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Influence of Plastic Waste on the Workability and Mechanical Behaviour of Asphalt Concrete

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Abstract: The use of plastic waste as a bitumen extender added throughout the manufacturing process of asphalt concrete contributes value to that type of waste. Moreover, this type of polymer can improve some mechanical properties of asphalt concrete without weakening its workability and other mechanical characteristics too much. The study aimed to address these issues for four types of plastic waste, using different plastic contents added by the dry process and compared the results with a conventional mixture without plastic. A set of laboratory tests, such as volumetric parameter evaluation, the Marshall, gyratory compactor, and indirect tensile tests, repetitive four-point bending; and repetitive compression, assessed the workability and mechanical behavior of the studied materials. The results show that, although the addition of plastic waste reduces workability, the asphalt concrete retains satisfactory handling conditions. By adding plastic waste, the asphalt concrete becomes more elastic, and the stiffness values of the material are adequate to apply the material in a pavement surface layer. The resistance to fatigue cracking was at a suitable level for the asphalt mixtures studied. Adding the plastic waste in the study generally improved resistance to permanent deformation, although the performance was plastic type and content dependent.

Keywords: dry process; mechanical performance; plastic waste; workability

Citation: Fonseca, M.; Capitão, S.; Almeida, A.; Picado-Santos, L. Influence of Plastic Waste on the Workability and Mechanical Behaviour of Asphalt Concrete. *Appl. Sci.* **2022**, *12*, 2146. https://doi.org/10.3390/app12042146

Academic Editor: Dario De Domenico

Received: 9 January 2022
Accepted: 15 February 2022
Published: 18 February 2022

1. Introduction

According to Plastics Europe [1], the European member states have been adopting increasing landfill restrictions to plastic waste. They are also supporting efforts to add value to those by-products within the plastic industry and other sectors. Implementing these policies has led to a reduction of quantities of plastic waste disposed in landfills, with a decrease of around 44% from 2006 to 2018 [1]. Nevertheless, the available data show that more than 7.2 Mt of plastic waste was sent to landfills in 2018 in European member states. In Portugal, the recycling rate of plastic from packaging was 36% in 2019, but the recycling into new packages was only 11% in 2020 [2].

The circumstances show that there is still a considerable way to reduce plastic use and the valorization of plastic waste in its industry and others. Therefore, the incorporation of plastic waste in asphalt mixtures for highway pavement has been identified as an opportunity, most intensely studied over the last decade [3–9]. The opportunity lies in several aspects: the potential to improve the properties of the bituminous mixtures, the cost reduction by using cheaper polymers to improve the rheology of bitumen, the ease of use when the plastic waste is added directly to the plant in the production process of asphalt concrete (so-called dry process), and the contribution to value to considerable quantities of plastic waste instead of disposing it in landfills (circular economy).

Nevertheless, there are some concerns about the potential for the production of additional emissions when plastic waste is incorporated in asphalt concrete and for the generation of microplastics. There is a possibility of the pavement releasing plastic particles, from a few nanometers to 5 mm in dimension [10], which can be harmful to human and other species' health [11]. These issues associated with microplastic are still under evaluation by the scientific community [12,13]. Despite that, it must be emphasized that several studies identified the presence of microplastics in road dust from different sources even when asphalt materials do not incorporate plastic waste [14–16]. The results on the use of plastic waste as a polymer for bitumen modification and as aggregate replacement in asphalt concrete show that there is potential to achieve environmental advantages compared to virgin polymers and natural aggregates [17].

The studies carried out so far show that the performance of asphalt mixtures incorporating plastics waste depends on several aspects, i.e., plastic type [18] and content [19,20]; temperature and time of mixing [18]; and production process (dry—plastic waste added while mixing all the constituents or wet—plastic waste combined with bitumen before mixing) [21].

The dry process is more straightforward than the wet process because there is no need to use special equipment, such as bitumen stirrers, to blend the bitumen and the plastic waste. Nevertheless, instead of using plastic as a substitute for part of the mineral aggregates as usual in the dry process, plastic waste can be added to work as a bitumen-extender polymer. In this case, it aims to improve the performance of the asphalt concrete, even if it is added in the mixing process when all the constituents are blended [22]. The plastic and the bitumen interact at the manufacturing temperature during the mixing and transport. If the temperature is high enough, the plastic can absorb some of bitumen's lighter components [23].

Moreover, some polymer wastes, such as low-density polyethylene (LDPE), are challenging to diffuse into bitumen in the wet process and tend to separate in storage even after high-shear mixes [12,24]. Therefore, techniques such as chemical stabilization, chemical functionalization of the polymer, or binder blending at the asphalt concrete plant (dry process) are recommended to reduce those problems [4,12]. It must also be emphasized that asphalt concrete produced by the dry or wet methods is generally comparable in its volumetric properties and mechanical performance [3,25].

Most studies on the use of plastic waste considered the use of plastic-modified bitumen produced via the wet process. They predicted the mechanical behaviour of asphalt mixes based on the rheology of the modified binder [26–29]. Differently, this study aimed to evaluate the asphalt concrete when plastic waste is added via the dry process as a bitumen extender. Therefore, the mechanical behavior of the asphalt mixtures was evaluated using performance tests over the mixes (cracking and permanent deformation resistance, and water sensitivity) instead of predicting it from bitumen rheology. A performance-based mix-design procedure is crucial for designing pavement layers with plastic-waste-modified asphalt concrete because this material is not conventional asphalt concrete.

This project involved the study of asphalt concrete incorporating four different types of plastic waste: ABS (acrylonitrile butadiene styrene), HDPE (high-density polyethylene), HDPE500, and LDPE(uw) (low-density polyethylene from urban waste).

The laboratory plan allowed the conclusion that the types of plastic waste added as bitumen extenders may reduce the workability of the asphalt concrete if the handling temperature and the quantity of plastic waste added are not adequate. In addition, since the level of uncertainty of the materials' behaviour is higher than usual, the mix-design procedures should be based on fundamental tests involving mechanical performance evaluation.

2. Materials and Methods

2.1. Bitumen and Aggregates

The asphalt binder applied to manufacture the asphalt mixtures was a conventional 35/50 penetration grade bitumen. This binder had a penetration of 45 × 0.1 mm at 25 °C (EN 1426 [30]), and a softening point of 52 °C (EN 1427 [31]).

The coarser aggregate fractions (8/20 and 4/12) consisted of 100% crushed gneiss particles, whereas the finer aggregate fractions (crushed sand 0/4 and filler) were obtained from crushed limestone rocks. The percentages of the granular fractions in the blend of aggregates were as follows: gneiss 8/20: 15%; gneiss 4/12: 36.4%; limestone sand 0/4: 45.6%, and limestone filler: 3%. Figure 1 shows the obtained gradation superposed to the gradation limits defined in the Portuguese specification [32] for surface pavement layers (AC 14 surf 35/50). Table 1 summarizes the aggregates' physical properties considered in the EN 13043 [33] and the Portuguese specifications' requirements.

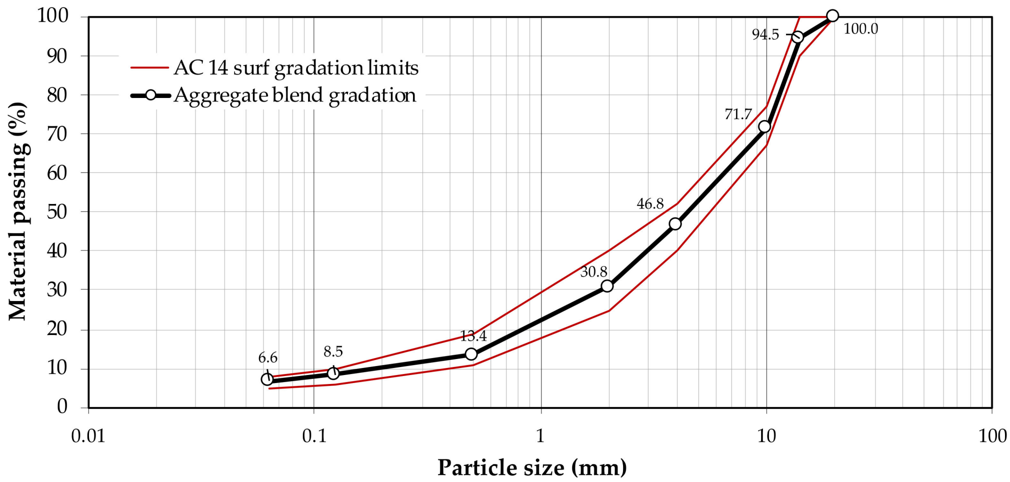

Figure 1. Grading of the aggregate's mixture and specification gradation limits.

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]	%	FI_{15}	FI_{15}	—	—	FI_{20}
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	$\nu_{28/38}$
Delta ring and ball (°C)	EN 13179-1 [41]	°C	—	—	—	14	$\Delta_{R\&B}$

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 different types of plastic waste used as polymers in this project were collected in a dedicated recycling facility that collects plastic waste from different sources (urban and industrial sources). After receiving the plastic waste, this facility separates the plastic types; trims the elements into a specific gradation; and washes, dries, and extrudes the material to produce pellets. The plastic waste applied in this study was collected just before the pellets' production to reduce the recycling cost and the emissions associated with energy consumption. Figure 2 shows the four types of plastics used in this study, namely, ABS (acrylonitrile butadiene styrene), HDPE (high-density polyethylene), HDPE500 (a cheaper 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). Typical values for the melting point of LDPE and HDPE are approximately 120 and 140 °C, respectively. Because ABS is an amorphous polymer, it does not have an actual melting point, but it changes from a glassy to a rubbery state (glass-transition temperature) at around 100 °C.

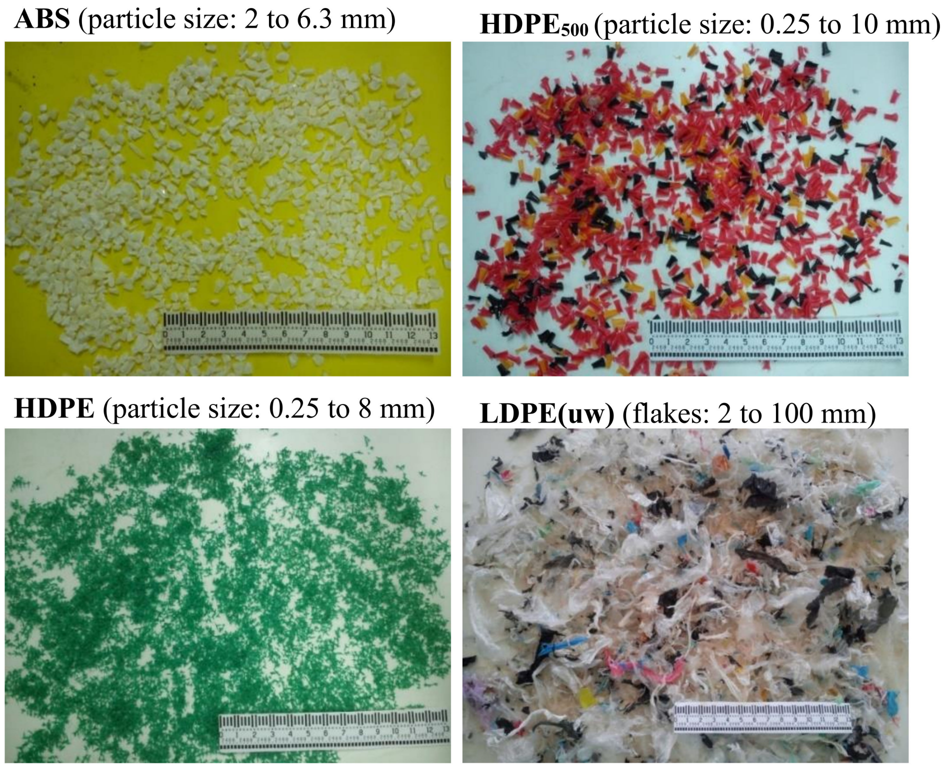

Figure 2. Types of plastic waste used as polymers in the studied asphalt mixtures in the present study.

2.3. Methods

2.3.1. Experimental Plan

Figure 3 illustrates the experimental plan carried out to evaluate the volumetric, workability, Marshall, and mechanical properties of all the studied mixtures, including a conventional asphalt concrete (AC 14 surf 35/50) as a reference mixture with 5% of bitumen content by weight of the total mixture. The plan's implementation required the production of mixtures and the subsequent compaction of cylindrical and prismatic specimens as described below.

2.3.2. Manufacture of Asphalt Mixtures and Production of Specimens

The experimental plan started with the manufacture of the asphalt mixtures according to EN 12697-35 [42] in a heated planetary mixer. Apart from the reference mixture, each type of plastic waste was incorporated to produce three alternative blends by replacing 4%, 6%, and 8% of the bitumen mass by plastic waste. In total, the study involved the assessment of 13 different compositions. The mixtures were produced by the so-called dry process, which consists in adding plastic waste into the mixer bowl during the manufacturing process. The mixing temperature varied between 165 and 170 °C.

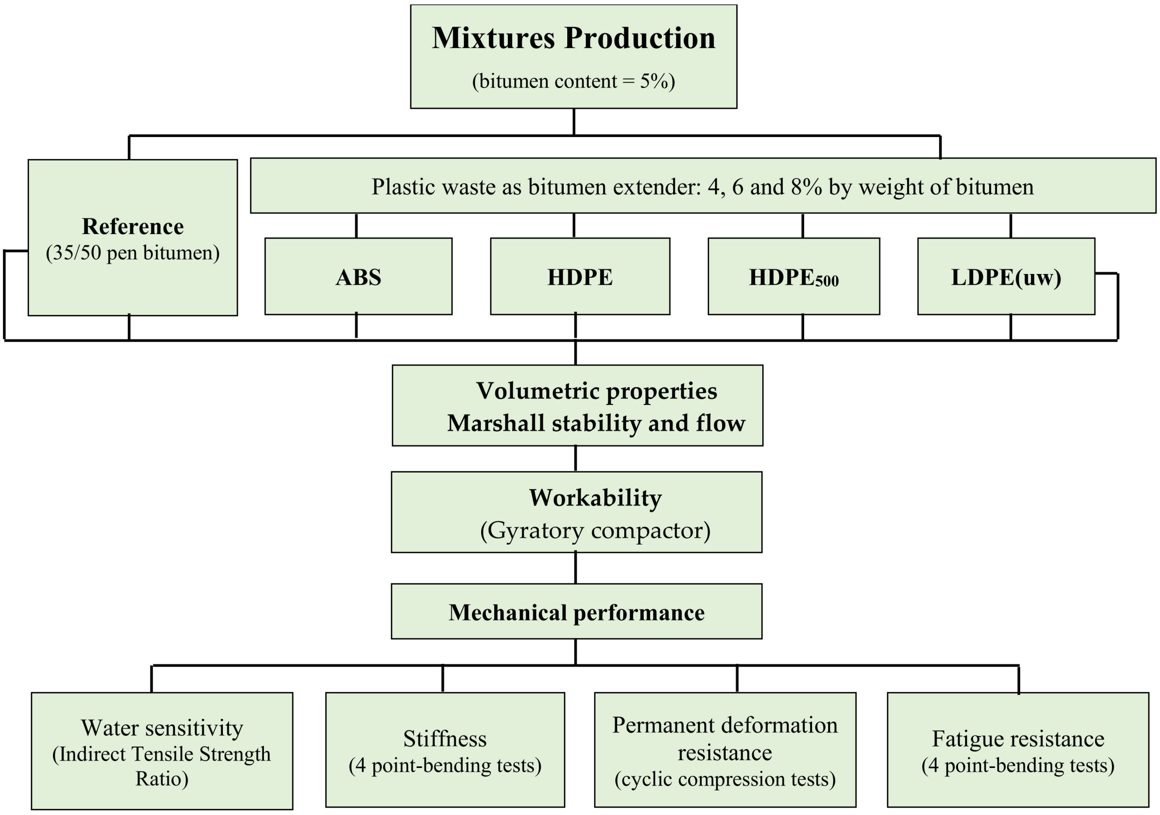

Figure 3. Experimental plan carried out in the study.

In the first stage of the study, the analysis of the mixtures' volumetric and Marshall properties was carried out on cylindrical specimens with 101.6 ± 0.1 mm diameter and 63.5 ± 2.5 mm height, compacted according to EN 12697-30 [43], by applying 75 blows to each face of specimens. For water sensitivity evaluation, the same type of specimens was used. Evaluating the mixtures' workability also required the production of cylindrical specimens in a gyratory compactor with a diameter of 150 mm and a height of 115 mm (EN 12697-31 [44]).

The study on permanent deformation resistance required moulding further cylindrical specimens, with a diameter of 150 mm and height of 60 mm. A vibrating hammer compacted the samples by applying from 2000 to 4000 pulses per min, according to the principles provided by EN 12697-32 [45]. The equipment's circular tamping foot was used for 1.5 min on each specimen's face. Laboratory prismatic specimens (400 × 52 × 52 mm^3) were cut from slabs compacted in a mould with a two-axle tandem-vibrating roller.

Figure 4 illustrates the production of mixtures and specimens used to evaluate volumetric properties and mechanical performance throughout the study.

2.3.3. Volumetric Properties and Marshall Stability and Flow

Four Marshall cylindrical specimens per mixture composition were assessed for their void content (EN 12697-8 [46]) and voids in the mineral aggregate (VMA) based on the values measured for density (EN 12697-9 [47]) and maximum density (EN 12697-5 [48]). Incorporating plastic waste into the asphalt mixtures is likely to influence the volumetric properties of the materials in comparison to those of the reference mixtures.

The Marshall compression test (EN 12697-34 [49]) provided results for the Marshall stability and flow for the same specimens at 60 °C.

(a) (b) (c) (d) (e)

Figure 4. View of the mixing procedure and production of specimens: (**a**) incorporation of plastic waste by the dry process; (**b**) compaction of slabs with a tandem roller; (**c**) compaction of cylindrical specimens with a vibrating hammer; (**d**) prismatic and cylindrical specimens to mechanical performance evaluation; (**e**) gyratory compactor and cylindrical specimen moulded.

2.3.4. Workability

The analysis of compaction curves from a gyratory compactor is a well-known methodology to evaluate the workability of asphalt mixtures. When the number of gyrations applied on the mixture inside a cylindrical mould increases, the bulk density of the material also increases. Workability is then assessed based on the bulk density of asphalt mixtures as the number of gyrations increases. These compaction curves were modeled according to the standard EN 12697-10 [50]. These curves were used to determine the air void content for one gyration, v(1), and the slope of the compaction curve, k.

The compaction energy index, CEI, is an energetic index also derived from the compaction curves to evaluate compactability. This parameter corresponds to the area under the curve between the eighth gyration and the gyration for which the density achieves 92% of the maximum density [51]. Lower values of CEI represent better compactability of the mixture because the necessary energy to achieve the pavement's void content requirements is also lower.

2.3.5. Mechanical Performance

Indirect tensile strength (ITS) allowed the determination of the water sensitivity of the studied asphalt mixtures, at 25 °C, according to EN 12697-23 [52]. Both specimens subjected to conditioning in water ("wet") and specimens not exposed to those conditions ("dry") were tested in the ITS to determine the ratio (ITSR) between the ITS of wet specimens and the ITS of dry specimens as indicated in EN 12697-12 [53].

The stiffness and phase angle of the studied asphalt mixtures were assessed from four-point bending tests following EN 12697-26 [54]. This evaluation was performed only for 6% of plastic content and did not consider the mixture with HDPE500. This bending test was carried out under controlled displacement conditions (strain level of 50 μm/m) at 20 °C, by applying frequency sweep sine wave loadings at 10, 8, 6, 4, 2, and 1 Hz.

The fatigue resistance of the blends was also evaluated in four-point bending tests following EN 12697-24 [55], carried out for the same compositions tested for stiffness. The tests were also performed at 20 °C in displacement-control conditions, applying repetitive sinusoidal loads with a frequency of 10 Hz and three strain levels (150, 250, and 350 μm/m). According to the applicable standard, 50% loss of the initial stiffness defined the number of loading cycles that leads the specimens to failure. A regression analysis performed over the tensile strain results versus the number of cycles was applied to determine the resistance to fatigue cracking parameters.

Permanent deformation resistance testing involved performing cycling compression tests following the procedure described in EN 12697-25 [56] at 60 °C. Although at the pavement surface the temperature may achieve values above 60 °C in hot climates, this value is representative of the highest possible in-service pavement temperature of wearing courses considering the use of in-service temperature prediction methods derived from air temperatures observed in Portugal [57]. Moreover, other tests used to assess permanent deformation resistance, such as the wheel-tracking tests according to EN 12697-22, are typically performed at 60 °C. However, it should be underlined that at 2.5 cm depth in a 5 cm wearing course formed by a conventional continuously graded asphalt concrete, a 60 °C temperature is sporadically reached. The specimens were subjected to a periodical loading pulse of 100 kPa, with a loading time of one second and a rest period with the same duration. The accumulated deformation was recorded by two vertical displacement transducers. The test consists in applying 3600 loading cycles on the specimen. However, the test finishes before that if the permanent deformation exceeds 4% microstrain. The loading plate used had a diameter of 100 mm. The slope of the deformation curve (fc) and the accumulated deformation up to the end of the test (ε3600) distinguish the resistance of the asphalt mixtures to permanent deformation. Figure 5 shows aspects of the mechanical performance tests performed throughout the study.

(**a**) (**b**) (**c**)

Figure 5. Mechanical performance tests: (**a**) four-point bending test; (**b**) indirect tensile strength test; and (**c**) cyclic compression test.

3. Results

3.1. Evaluation of Volumetric Properties

Figure 6 presents the results obtained for void content and VMA (average of four Marshall specimens) for the reference asphalt mixture and the asphalt mixtures with the four different types of plastic waste in different percentages of bitumen.

The Portuguese specification for asphalt mixtures requires a minimum of 14% for VMA. Regarding void content, the range requirement is 3% to 5% for a conventional AC 14 surf 35/50.

Except for LDPE(uw), the results show that up to 4% of plastic content by mass of binder, the effect of incorporating plastic waste on the VMA and void content is not substantial. However, it must be emphasized that 4% of plastic content corresponds to just 0.2% of the total mixture's mass and the binder represents a little less than 5%. Moreover, the particle sizes and the stiffness of some plastics used may also influence the results. Coarser plastic grains (e.g., HDPE: 0.25 to 8 mm; HDPE500: 0.25 to 10 mm) are likely to increase the asphalt mixture's voids and, consequently, the VMA values.

HDPE and HDPE500 require higher temperatures to soften. Therefore, for 6% and 8% of plastic content, higher viscosity of the bitumen-plastic blend may happen. More viscous binders cause a thicker film of binder around the aggregates, increasing the voids between the particles. Another possible phenomenon is the higher quantity of stiffer polymer that does not combine with bitumen because of its higher softening temperature.

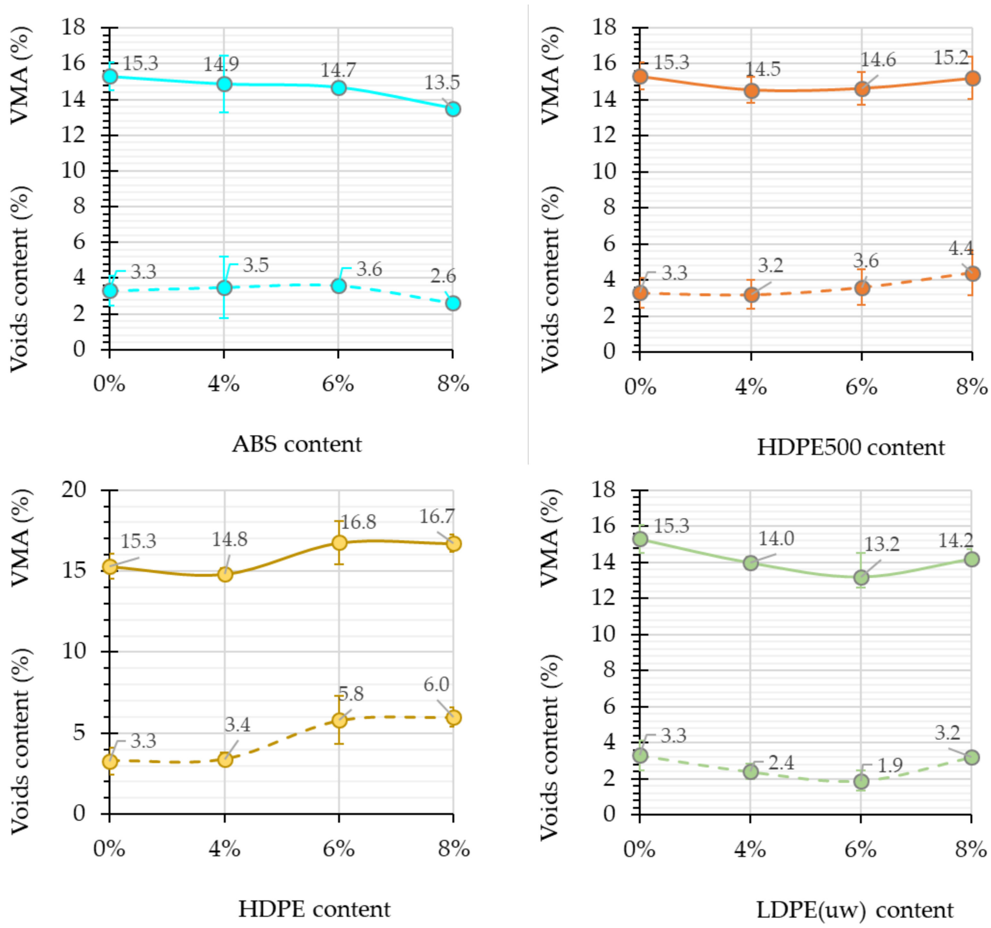

Figure 6. Variation of volumetric properties with the plastic waste content.

3.2. Marshall Stability and Flow

Figure 7 shows the results obtained in the Marshall compression tests, stability, and flow (average of four Marshall specimens), for asphalt mixtures under testing. The results reveal that different types of plastic waste incorporated in asphalt concrete increased the stability values. Although this trend was observed in all the studied blends, this increase was more visible for specimens with 4% of ABS and HDPE500. For the HDPE and LDPE(uw), stability generally increased as the plastic content increased.

The results did not allow absolute conclusions on the combined effect of gradation of plastic waste or its stiffness on the stability and flow variation. There is also the influence of the air void content, which is generally considered an important parameter in the results of the Marshall compression tests.

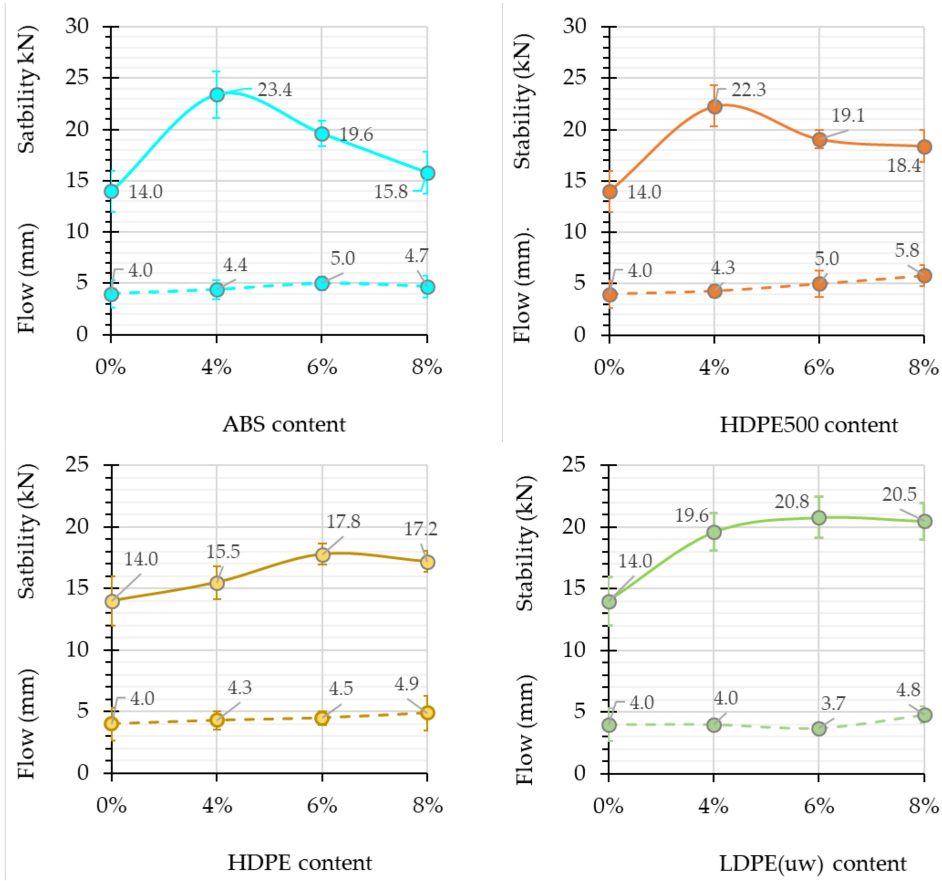

Figure 7. Marshall stability and flow as a function of plastic waste content.

3.3. Workability

Adding plastic waste to conventional asphalt concrete may reduce the ease of laying down and compaction of the mixtures (average of two gyratory compactor specimens). The results summarized in Figure 8 for the indicators ν(1), k, and CEI consist of evaluating those issues, which are particularly important in studied cases because the added polymers are likely to harm the general workability of the mixtures.

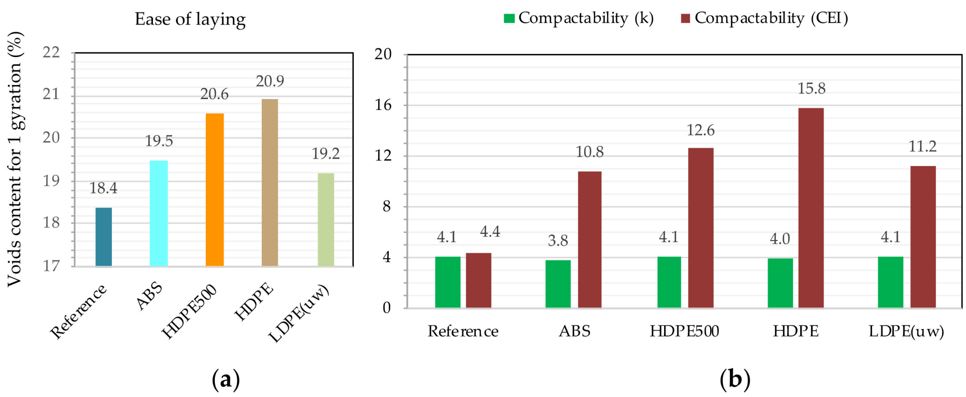

Figure 8. Workability of reference and asphalt concrete with 6% of different plastic waste used as additives: (**a**) ease of laying and (**b**) compactability based on *k* and *CEI*.

The results indicate that joining plastic waste reduces the asphalt mixtures' workability. Generally, the binder's viscosity rises as the plastic content increases so that the mixtures become less workable. The results presented for 6% of plastic content reveal that tendency. In LDPE(uw) flakes, the binder's viscosity is likely to suffer just a slight increase compared to the 35/50 pen bitumen used as reference. This happens because LDPE(uw) flakes melt at temperatures well below the mixing temperatures to produce the mixtures. Therefore, Figure 8 reveals that the lay-down operation will not be particularly impaired by adding LDPE(uw). The mixtures with the other plastic types, which soften at higher temperatures, require a little more effort to lay-down, which was proved by the authors' experience during the laboratory experiments.

3.4. Water Sensitivity

The indirect tensile strength (ITS) results for the dry and wet specimens and the ITS ratios are presented in Figure 9 (average of three cylindrical specimens). There is no evidence that both plastic type and content influence the ITS values of asphalt mixtures. HDPE and LDPE(uw) increased the ITS values measured for the reference mixture on non-conditioned specimens, whereas ABS only increased ITS to 4% and 6% of plastic content. For wet conditions, the added plastic waste did not improve ITS in dry conditions. Because the reference mixture has a good ITSR result (ITSR around 110%), improvements in resistance to water were hard to achieve with the incorporation of plastic waste polymers. As occurs in this case, when the moisture resistance is excellent, the normal variation of the ITS results may deliver values of ITSR above 100%, mainly if the testing temperature is 25 °C. Only for the case of 6% HDPE500, the value of ITSR was under the typical requirements of 80%. Although the asphalt mixtures with plastic waste had good water sensitivity performance compared with the typical requirements, in the case of ABS and HDPE500, plastic contents above 6% are likely to decrease the ITS values.

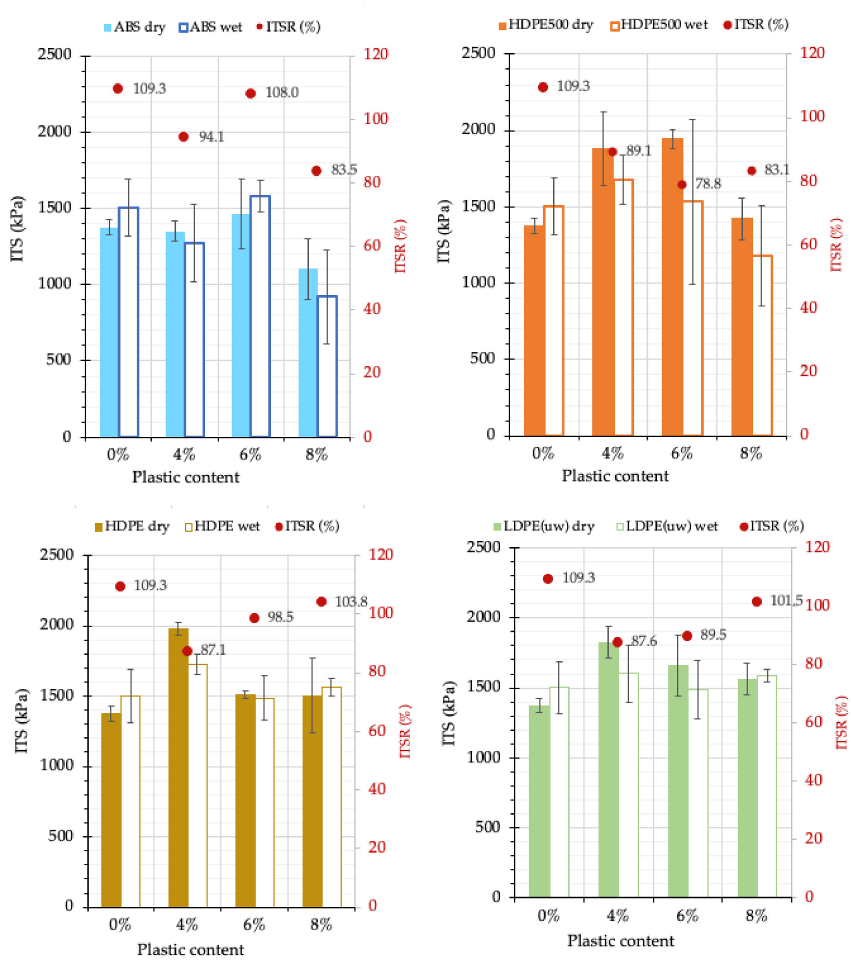

Figure 9. Indirect tensile strength (ITS) in dry conditions and ratio between ITS measured on wet and dry specimens (ITSR) as a function of plastic waste content.

3.5. Stiffness and Phase Angle

Figure 10 shows the values of stiffness and phase angles measured for the reference and modified asphalt mixtures with 6% of plastic waste content by mass of bitumen.

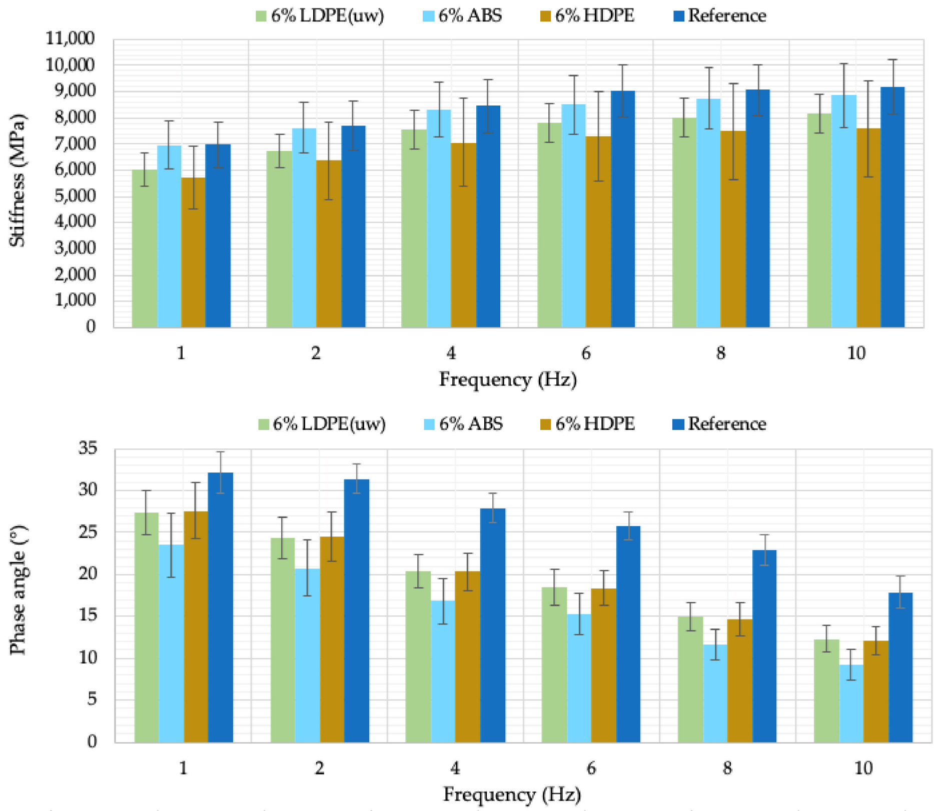

Figure 10. Stiffness and phase angle results obtained from four-point bending tests at 20 °C as a function of the loading frequency.

The incorporation of plastic waste decreased the measured stiffness compared to that of the reference asphalt mixture. With the lower phase angle values, there is some evidence that the plastics somewhat improved the mixtures' flexibility. This tendency was also observed based on the consistent reduction of the stiffness values for all the blends with plastic waste. Because HDPE has coarser gradation and possibly higher softening temperature, these characteristics can hamper the plastic–bitumen interface, thus reducing the stiffness values. It must be emphasized that typical stiffness values at 20 °C, considering a traffic speed from 50 to 65 km/h (comparable with frequencies of 8 to 10 Hz), are in the range of 5200 to 7600 MPa. Therefore, the asphalt mixtures with plastic waste presented good stiffness values, suitable for a pavement surface layer.

3.6. Fatigue Resistance

Figure 11 presents the fatigue resistance results represented by the strains needed to lead the specimens to fatigue failure after 1 million loading cycles (ε6), 100,000 loading cycles (ε5), and 10,000 loading cycles (ε4). The results refer to asphalt mixtures with 6% of plastic waste content by mass of bitumen.

For high strain levels, HDPE brings some increase of fatigue resistance, whereas LDPE(uw) does not. Joining ABS to the asphalt mixture led to a behaviour equal to or better than that of the unmodified one. Except for ABS, the values of ε6, which correspond to lower levels of strain, on incorporating plastic waste into the asphalt mixtures did not change notably their resistance to fatigue cracking. A significant feature is that incorporating 6% of plastic waste into the reference asphalt mixture does not jeopardize adequate fatigue performance, even when resistance to fatigue cracking slightly drops.

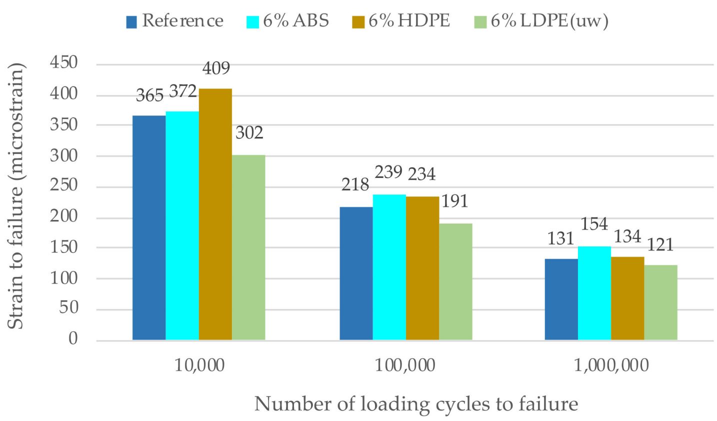

Figure 11. Comparison of tensile strain at 10,000, 100,000, and 1 million loading cycles used as a fatigue resistance indicator at 20 °C.

3.7. Permanent Deformation Resistance

Figure 12 presents the deformation curves for the cyclic compression tests. Although the curves are not direct performance indicators, they allow us to observe the general resistance of the asphalt mixtures. Apart from the mixture with 4% ABS, all the others with the same percentage of plastic waste revealed more deformation than the reference mixture. For 8% of plastic waste, only the mixture with HDPE had higher deformation than the reference. Apart from the exceptions mentioned, generally speaking, the more the plastic waste quantity, the more resistance to deformation is expected to occur.

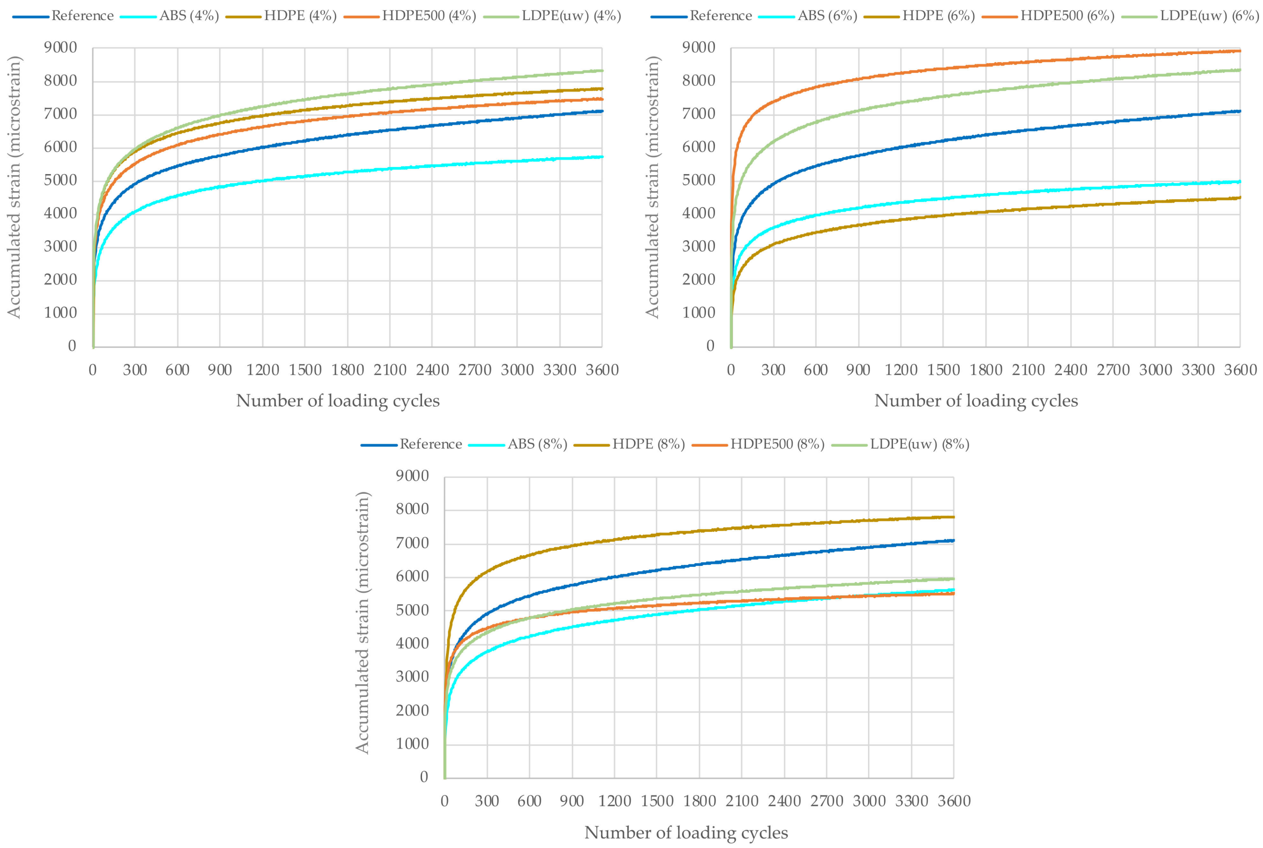

Figure 12. Variation of the accumulated permanent deformation measured in cyclic compression tests at 60 °C for both the reference and the asphalt concrete with different plastic wastes.

Figure 13 highlights the influence of plastic content in the resistance of the asphalt mixtures to permanent deformation measured in the cyclic compression test. Although there is no clear conclusion, the results allow us to present a number of findings. Increasing from 4% to 6% of ABS or HDPE was beneficial but from 6% to 8% was not. In the case of HDPE500 and LDPE(uw), only the 8% content showed an improvement of resistance. The lower quantities of HDPE500 seem to have a detrimental contribution. Therefore, the percentage of plastic should be conveniently studied to ensure that the improvement sought is achieved.

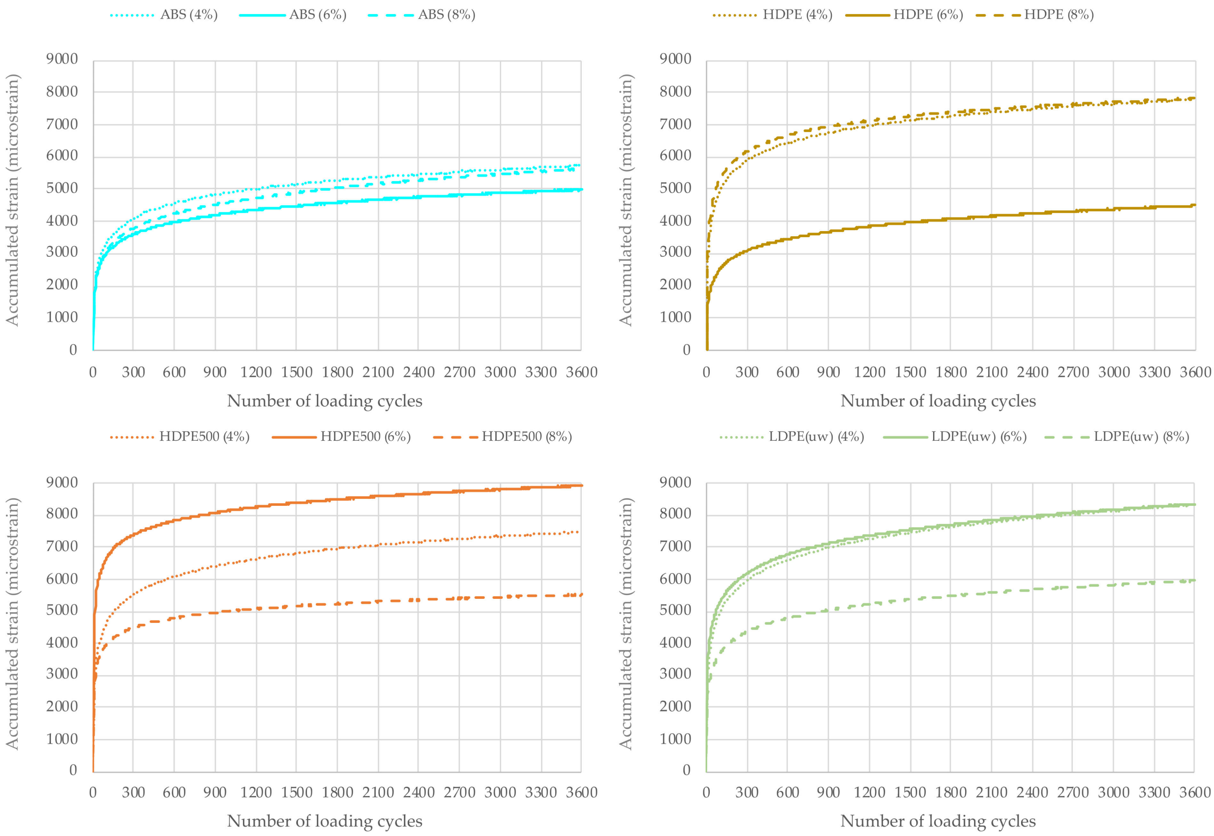

Figure 13. Influence of the plastic waste content on the accumulated permanent deformation measured in cyclic compression tests at 60 °C for the four types of plastic waste used.

A more detailed analysis of the deformation curves provided the values of *fc* (creep rate in the quasi-linear zone) and ε3600 represented in Figure 14.

Considering the results measured for *fc* and ε3600, the resistance to permanent deformation of the studied mixtures is ranked as shown in Table 2. The combined ranking is obtained by adding the ranking positions of both parameters.

The results show that the permanent deformation resistance depends on plastic type and content. The deformation curves are used to derive two parameters. The cyclic compression test shows that ABS increases rutting resistance whatever the considered content and evaluation parameter. Regarding creep rate (*fc*), the different types of plastics improve the resistance to permanent deformation as compared to the mixture without plastic. Overall, the of 6% and 8% plastic contents were the most effective. The results for ε3600 were not entirely aligned with those of *fc*. In this case, and for 4% of plastic, only ABS delivered better permanent deformation than the reference mixture. Increasing the plastic content to 8% increased the rutting resistance, except for HDPE500.

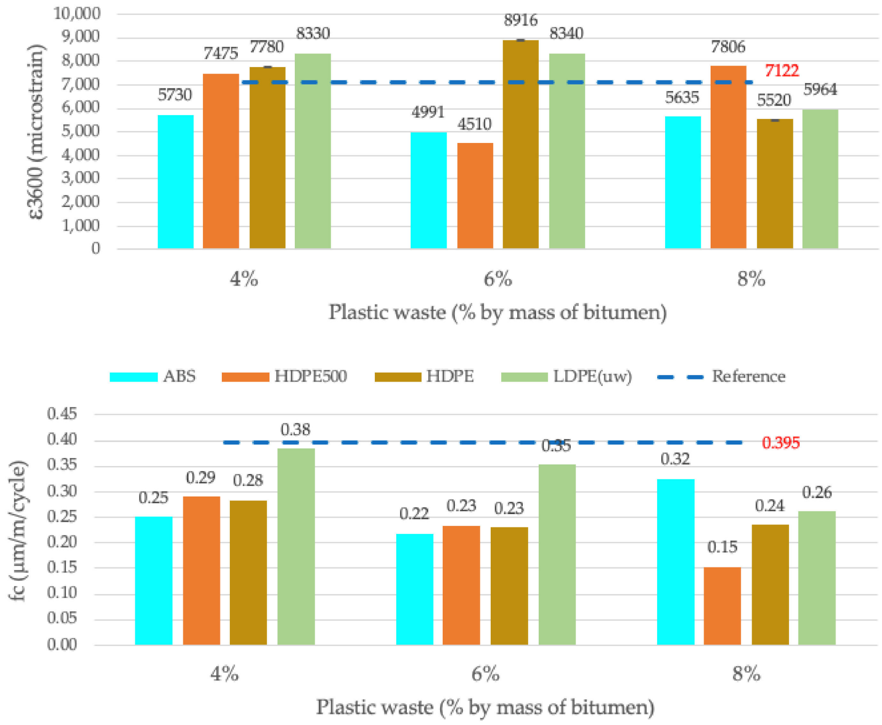

Figure 14. Results for the accumulated strain (ε3600) and creep rate (*fc*).

Table 2. Permanent deformation resistance ranking derived from cyclic compression tests at 60 °C.

Ranking	Parameter		Both Parameters
	ε3600	**fc**	
Best	HDPE500 6%	HDPE500 8%	ABS 6%
	ABS 6%	ABS 6%	HDPE500 6%
	HDPE 8%	HDPE 6%	HDPE 8%
	ABS 8%	HDPE500 6%	ABS 4% | HDPE500 8%
	ABS 4%	HDPE 8%	—
	LDPE(uw) 8%	ABS 4%	LDPE(uw) 8%
	Reference	LDPE(uw) 8%	ABS 8%
	HDPE500 4%	HDPE 4%	HDPE 6%
	HDPE 4%	HDPE500 4%	HDPE 4% | HDPE500 4%
	HDPE500 8%	ABS 8%	—
	LDPE(uw) 4%	LDPE(uw) 6%	Reference
	LDPE(uw) 6%	LDPE(uw) 4%	LDPE(uw) 4% | LDPE(uw) 6%
Worst	HDPE 6%	Reference	—

4. Discussion

The most used specifications generally use requirements for volumetric properties without supporting these requirements in the resulting mechanical performance of the asphalt mixtures. They suppose that a specific choice of values based on previous practice will result in appropriate workability and mechanical properties. Nevertheless, this may not occur for asphalt mixtures with plastic waste used as a binder modifier. Because the characteristics of the added polymer may considerably change between asphalt mixtures, that way of establishing requirements is not appropriate. Moreover, the interaction between the asphalt mixtures' constituents also depends on the circumstances of mixing and compaction (temperature, compaction energy, type of bitumen and content, or type of aggregates, to mention the most relevant). Therefore, volumetric properties should be analyzed in combination with the evaluation of other aspects, such as workability and mechanical performance.

4.1. Volumetric Properties, Marshall Results, and Workability

Although the air voids measured for the mixture with LDPE(uw) (Figure 6) were under the requirements for 4% and 6% of plastic waste content, the Marshall stability and flow results were satisfactory. Moreover, the relationship between air voids and workability seems to be poor. The results shown in Figure 8 reveal that the type of plastic and, therefore, the viscosity of the resulting binder, seem to have a much higher influence on the workability of the asphalt mixtures than the volumetric properties observed for the different mixtures with different plastic contents.

The parameter used to assess the ease of laying (Figure 8—void content for one gyration) shows that using 6% of plastic weight by the mass of bitumen is likely to affect the laying down conditions of the resulting asphalt concrete. Nevertheless, no issues were detected throughout the laboratory procedures in handling the asphalt mixtures produced.

The two parameters used to evaluate the mixtures' ease of compaction lead to quite different conclusions. The compaction curve slope, k, did not depict any noticeable differences between the tested mixtures, probably because the mixtures' air voids were quite similar [58]. On the contrary, CEI revealed much more capacity to distinguish the mixtures' compactability. The stiffer plastic waste, such as HDPE and HDPE500, had a higher contribution to reducing compactability than ABS and LDPE. It must be emphasized that despite the results showing a considerable increase for CEI in the asphalt mixtures with plastic waste, the increase of just 0.5% of neat bitumen content would have a highly noticeable influence [58].

In order to better evaluate the workability of the studied asphalt mixtures, Figure 15 compares the obtained results (for 6% of plastic content) with SUPERPAVE's recommendations [59].

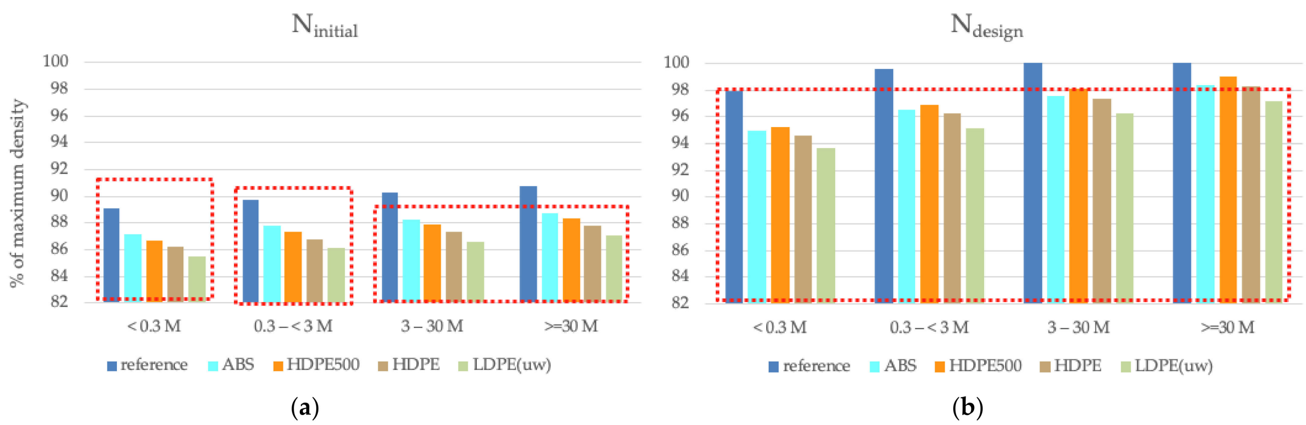

Figure 15. Comparison of the workability measured in gyratory compaction tests with the SUPERPAVE limits for (**a**) $N_{initial}$ and (**b**) N_{design}.

SUPERPAVE considers the two following indicators: $N_{initial}$ and N_{design}. The first one defines the adequate number of gyrations to achieve the air void content required at the construction site, just after the pavement is finished. If the void volume after $N_{initial}$ is too low, the mixture compacts too easily, and stability problems might be expected after opening to traffic. N_{design} is the number of gyrations that reproduces the probable mixture compaction after the lifespan of the asphalt mixture (4% in SUPERPAVE). The requirements vary as the number of the predicted equivalent standard axles loads of 80 kN (ESALs) for pavements with less than 0.3 million ESALs (very light traffic) to 30 million ESALs or higher volumes (very heavy traffic).

Figure 15 shows the results and the requirements (in red dots) in terms of the percentage of the maximum density. They reveal that incorporating plastic reduces the values of $N_{initial}$ and N_{design}. Consequently, the reference asphalt concrete is not satisfactory for the long term, whereas the asphalt mixtures with plastic waste are suitable for pavements with up to 3 million ESALs. Furthermore, even for heavily loaded pavements, the asphalt mixtures with plastic waste show a much better behaviour in compactability than the reference and are close to the acceptable threshold.

4.2. Stiffness and Phase Angle

Figure 16 presents the black diagram resulting from the stiffness and phase angle results. As mentioned earlier, the level of stiffness measured on plastic-waste-modified mixtures are appropriate for a typical pavement surface layer. In addition, Figure 16 shows that, for the same level of stiffness, phase angle values are considerably lower for the mixtures with plastic waste than for the reference, from about 9 degrees lower for ABS to 20 degrees for HDPE, at 10 Hz. These results mean that the incorporation of plastic waste increases the elastic behaviour of the asphalt mixture. It is interesting to observe that ABS shows almost the same phase angle difference (approx. 9 degrees) for all the stiffness values compared to the reference. This tendency is not followed by the results measured for LDPE(uw) and HDPE, for which the lower stiffness values are connected with phase angle results around 8 degrees lower. In contrast, that difference is about 16 degrees for the higher stiffness values. These results may be interpreted as an inferior contribution of LDPE(uw) and HDPE to elasticity when the loading frequency (or the loading speed) is lower. Even so, there is a significant contribution of the used types of plastic waste to the elastic behaviour of the asphalt mixtures.

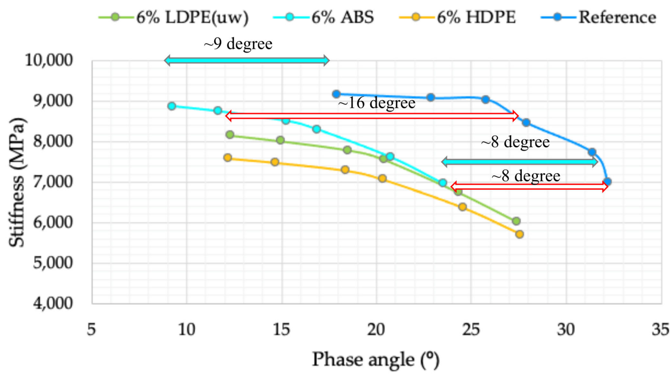

Figure 16. Black diagram derived from four-point bending tests at 20 °C.

4.3. Resistance to Fatigue

Complementarily to the results presented before for the fatigue resistance, the most relevant outcome is that incorporating 6% of plastic waste by weight of bitumen into the reference asphalt mixture keeps the fatigue resistance at a satisfactory level to use the asphalt mixture in pavement layers. Other authors [60,61] observed better asphalt mixture fatigue resistance by adding PET. In contrast, studies that used LDPE (2.5% by weight of bitumen) [62] obtained results comparable to this study. Despite the detrimental contribution of LDPE to fatigue resistance, after short-term aging, the mixtures with LDPE had better fatigue resistance than the reference [7].

According to the findings, the use of the plastic types, as investigated in this study, should be not considered a primary choice to improve the fatigue resistance of asphalt concrete.

4.4. Resistance to Permanent Deformation

Regarding the resistance to permanent deformation of asphalt concrete, the findings show that the types of plastic waste used in this project have significant potential. Nevertheless, the achieved resistance to permanent deformation depends on plastic kind and content. Therefore, a fundamental mix design including performance testing to permanent deformation resistance should support the decision on the composition of the asphalt mixture with plastic waste. The findings of this project are aligned with the literature, which presents some conflicting results for different types of plastic waste. For example, Lastra-González et al. [63] observed increased permanent deformation by adding polyethylene (PE) and polypropylene (PP) to the asphalt mixture, whereas polystyrene (PS) reduced the resistance. Lastra-González et al. [64] and others [7,22] also found improvements in rutting resistance with plastic film (LDPE) incorporation using a wheel-tracking test at 60 °C.

5. Conclusions

The study described in this paper focused on evaluating the volumetric and Marshall properties, workability, and mechanical performance of asphalt concrete with plastic waste (ABS, HDPE, HDPE500, and LDPE(uw)), added by the dry process, aiming to replace part of the bitumen. The volumetric properties, Marshall stability, and flow were assessed to compare the results with the usual requirements. The study continued to the workability and performance-oriented testing program based on gyratory compactor tests and fundamental properties of the studied blends.

The analysis of data obtained from the laboratory testing plan allowed for the conclusions presented below:

- The type of plastic revealed a much higher effect on the workability of the asphalt mixtures than the volumetric properties.
- The plastic types and contents used did not reveal substantial water sensitivity issues for the asphalt concrete.
- Unlike the reference asphalt mixtures (without plastic), the mixes with plastic waste revealed suitability in the long-term (up to 3 million ESALs), based on SUPERPAVE criteria.
- The asphalt mixtures with plastic waste offered values for stiffness suitable for pavement surface layers.
- The use of plastic waste increased the elastic behaviour of the asphalt mixtures.
- The contribution of ABS to the elasticity of the mixture was roughly the same for all the stiffness values.
- The inclusion of 6% of HDPE, ABS, or LDPE(uw) into the reference asphalt mixture did not put the asphalt concrete's fatigue performance at risk.
- Globally, the asphalt concrete with plastic waste revealed better resistance to permanent deformation than the reference. Nevertheless, it must be emphasized that the performance varied with plastic type and content and also with the performance parameter considered.
- Except for LDPE(uw), 6% and 8% of plastic waste tended to be the most effective to increase resistance to permanent deformation.

Lastly, the activities completed in this study showed that incorporating the types of plastic waste used by the dry method as a bitumen extender can improve some properties of asphalt concrete. Moreover, this way of plastic waste recovery will help to reduce the inadequate disposal of plastic waste in nature. As it happens for other techniques based on recycling of by-products, the authors are aware that the studies on this type of asphalt concrete must continue to obtain a full understanding of its long-term behaviour and environmental impact and the life cycle analysis.

Author Contributions: Conceptualization, S.C.; methodology, M.F., S.C., A.A. and L.P.-S.; formal analysis, M.F., S.C., A.A. and L.P.-S.; investigation, M.F. and S.C.; writing—original draft preparation, S.C.; writing—review and editing, M.F., S.C., A.A. and L.P.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the technical personnel working at the Laboratory of Highways Pavements (LPR) of Instituto Superior de Engenharia, Instituto Politécnico de Coimbra. The authors would also like to express their special thanks of gratitude to the companies Ambiente—Recuperação de Materiais Plásticos, S.A. and LifePoly, Lda., for providing the plastic waste used in this study, and Contec—Construção e Engenharia, S.A., for providing the aggregates and bitumen.

Conflicts of Interest: The authors declare no conflict of interest.

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