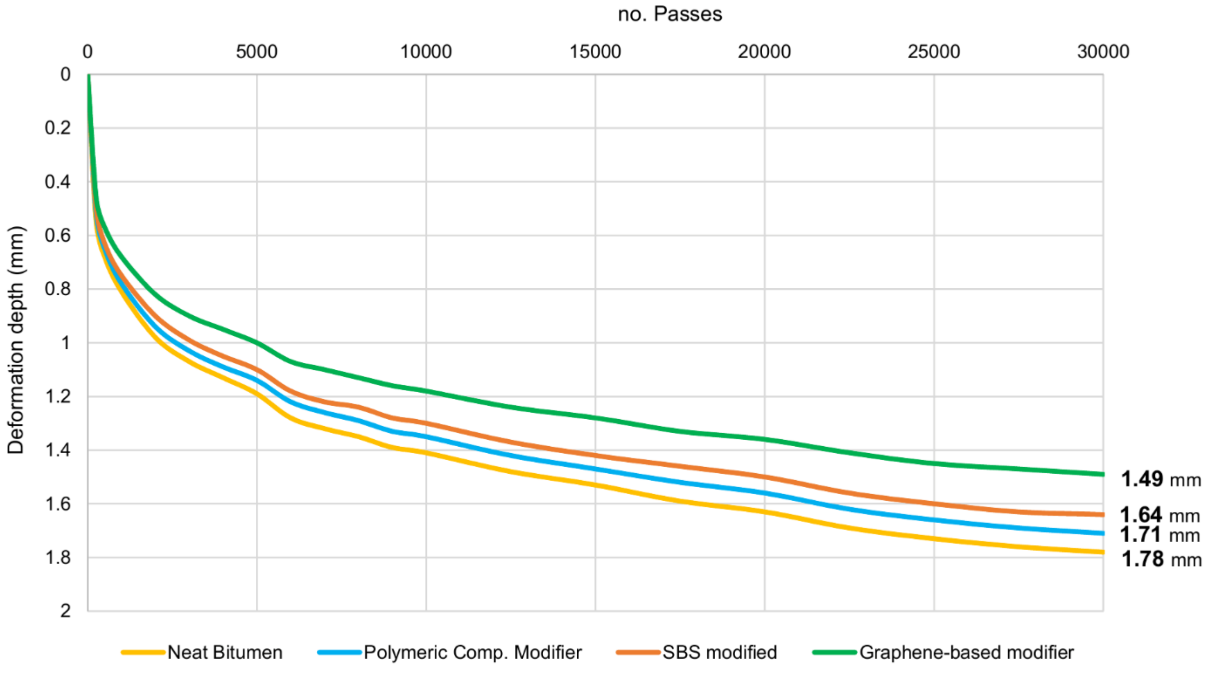

Figure 9: Permanent deformation vs. no. of passes

3.5. Fatigue Endurance

Fatigue is one of the main failure modes of the pavement structure, which results in degradation of the bond between pavement materials and finally the pavement structure. Two phases of degradation process occur during fatigue cracking. The first phase corresponds to degradation resulting from damage that is uniformly distributed throughout the material. This phase is manifested by the initiation and propagation of a network of ‘micro-cracks’ which results in a decrease in the macroscopic rigidity (stiffness modulus) of the material. The second phase starts with the coalescence of these ‘micro-cracks’ and the appearance of ‘macro-cracks’ which propagate within the material [14].

The knowledge of the fatigue behaviour of asphalt mixture is important in the mix design and evaluation of a highway and/or airport pavement, hence many test methods have been used to study the fatigue behaviour of asphalt mixtures.

However, the repeated-load indirect test, also known as Indirect Tensile Fatigue Test (ITFT) has been found a suitable method for assessing the fatigue characteristics of asphalt mixtures. Here, ITFT was carried out according to European EN 12697-24 standard and under stain control condition. The results shown in Figure 10 represents the fatigue endurance of the tested mixtures. According to the results it can be seen that at the medium level of stress the mixture containing graphene-based modifier performed better compared to other mixtures. For instance, considering the stress level of 250kPa, the Number of cycles to failure (N_f) for Graphene-based modified mixture, polymeric compound modified mixture, SBS modified mixture and the neat bitumen mixture were: 410 080, 255 847, 135 122, and 52 312, respectively.

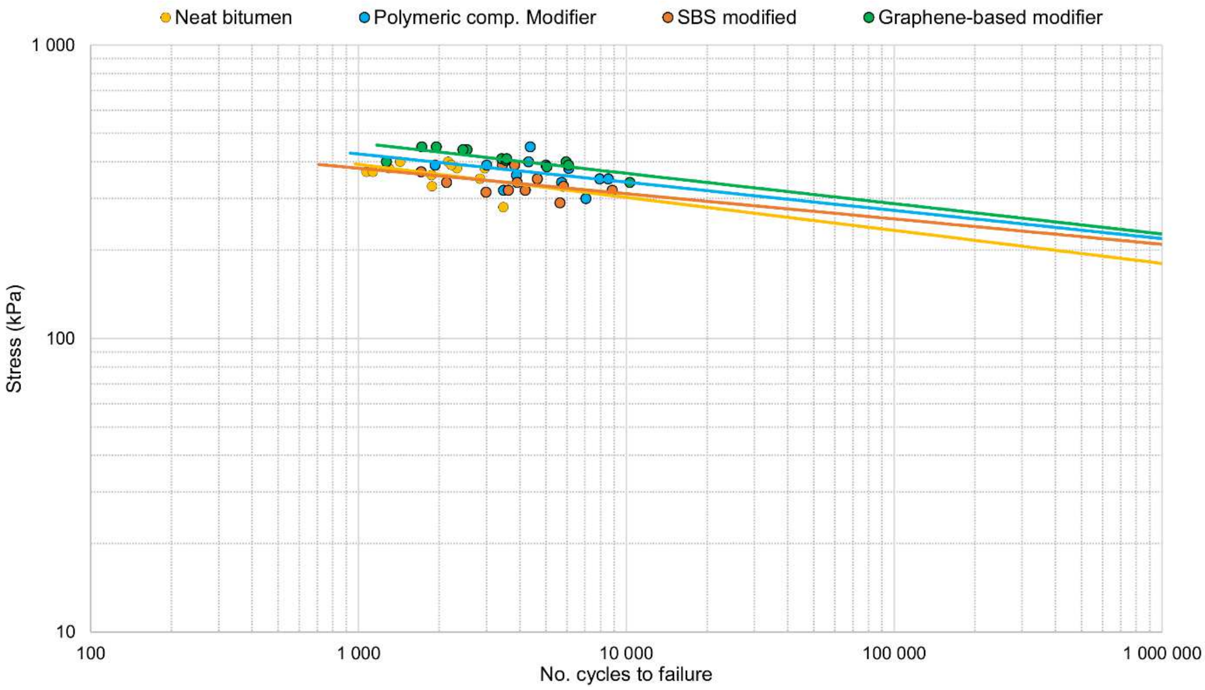

Figure 10: Fatigue endurance performance

4. Conclusions

This paper represents the test results of 4 different asphalt mixtures, which were obtained by an in-situ test and laboratory investigations on the specimens produced of asphalt mixture samples from a laid trial section. The authors aimed for comparing the performance of an innovative graphene-based asphalt modifier with commonly used SBS modification and a mixture of containing a polymeric compound of elastomer and plastomer. Overall, the results showed the superiority of the mixtures containing the graphene-based asphalt modifier compared to other tested mixtures. These results were in line to the early stage experimental works in the laboratory, which shows the validity of the obtained data. Followings are some of the highlights, which were notified during this study:

- HWD in situ test results showed almost double elastic moduli for the asphalt layer containing graphene-based modifier compared to the mixture made with neat bitumen. It is noteworthy that these obtained results were also more consistent when compared to the test results of other three mixtures.
- ITS test showed 35% increase in tensile properties for the mixture containing graphene-based asphalt modifier compared to the mixture made with neat bitumen.
- Thermal sensitivity and load distribution properties of the mixtures were investigated by means of ITSM test. According to the results, the addition of graphene-based modifier increased the ITSM values at all the tested temperature range. The superiority of this mixture up to+70% compared to other mixtures at high temperature, makes this product very suitable particularly for heavy-duty pavements and/or pavements, which are subjected to high temperature.
- The addition of graphene-based modifier to the asphalt mixture resulted in higher resistance to permanent deformation compared to the reference mixtures.
- The resistance to Fatigue of the mixtures was compared by means of ITFT. According to the results, it was found out that at the medium level of stress (e.g. 250kPa), which is frequently considered as for testing fatigue properties the graphene-based mixture performed better than other tested mixtures.

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