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EFFECT OF PLASTIC WASTE ON THE MECHANICAL PROPERTIES OF ASPHALT CONCRETE

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Abstract: Plastic trash is given value when it is used as a bitumen extender and mixed in with the asphalt concrete during production. Additionally, this form of polymer can enhance several mechanical features of asphalt concrete without significantly reducing its workability and other mechanical attributes. The study used various plastic contents added through the dry process to solve these difficulties for four distinct types of plastic trash and compared the outcomes to a traditional combination devoid of plastic. The workability and mechanical behaviour of the investigated materials were evaluated by a series of laboratory tests, including volumetric parameter assessment, the Marshall, gyratory compactor, and indirect tensile tests, repeated four-point bending, and repetitive compression. The findings demonstrate that while the inclusion of plastic garbage decreases workability, the asphalt concrete nevertheless maintains favourable handling characteristics. When plastic trash is added to asphalt concrete, the material becomes more elastic and has stiffness values that are suitable for use as a top layer of pavement. The asphalt mixes under study have a satisfactory level of resistance to fatigue cracking. Although the performance varied according on the plastic type and content, adding the waste plastic to the research typically enhanced resistance to permanent deformation.
Keywords: dry process; mechanical performance; plastic waste; workability.

1.Introduction

The European Union's member states have adopted rising landfill regulations for plastic waste, according to Plastics Europe [1]. Additionally, they are supporting initiatives made by the plastic industry and other industries to give these byproducts more value. Implementing Between 2006 and 2018 there was a 44% drop in the amount of plastic garbage dumped in landfills as a result of these measures [1]. However, the information that is currently available indicates that in 2018, landfills in European member states received more than 7.2 Mt of plastic garbage. In Portugal, plastic from packaging was recycled 36% in 2019, but just 11% of the plastic was recycled into new packages in 2020 [2]. The situation demonstrates that there is still a long way to go in terms of reducing the usage of plastic and the commercialization of plastic waste in this business and others. Consequently, it has been determined that adding plastic trash to asphalt mixes for highway paving is a problem.

potential, which has been heavily researched over the past 10 years [3-9]. The opportunity can be seen in a number of ways, including the potential to enhance the properties of bituminous mixtures, the cost savings from using less expensive polymers to enhance bitumen's rheology, the simplicity of use when plastic waste is added directly to the plant during the so-called dry process of making asphalt concrete, and the potential to add value to large amounts of plastic waste rather than disposing of it in landfills (circular economy). However, there are also worries over the possibility for the formation of microplastics and additional emissions when plastic trash is mixed with asphalt concrete. There is a chance that the pavement will release plastic particles ranging in size from a few nanometers to 5 mm [10], which can be dangerous to the health of people and other animals [11]. The scientific community is presently evaluating these microplastic-related problems [12,13]. It must be emphasised, however, that several investigations have found microplastics in road dust coming from a variety of sources, even when asphalt components don't include plastic waste [14–16]. In comparison to virgin polymers and natural aggregates, the results of using plastic waste as a polymer for bitumen modification and as a substitute for aggregate in asphalt concrete indicate the possibility of achieving environmental benefits [17]. According to studies done so far, the performance of asphalt mixtures containing plastic waste depends on a number of factors, including the plastic's type [18] and content [19,20], the temperature and time of mixing [18], and the production method (dry—plastic waste is added while mixing all the constituents, or wet—plastic waste is combined with bitumen before mixing) [21].

The dry technique is simpler than the wet process since the bitumen and the waste plastic don't need to be mixed with specialised machinery like bitumen stirrers. However, plastic waste can be used to act as a bitumenextender polymer rather than being used as a replacement for some of the mineral aggregates as is customary in the dry process. Even though it is added during the mixing process, after all the components have been mixed, the goal in this case is to enhance the performance of the asphalt concrete [22]. During mixing and transportation, the plastic and bitumen interact at the production temperature. The plastic can absorb some of the lighter components of bitumen if the temperature is high enough [23]. Furthermore, even after high-shear mixes, some polymer wastes, such as low-density polyethylene (LDPE), have a tendency to separate in storage. These wastes are difficult to diffuse into bitumen in the wet process [12,24]. In order to lessen those issues, methods like chemical stabilisation, chemical functionalization of the polymer, or binder mixing at the asphalt concrete plant (dry process) are advised [4,12]. The fact that asphalt concrete made using the dry or wet processes often has equal volumetric characteristics and mechanical performance must also be emphasised [3,25]. The wet process's production of plastic-modified bitumen was taken into account in the majority of research on the usage of plastic waste. On the basis of the rheology of the changed binder, they projected the mechanical behaviour of asphalt mixtures [26–29]. On the other hand, this study attempted to assess the asphalt concrete after the addition of plastic waste through the dry process as a bitumen extender. As a result, rather than inferring it from bitumen rheology, the mechanical behaviour of the asphalt mixtures was assessed utilising performance tests over the mixes (cracking and permanent deformation resistance, and water sensitivity). Designing pavement layers with plastic waste-modified asphalt concrete is essential because this material differs from standard asphalt concrete in several important ways. In this investigation, four distinct forms of plastic waste—ABS (acrylonitrile butadiene styrene), HDPE (high-density polyethylene), HDPE500, and LDPE(uw)—were studied as they were used in asphalt concrete. The laboratory setup allowed for the conclusion that, if the handling temperature and amount of plastic waste supplied are insufficient, the types of plastic waste provided as bitumen extenders may affect the workability of the asphalt concrete. Aside from thatThe mix-design methods should be based on fundamental testing including mechanical performance assessment since the level of uncertainty of the materials' behaviour is higher than typical.

2. Materials and Methods

2.1. Bitumen and Aggregates

A typical 35/50 penetration grade bitumen was used as the asphalt binder to create the asphalt mixes. According to EN 1426 [30] and EN 1427 [31], this binder has a penetration of 45 0.1 mm at 25 °C and a softening point of 52 °C. The smaller aggregate fractions (crushed sand 0/4 and filler) were made from crushed limestone rocks, in contrast to the coarser aggregate fractions (8/20 and 4/12), which were made entirely of crushed gneiss particles. Gneiss 8/20: 15%; Gneiss 4/12: 36.4%; Limestone Sand 0/4: 45.6%; and Limestone Filler: 3% were the percentages of the granular fractions in the mix of aggregates. The resulting gradation for the surface pavement layers (AC 14 surf 35/50) is shown in Figure 1 superposed to the gradation limitations specified in the Portuguese specification [32].

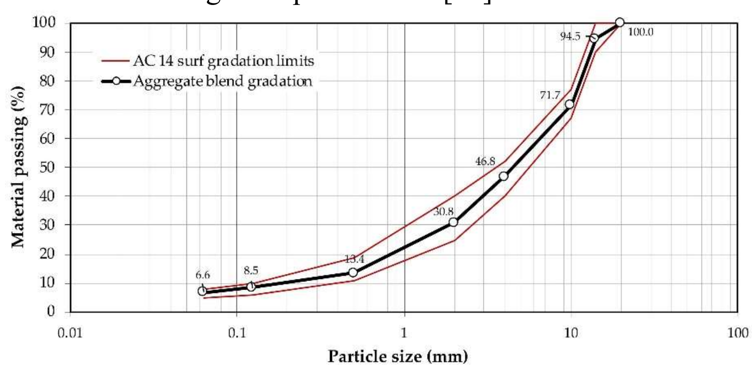

Figure 1. Grading of the aggregate's mixture and specification gradation limits.

Table 1. Physical properties of aggregates and specifications requirements.

Property	Standard	Units	Gneiss 8/20	Gneiss 4/12	Sand 0/4	Filler	Limit
Flakiness index (FI)	EN 933-3 [34]	%	FI15	FI15	—	—	FI20
Resistance to fragmentation: Los Angeles (LA)	EN 1097-2 [35]	%	LA_{20}	LA_{20}	—	—	LA_{30}
Reistance to wear: micro-Deval (M_{DE})	EN 1097-1 [36]	%	$M_{DE}10$	$M_{DE}10$	—	—	$M_{DE}15$
Polished stone value (PSV)	EN 1097-8 [37]	%	PSV_{50}	PSV_{50}	—	—	PSV_{50}

Water absorption (WA)	EN 1097-6 [38]	%	0.5	0.6	0.6	—	$WA_{24}1$
Assessment of fines: methylene blue (MB_F)	EN 933-9 [39]	g/kg	—	—	MB_F10	MB_F10	MB_F10
Voids of dry compacted filler (ν)	EN 1097-4 [40]	%	—	—	—	32	$^{v}28/38$
Delta ring and ball (˚C)	EN 13179-1 [41]	◦C	—	—	—	14	ΔR&B

Note: According to the European standards (EN), the requirements for each parameter are indicated through acronyms and numbers that represent one of the categories considered in EN 13043 for aggregates.

2.2. Plastic Waste

The various plastic waste kinds that were utilised as polymers in this experiment were gathered at a special recycling facility that collects plastic trash from various sources (including municipal and industrial sources). This facility sorts the plastic trash into several categories, cuts the components into a certain gradation, washes, dries, and extrudes the material to create pellets. To minimise the cost of recycling and the emissions related to energy use, the plastic debris used in this study was collected right before the pellets were made. ABS (acrylonitrile butadiene styrene), HDPE (high-density polyethylene), HDPE500 (a less expensive alternative to the standard HDPE for less demanding situations in terms of wear resistance and impact), and LDPE (uw) (low-density polyethylene from urban waste) are the four types of plastics used in this study. LDPE and HDPE typically have melting points of around 120 and 140 C, respectively.

Since ABS is an amorphous polymer, it lacks a true melting point but instead transitions from a glassy to a rubbery state at a temperature of around 100 °C (glass-transition temperature).

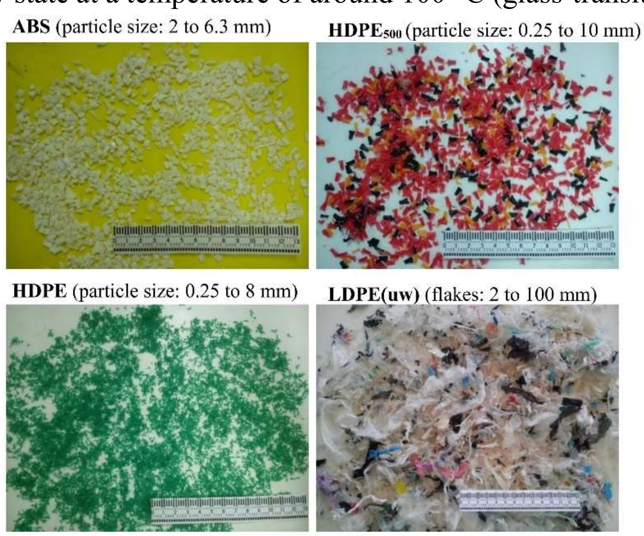

Figure 2. Types of plastic waste used as polymers in the studied asphalt mixtures in the present study.

2.3. Methods

2.3.1. Experimental Plan

A conventional asphalt concrete (AC 14 surf 35/50) was used as a reference mixture in Figure 3 to show how the experimental plan was carried out to assess the volumetric, workability, Marshall, and mechanical properties of all the mixtures under study. This mixture contained 5% bitumen by weight of the total mixture. The creation of mixes and the subsequent compaction of cylinder- and prism-shaped specimens as outlined below were necessary for the plan's execution.

2.3.2. Manufacture of Asphalt Mixtures and Production of Specimens

The experimental strategy began with the creation of the asphalt mixtures in a heated planetary mixer in accordance with EN 12697-35 [42]. Each type of plastic waste was added in addition to the reference mixture to create three different blends by taking the place of 4%, 6%, and 8% of the bitumen mass with plastic trash, respectively. The study entailed evaluating 13 distinct compositions in all. The so-called dry technique, which entails adding plastic debris to the mixer bowl throughout the production process, was used to create the combinations. The temperature while mixing ranged from 165 to 170 C.

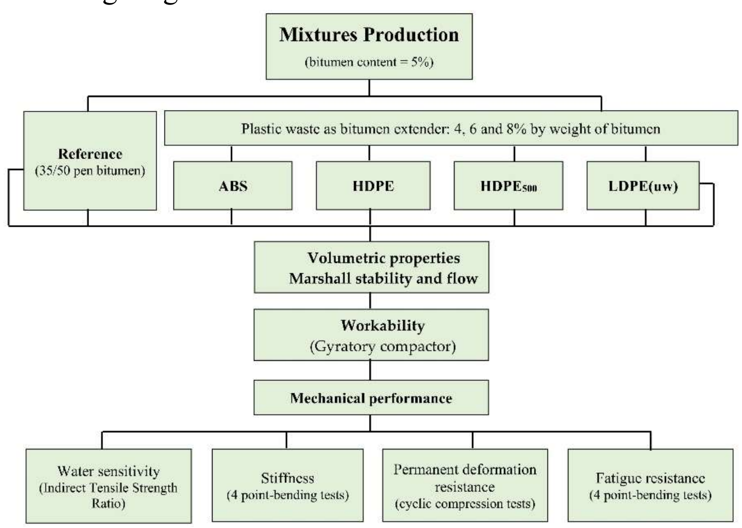

Figure 3. Experimental plan carried out in the study.

2.3.3 Volumetric characteristics, Marshall stability, and flow

Based on the measurements made for density (EN 12697-9 [47]) and maximum density (EN 12697-5 [48]), the void content (EN 12697-8 [46]) and voids in the mineral aggregate (VMA) of four Marshall cylindrical specimens per mixture composition were evaluated. The volumetric characteristics of the materials relative to the reference mixes are anticipated to change as a result of adding plastic trash to the asphalt mixtures. For the identical specimens at 60 °C, the Marshall compression test (EN 12697-34 [49]) produced findings for the Marshall stability and flow.

2.3.4. Workability

To assess the workability of asphalt mixes, a well-known methodology is the examination of compaction curves from a gyratory compactor. The number of rotations imparted to the mixture within a cylindrical mould grows along with a corresponding rise in bulk density. As the number of gyrations rises, workability is then evaluated based on the bulk density of asphalt mixes. These compaction curves were modelled based on EN 12697-10 [50], a standard. These curves were utilised to calculate the slope of the compaction curve, k, as well as the air void content for one gyration, v(1).

2.3.5. Mechanical Performance

According to EN 12697-23, indirect tensile strength (ITS) at 25 °C made it possible to determine the examined asphalt mixes' water sensitivity [52]. According to EN 12697-12 [53], the ratio (ITSR) between the ITS of wet specimens and the ITS of dry specimens was measured using both specimens subjected to conditioning in water (referred to as "wet") and specimens not exposed to those circumstances (referred to as "dry"). Four-point bending tests carried out in accordance with EN 12697-26 were used to determine the stiffness and phase angle of the asphalt mixes under study [54]. This analysis did not take into account the mixing with HDPE500 and was only done for 6% of plastic content. This bending test was performed at 20 °C with a controlled displacement (strain level of 50 m/m).

3. Results

3.1. Evaluation of Volumetric Properties

The findings for the reference asphalt combination and the asphalt mixes with the highest void content and VMA (average of four Marshall specimens) are shown in Figure 6. distinct amounts of bitumen in four distinct forms of plastic garbage. For VMA, the Portuguese standard for asphalt mixes calls for a minimum of 14%. For a standard AC 14 surf 35/50, the required void content ranges from 3% to 5%. With the exception of LDPE(uw), the findings indicate that integrating plastic waste has no impact on the VMA and void content up to 4% of plastic content by mass of binder. It must be emphasised, nonetheless, that the binder accounts for somewhat less than 5% of the mixture's mass, while the 4% plastic ingredient makes for just 0.2% of it. Moreover, The results might also be impacted by the polymers' rigidity and particle sizes.

The voids in the asphalt mixture and, as a result, the VMA values, are likely to rise with coarser plasticgrains (e.g., HDPE: 0.25 to 8 mm; HDPE500: 0.25 to 10 mm). Higher temperatures are necessary for HDPE and HDPE500 to soften. Therefore, a greater viscosity of the bitumen-plastic mix may occur for 6% and 8% of plastic content. Increased gaps between the particles result from thicker binder films around aggregates created by more viscous binders.

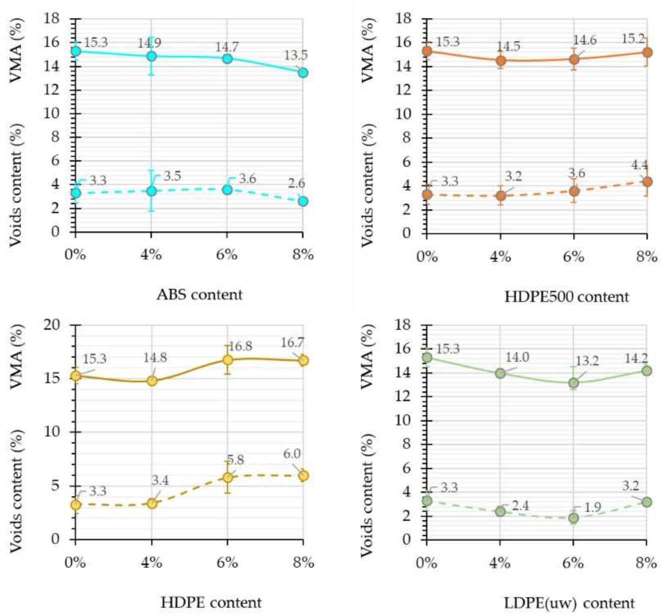

Figure 6. Variation of volumetric properties with the plastic waste content.

3.2. Marshall Stability and Flow

The results of the Marshall compression tests, stability tests, and flow tests (average of four Marshall specimens) for the asphalt mixes being tested are shown in Figure 7. The outcomes demonstrate that adding various plastic wastes to asphalt concrete improves the stability values. All of the mixes under study showed this tendency, however the rise was most obvious in specimens with 4% ABS and HDPE500. The stability of HDPE and LDPE(uw) typically improved with plastic content.

The findings precluded drawing definitive conclusions about the combined impact of plastic waste's gradation or stiffness on flow variance and stability. There is also the impact of the air void content, which is typically regarded as a crucial factor in the Marshall.

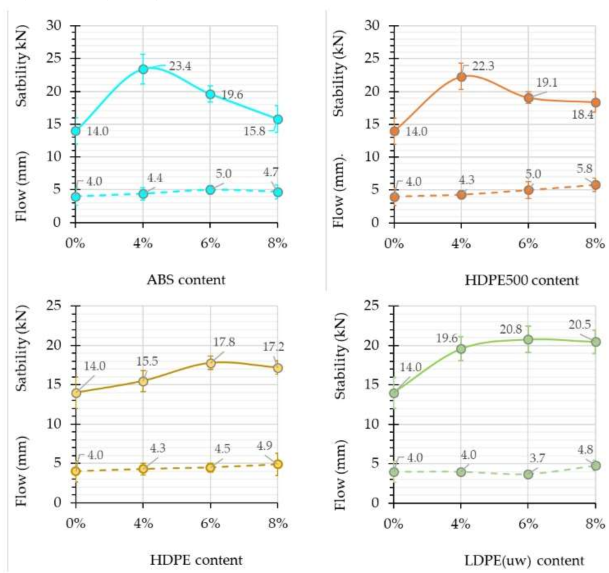

Figure 7. Marshall stability and flow as a function of plastic waste content.

3.3. Workability

The ease of putting down and compaction of standard asphalt concrete may be affected by the addition of plastic garbage (average of two gyratory compactor specimens). The findings for the indicators v(1), k, and CEI are evaluated in Figure 8, and they are particularly significant in the circumstances under consideration since the additional polymers are expected to negatively impact the mixes' overall workability.

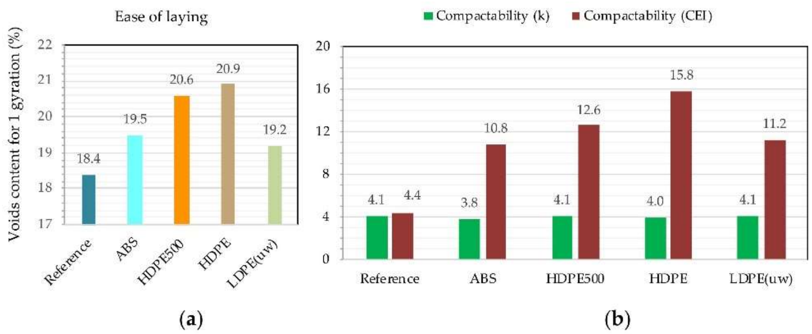

Figure 8. Workability of reference and asphalt concrete with 6% of different plastic waste used as additives: (**a**) ease of laying and (**b**) compactability based on *k* and *CEI*.

The findings show that adding plastic debris decreases the workability of the asphalt mixes. In general, the viscosity of the binder increases as the plastic component decreases, making the mixes harder to work with. The results for the 6% plastic content show this propensity. The viscosity of the binder in LDPE (uw) flakes is most likely to only slightly increase in comparison to the 35/50 pen bitumen used as a reference. This occurs because the LDPE (uw) flakes need to melt much below the temperatures at which the mixes are created. As a result, Figure 8 shows that the lay-down operation won't be significantly hampered by the addition of LDPE(uw). The authors' experience in the laboratory revealed that combinations of other plastic kinds, which soften at higher temperatures, take a bit more effort to lay-down.

3.4. Water Sensitivity

Figure 9 (mean of three-cylinder specimens) shows the indirect tensile strength (ITS) values for the dry and wet specimens as well as the ITS ratios. There is no proof that the kind of plastic or its concentration affects the ITS ratings of asphalt mixes. While ABS only enhanced ITS to 4% and 6% of plastic content, HDPE and LDPE(uw) increased the ITS values measured for the reference combination on unconditioned specimens. The additional plastic debris did not enhance ITS in wet circumstances. Because the reference combination had a good ITSR performance (ITSR about 110%), adding plastic waste polymers made it difficult to increase water resistance. When the moisture resistance is excellent, as it was in this instance, the usual variance of the ITS findings may provide values of ITSR exceeding 100%, especially if the testing temperature is 25 ◦C. Only in the instance of 6% HDPE500 did the value of ITSR fall short of the usual standards of 80%. Although the water sensitivity performance of the asphalt mixes including plastic waste was good compared to the usual criteria, ABS and HDPE500 had plastic concentrations exceeding 6% that are likely to lower the ITS values.

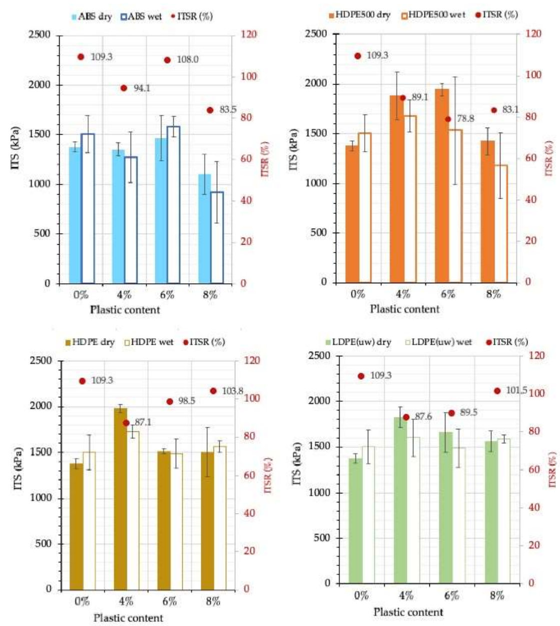

Figure 9. Indirect tensile strength (ITS) in dry conditions and ratio between ITS measured on wet and dry specimens (ITSR) as a function of plastic waste content.

3.5. Stiffness and Phase Angle

Figure 10 displays the stiffness and phase angle measurements made for the reference and modified asphalt mixes with 6% by mass of plastic trash.

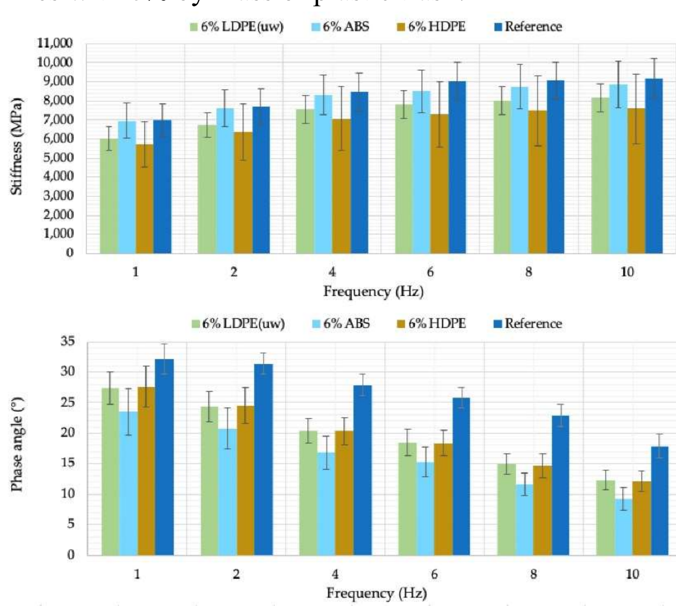

Figure 10. Stiffness and phase angle results obtained from four-point bending tests at 20 ˚C as a function of the loading frequency.

When compared to the reference asphalt mixture, the stiffness measurement was reduced by the addition of plastic garbage. There is some indication that the plastics slightly increased the mixes' flexibility because of the reduced phase angle values. Based on the continuous decrease in stiffness values for all of the mixes with plastic waste, this tendency was also seen. Inhibiting the plastic-bitumen interaction and perhaps having a greater softening temperature, HDPE's properties can lower the stiffness values. The usual stiffness values at 20 °C, considering a traffic speed of 50 to 65 km/h (equivalent to frequencies of 8 to 10 Hz), must be emphasised. These values are in the range of 5200 to 7600 MPa. Consequently, the asphalt mixes including plastic trash showed good rigidity.

3.6. Fatigue Resistance

Figure 11 displays the findings of the fatigue resistance measured by the stresses required to cause specimens to fail after 1,000,000 loading cycles (6), 100,000 loading 5,000 loading cycles, and 10,000 loading cycles. The findings apply to asphalt mixes that contain 6% plastic waste by mass of bitumen. While LDPE(uw) does not enhance fatigue resistance under high strain levels, HDPE does. When ABS was added to the asphalt mixture, the behaviour was on par with or better than that of the original. With the exception of ABS, the values of 6, which correlate to lower levels of strain, did not significantly affect the asphalt mixes' resistance to fatigue cracking.

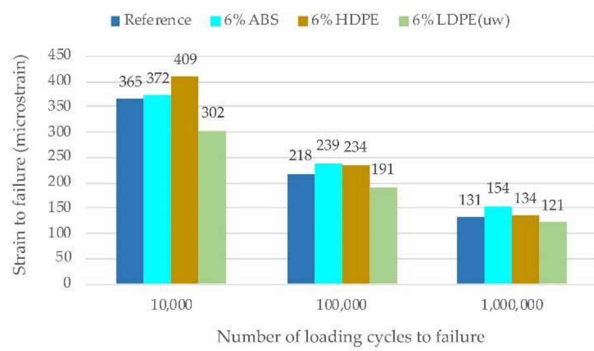

Figure 11. Comparison of tensile strain at 10,000, 100,000, and 1 million loading cycles used as a fatigue resistance indicator at 20 ˚C.

3.7. Permanent Deformation Resistance

The deformation curves for the cyclic compression tests are shown in Figure 12. The curves allow us to see the overall resistivity of the asphalt mixes even if they are not direct performance indicators. All of the mixtures with the same quantity of plastic waste showed higher deformation than the reference combination, with the exception of the one with 4% ABS.

Only the HDPE combination exhibited a larger deformation than the standard for the 8% of plastic waste. Absent the aforementioned exceptions, generally speaking, more resistance to deformation is anticipated the more plastic waste there is.

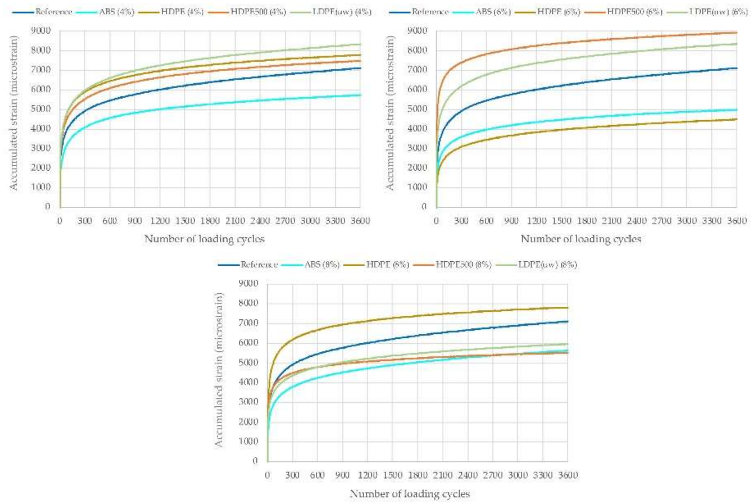

Figure 12. Variation of the accumulated permanent deformation measured in cyclic compression tests at 60 ˚C for both the reference and the asphalt concrete with different plastic wastes.

Figure 13 illustrates how plastic content affects how resistant asphalt mixes are to permanent deformation as determined by the cyclic compression test. We may give a variety of discoveries thanks to the results, even though there is no obvious conclusion. It was advantageous to increase ABS or HDPE from 4% to 6%, but from 6% to 8% was not. Only the 8% content in the cases of HDPE500 and LDPE(uw) shown an improvement in resistance.

The lower HDPE500 concentrations appear to be hazardous. To guarantee that the desired improvement is made, it is therefore convenient to study the percentage of plastic.

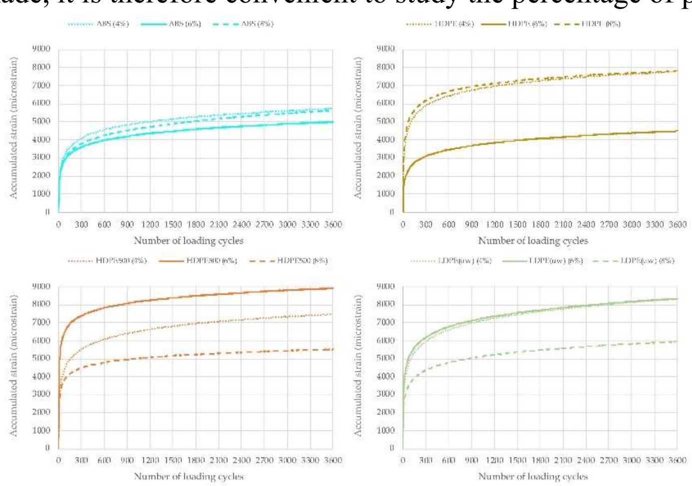

Figure 13. Influence of the plastic waste content on the accumulated permanent deformation measured in cyclic compression tests at 60 ˚C for the four types of plastic waste used.

4. Discussion

The most popular specifications frequently include volumetric property criteria without demonstrating how these requirements affect the mechanical performance of asphalt mixes. They assume that a certain set of values based on prior experience will produce suitable mechanical and workability attributes. However, with asphalt mixes using waste plastic as a binder modifier, this might not happen. That method of generating criteria is inappropriate since the properties of the additional polymer might differ significantly different asphalt mixes. Additionally, the conditions of mixing and compaction (temperature, compaction energy, type of bitumen and content, or type of aggregates, to name the most pertinent) affect how the components of asphalt mixes interact. Consequently, analysis of volumetric features should be combined with the evaluation.

4.1. Volumetric Properties, Marshall Results, and Workability

Although the LDPE (uw) mixture's air void measurements (Figure 6) fell below the 4% and 6% plastic waste content standards, the Marshall stability and good flow outcomes. Additionally, there seems to be a weak correlation between workability and air voids. According to the findings presented in Figure 8, the viscosity of the resultant binder and the kind of plastic appear to have a far greater impact on the workability of asphalt mixes than the volumetric attributes shown for the various mixtures with various plastic amounts.

Utilising 6% of plastic weight by the mass of bitumen is likely to have an impact on how easily something is laid down, according to the criterion used to measure ease of laying (Figure 8—void content for one gyration).

4.2. Stiffness and Phase Angle

ults. As was already established, a typical pavement surface layer may be predicted based on stiffness measurements made on mixes changed with plastic trash. Additionally, Figure 16 displays phase angle values are much lower for mixes with plastic waste than for the reference, ranging from roughly 9 degrees lower for ABS to 20 degrees lower for HDPE, at 10 Hz, for the same amount of stiffness. These findings indicate that adding plastic debris to asphalt mixtures makes them more elastic. It's noteworthy to note that, when compared to the reference, ABS exhibits almost the same phase angle difference (around 9 degrees) for all stiffness settings. The results for LDPE(uw) and HDPE, for which the lower stiffness values are associated with phase angle results that are around 8 degrees lower, do not follow this pattern. In comparison, with the higher stiffness levels, that difference is closer to 16 degrees. These findings suggest that LDPE(uw) and HDPE provide less of a contribution to elasticity when loading frequency (or loading speed) decreases. However, the elastic behaviour of the asphalt mixes is significantly influenced by the utilised forms of plastic trash.

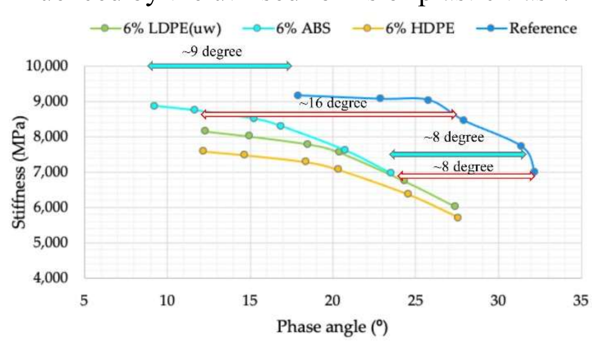

Figure 16. Black diagram derived from four-point bending tests at 20 ˚C.

4.3. Resistance to Fatigue

In addition to the fatigue resistance results previously reported, the most pertinent finding is that adding 6% of plastic waste to bitumen in the reference asphalt mixture maintains the fatigue resistance at a level that is acceptable for use in pavement layers. By using PET, several scientists [60, 61] showed improved asphalt mixture fatigue resistance. In contrast, experiments using LDPE (2.5% by weight of bitumen) [62] produced outcomes similar to those of the present study. The mixes with LDPE exhibited superior fatigue resistance than the reference during short-term ageing, despite the fact that LDPE has a negative impact on fatigue resistance [7].

4.4. Resistance to Permanent Deformation

The results demonstrate that the types of plastic trash employed in this experiment have substantial promise with regard to the resistance to permanent deformation of asphalt concrete. However, the kind and amount of the plastic will determine the resistance to permanent deformation that may be obtained. Therefore, a basic mix design that includes performance testing to support the choice on the composition of the asphalt mixture with permanent deformation resistance waste plastic. The research's findings are consistent with several contradictory findings for various forms of plastic garbage in the literature. For instance, Lastra-González et al. [63] found that adding polyethylene (PE) and polypropylene (PP) to the asphalt mixture enhanced permanent deformation whereas polystyrene (PS) decreased resistance. Improvements in rutting resistance were also discovered by Lastra-González et al. [64] and others [7,22].

5. Conclusions

The purpose of the study detailed in this paper was to assess the workability, Marshall characteristics, and mechanical performance of asphalt concrete containing plastic trash. (ABS, HDPE, HDPE500, and LDPE(uw)) are added during the dry process with the intention of partially replacing the bitumen. To compare the outcomes with the standard standards, the volumetric characteristics, Marshall stability, and flow were evaluated. The study went on to a performance-focused testing programme based on gyratory compactor tests and the core characteristics of the investigated blends.

The following conclusions are the result of the examination of the data from the laboratory testing plan:

- The volumetric qualities had far less of an impact on the asphalt mixes' workability than the type of plastic.
- No significant water sensitivity concerns for the asphalt concrete were found in the plastic kinds and contents employed.
- When compared to the reference asphalt mixtures (which did not contain plastic), the plastic waste-infused mixtures demonstrated suitable over the long period (up to 3 million ESALs), according to SUPERPAVE standards.
- The stiffness values provided by the asphalt mixes with plastic waste are appropriate for pavement surface layers.
- The elastic behaviour of the asphalt mixes was improved by the use of plastic trash.
- For all stiffness levels, ABS contributed nearly the same amount to the mixture's elasticity.
- The fatigue performance of the reference asphalt concrete was unaffected by the addition of 6% HDPE, ABS, or LDPE(uw).

- Globally, the reference was less resistant to permanent deformation than the asphalt concrete containing plastic waste. However, it must be emphasised that the performance varied depending on the kind and composition of the plastic as well as the performance parameter taken into account.
- With the exception of LDPE(uw), 6% and 8% of plastic waste tended to enhance resistance to permanent deformation the greatest.

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