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Full Recycling of Asphalt Concrete with Waste Cooking Oil as Rejuvenator and LDPE from Urban Waste as Binder Modifier

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Abstract: Some research projects have studied full recycling of reclaimed asphalt pavement (RAP). Several additives have been used to rejuvenate the RAP's aged bitumen. The authors previously studied full recycling of RAP rejuvenated with waste cooking oil (WCO). The asphalt concrete (AC) manufactured revealed good mechanical behaviour except for rutting resistance. Therefore, they decided to also include in the asphalt mixtures low density polyethylene (LDPE) from urban waste as a low-cost polymer to improve that weak point and verify if this technique was feasible and with potential as a pavement material. A laboratory plan was conceived to evaluate the mechanical performance of two rejuvenated ACs with WCO and LDPE. Stiffness, water sensitivity, resistance to rutting and fatigue cracking were evaluated. The results showed that, despite some empirical parameters usually indicated in current specifications not being met, the performance of the studied asphalt mixtures was adequate and, thus, there are good expectations about the future use of these solutions in real pavements, particularly for low and intermediate traffic levels. Based on a global analysis of the performance observed, the main conclusion was that full recycling of AC with WCO and LDPE is feasible, and the score obtained was higher than that of a conventional AC used for comparison.

Keywords: circular economy; low density polyethylene; reclaimed asphalt pavement; sustainability; waste cooking oil

1. Introduction

Over the last decades, with the growing environmental concerns, several sectors of society and industry are changing their behaviour in terms of consumption resources, waste management, and efficiency of goods and services production. Recycling and reusing of non-renewable materials are becoming increasingly imperative in order to move towards a circular and sustainable economy as well as a sustainable use of resources. In particular, the industry of construction and maintenance of transport infrastructures is gradually applying environmentally friendly solutions, aiming to reduce its ecological footprint.

The incorporation of reclaimed asphalt pavement (RAP) in new asphalt mixtures is one of the most applied recycling techniques in pavement construction and maintenance by applying different production processes, such as hot-, warm-, half-warm- and cold-mix asphalt [1–6]. Apart from reducing the use of new non-renewable raw materials, the use of RAP may also contribute to reduce energy consumption and emissions, as well as to decrease disposal of that demolition waste in landfills [7].

Nevertheless, the use of RAP as a constituent of new asphalt mixtures, particularly when recycling incorporates high percentages of RAP, involves some challenges related to the capability of RAP's aged bitumen to act as a binder. As reported in the literature [8], it is usually recognised that bitumen suffers short- and long-term ageing, which involves different origins and mechanisms, such as oxidation and volatilisation of constituents [9]. These phenomena happen during manufacturing and construction activities of asphalt mixtures as well as throughout the pavement lifespan. An aged bitumen presents changes in its molecular groups, generally with increased amounts of stiffer fractions, which result in higher binder viscosity [10]. The ratio asphaltenes/maltenes, for instance, generally increases with ageing, resulting in a harder and brittle bitumen, with worse adhesion to aggregates and less coating properties [11].

Restoring the properties of an aged binder to a satisfactory level may be achieved by adding a considerable amount of virgin bitumen to the asphalt mixture and/or by applying appropriate rejuvenators. The rejuvenator ability to reactivate the aged binder is of major importance to achieve adequate performance of the asphalt mixture. The diffusion of rejuvenator into the asphalt binder is crucial to achieve adequate rejuvenation of the asphalt binder [12]. The temperature has been reported as the parameter with the highest influence on the diffusion rate [13]. Indeed, the literature reports that part of the RAP's aged bitumen—the "black rock"—does not blend with the rejuvenator, preventing bitumen from being reactivated as a binder [1,14]. The use of chemical rejuvenators, specifically developed to rejuvenate aged bitumen, is a costly part of RAP recycling [15]. Therefore, reusing some by-products as alternative rejuvenators can bring some advantages to paving technology, namely, by reducing costs.

Several studies carried out over the last years have aimed at using waste cooking oil (WCO) as an alternative rejuvenator for asphalt binders [12,15–19]. Although the worldwide production of WCO is not known with accuracy (Azahar et al. [20] stated a production of about 10 million tonnes per year), we know that a great part of WCO is landfilled or thrown into the sewers, losing its potential value and creating a significant negative environmental impact. For instance, according to the APA—the Portuguese Environmental Agency—WCO production in Portugal in 2018 was 74,351.9 tonnes, which represents a rise of about 280% in comparison to 2017. However, the available data for 2018 show that the recorded WCO is just 50% of new cooking oil production.

According to Zhang et al. [19] a better quality WCO to rejuvenate bitumen should have low acid value (i.e., mass of potassium hydroxide (KOH) in milligrams that is required to neutralize one gram of WCO). The higher the amount of free fatty acids (FFAs) in the WCO, the higher the acid value. FFAs of WCO increase with the applied heat, time of use, and the quantity of water resulting from frying activities [21]. Zhang et al. [19] concluded in a specific research project that WCO acid values in the range of 0.4 to 3.2 mg KOH/g are preferable regarding high-temperature rheology of rejuvenated bitumen. They also verified that WCOs with acid values between 0.4 and 0.7 mg KOH/g generally meet all the needed requirements for bitumen rejuvenation. Although samples of WCOs were obtained in controlled and undemanding conditions, this material may have acid values as low as 0.38 mg KOH/g [19], where commonly available WCOs have acid values from 1.32 to 3.6 mg KOH/g [21].

The literature states that blending WCO with bitumen has a considerable influence on the aged asphalt binder properties, showing a realistic potential of WCO as a bitumen rejuvenator. The observed trend among the studies was as follows: penetration considerably increases, softening point and kinematic viscosity (@135 °C) decrease [15,18], and the ratio of asphaltenes to maltenes decreases as a result of the growth in the ratio of lower molecular weight oily medium [15]. Despite these changes of properties, it has not been possible to improve the binder workability (based on viscosity) to the level of virgin (not aged) bitumen [12,15]. Regarding rheology performance, aged bitumen and WCO blends perform better than the aged binder at low temperature (based on PI—penetration index evaluation) as well as when the material is subjected to load repetition at higher strain levels at 25 °C (fatigue parameter) in a DSR—dynamic shear rheometer [12]. The higher the WCO percentage in the binder blend (acid value of 1.65 mg KOH/g), the lower the rutting resistance is (based on G*/sin δ—the rutting resistance parameter). Although the trend was similar, the experimental rutting resistance was considerably better in a similar binder blend with treated WCO (acid value of 0.54 mg KOH/g) [18].

The effect of adding WCO into asphalt mixtures is not widely disseminated yet. Although adding WCO to aged bitumen considerably rejuvenates its properties, regarding asphalt concrete (AC) with a high RAP percentage, the resulting characteristics depend considerably on the rejuvenator diffusion level within the blend.

Zaumanis et al. [12] studied the performance of a 9.5 mm Superpave mixture with 100% recycled asphalt, using 12% of WCO (by mass of binder). According to the results, the AC clearly passed the defined requirements for maximum rut depth (Hamburg wheel-tracking test). Also, gyratory compactor tests revealed better workability in comparison with that of a RAP mix without WCO. Regarding low-temperature cracking (based on indirect tension configuration to evaluate creep compliance and tensile strength results at −10 °C), an asphalt mixture with WCO performed better than a RAP mix without rejuvenator in terms of creep compliance and slightly below for tensile strength. Fatigue resistance estimated through fracture work density results (based on indirect test configuration at 19 °C) did not improve in comparison with that of a RAP mix without WCO.

Bitumen rejuvenation with WCO was applied by the authors' research team within an ongoing project dealing with full recycling of RAP aimed at manufacturing a low-cost and eco-efficient AC for pavements with low to medium traffic levels, ensuring adequate durability. To achieve that goal, the raw material processing was as minimal as possible. Since the needed performance of AC was achieved, taking the in-service conditions into account, some of the empirical requirements usually followed may have been overlooked.

Preliminary studies carried out by the authors' research team [22] considering full incorporation of RAP and WCO as rejuvenators revealed the need to improve permanent deformation resistance of the resulting asphalt concrete. Therefore, the authors decided to add a low-cost polymer—low density polyethylene (LDPE)—collected from urban waste containers as a binder modifier, trying to improve the aforesaid potential mechanical weakness of the resulting asphalt concrete. Indeed, the use of different plastic wastes as additives for asphalt concrete has been considered in several studies, generally with positive contributions to the mechanical performance of asphalt mixtures [23–25].

Moreover, the authors have already done some work in using flakes of LDPE collected from urban waste [26], with promising results in terms of permanent deformation resistance of asphalt concrete. That paper also summarized some issues related to the availability of plastic waste and its inadequate deposition in nature as well as the need of increasing its recycling level in order to reduce the environmental damage.

The laboratory results presented in this paper showed that full recycling of RAP is feasible by using WCO as binder rejuvenator and LDPE as binder modifier. The LDPE incorporation improved the resistance of the obtained asphalt concrete against permanent deformation, while keeping good performance related to fatigue cracking. This process required additional control of the manufacturing procedure, particularly with regard to homogeneity of mix composition from one production batch to the other.

2. Materials and Methods

2.1. Raw Materials: RAP, Aggregates, WCO, Virgin Bitumen and LDPE

The RAP used in this study was milled from a pavement surface course made of asphalt concrete (AC), designated *AC14 surf 35/50* according to the European standard EN 13108-1. The original composition of the in-service asphalt concrete was a blend of crushed quartzite and limestone aggregates, and 5% of bitumen (Table 1). The surface pavement layer used as source of RAP had a bulk density of 2382 kg/m^3 and 4.3% of voids content. However, the actual binder content of RAP measured by the ignition method (EN 12697-39) revealed a value of 4.5% instead of 5.0%.

Table 1. Reported composition of the original asphalt concrete (AC) used as a source to produce reclaimed asphalt pavement (RAP).

Aggregate Fraction	% by Mass of Total Blend
35/50 pen bitumen	5.00
quartzite 10/16	21.85
quartzite 4/10	22.80
quartzite 0/6.3	34.20
limestone 0/4	14.25
limestone filler	1.90

After burning the RAP's binder, the gradation of the aggregate blend was obtained by sieve analysis (EN 12697-2). Figure 1 shows the obtained gradation, which was superposed to the applicable grading envelope defined in the Portuguese specification [27] for surface pavement layers (*AC14 surf 35/50*). As generally happens, the milling process used to remove asphalt concrete from the pavement produced a considerable quantity of fine particles and, therefore, the resulting aggregate blend (from RAP) was finer than that indicated in the Portuguese specification. Considering the high proportion of RAP to be used, the observed change of aggregate particle size and angularity was expected to influence the volumetric properties of the asphalt concrete.

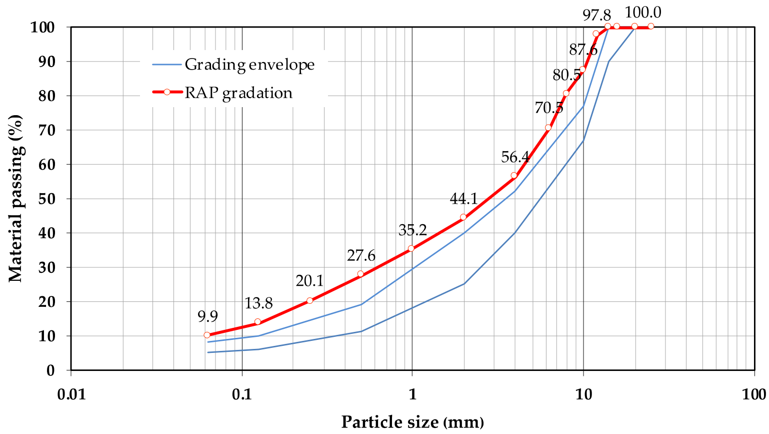

Figure 1. Gradation of the RAP aggregates blend and specification grading envelope.

The WCO used as a binder rejuvenator was a conventional waste sunflower oil. Apart from a simple filtration process carried out in order to remove the solid suspended particles (Figure 2), this material did not undergo any chemical treatment to reduce FFAs.

Figure 2. Simple filtration procedure applied to remove suspended particles from the waste cooking oil (WCO).

Some virgin 35/50 paving grade bitumen was also used to manufacture asphalt concrete with the intended binder content. The penetration (EN 1426) of this virgin binder was 45 × 0.1 mm and the softening point was 52 °C (EN 1427).

The flakes of LDPE were the same as used in a previous study [26], with a melting point from 100 to 125 °C and size between 2 and 100 mm (thickness up to 0.1 mm). They were collected from urban waste and processed in a plastic recycling plant. The recycling procedure included disaggregation of plastic bales and a number of steps to produce LDPE pellets after extrusion. This study used flakes collected before the extrusion process.

2.2. Methods

2.2.1. Framework of the Study

This study was developed in three stages. The first stage consisted in the analysis of asphalt mixtures with WCO or LDPE previously studied by the authors' research group. Moreover, this stage involved the analysis of the observed performance of the produced asphalt concrete mixes aiming at supporting the necessary adaptations to be considered in this work. The second stage comprised a preliminary evaluation of empirical properties and volumetric parameters as well as water sensitivity and permanent deformation resistance evaluation of the asphalt mixtures studied in this paper. The third stage included the evaluation of stiffness, resistance to fatigue, and permanent deformation resistance in wheel-tracking tests. Figure 3 summarizes the general framework of the study.

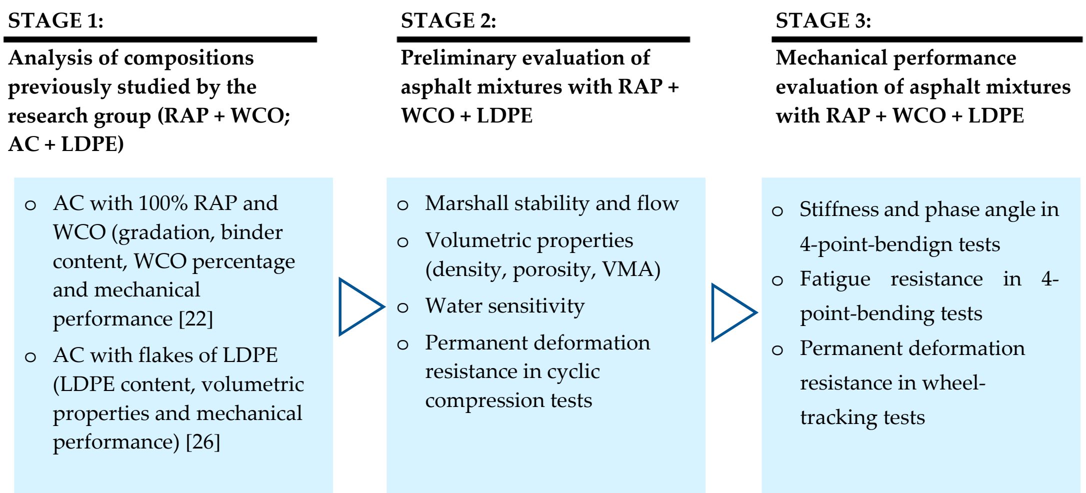

Figure 3. General framework of the study. Note: VMA—voids in the mineral aggregate.

2.2.2. Stage 1: Composition of AC with 100% of RAP and WCO

The blend manufactured in 2018 [22] was conceived based on a trial and error mix-design procedure. The RAP used in that blend was the same as available for this study, whose gradation is presented in Figure 1 with the (aged) binder content of 4.5%. Although this gradation does not fulfil the specification requirements, it was not corrected by adding any aggregate fraction for the sake of economy.

The blends were mixed in a planetary mixer by introducing the RAP at 165 °C in the bowl, whereas the virgin bitumen and the WCO were added at 140 °C. Several cylindrical Marshall specimens, with 101.6 ± 0.1 mm in diameter and 63.5 ± 2.5 mm in height, were compacted by applying 75 blows in each face of the specimen (EN 12697-30). Prior to compaction, both RAP and virgin bitumen 35/50 were kept at 165 °C in an oven for 30 min to allow a better diffusion of the WCO. Attempts involved adding 0.3% to 1.5% virgin bitumen 35/50, thus resulting in specimens with total binder contents from 4.8% to 6% (4.8%, 5.0%, 5.5%, and 6.0%). Simultaneously, the percentage of WCO varied from 4% to

20% (4%, 8%, 16%, 18%, and 20%) by mass of total bitumen (virgin + aged binder). The rejuvenator was not considered part of the blend's binder. Figure 4 shows an example of two specimens with the same binder content (5.5%) and different WCO content (16% and 8%), indicating a favourable contribution of WCO to the blend compactability (porosity values of 11.3% and 1.7% for 8% and 16% of WCO, respectively). Low WCO content did not allow an adequate workability and compaction, making the moulding process impossible due to lack of material cohesion.

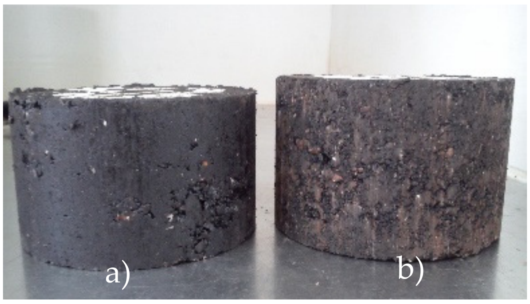

Figure 4. Specimens with a binder content of 5.5% compacted in the mix-design process: (**a**) 16% WCO; (**b**) 8% WCO.

Based on the results for Marshall stability (14.5 kN) and flow (3.9 mm) (EN 12697-34) and the objective of producing a low-cost blend, the selected formula consisted of adding 1% of virgin binder to the RAP (total binder content of 5.5% by mass of total mixture) and a WCO content of 18% by mass of total binder. A bitumen content of 5.5% was 0.5% higher than the reported value for the original AC. However, taking into account that a small part (not determined) of the RAP's aged bitumen was expected not to be reactivated, it was necessary to increase by 0.5% the binder content (i.e., 5.5% by mass of total mixture).

Specimens of AC with different shapes were prepared to evaluate the rejuvenated blend performance regarding stiffness, fatigue resistance, permanent deformation resistance, and water sensitivity. Table 2 summarizes the performed tests.

Table 2. Tests applied to evaluate the AC performance.

Property	Standard	Test Method	Specimen
Stiffness	CEN EN 12697-26	Four-point bending	Beam: 400 × 52 × 52 mm^3
Fatigue resistance	CEN EN 12697-24	Four-point bending	Beam: 400 × 52 × 52 mm^3
Permanent deformation resistance	CEN EN 12697-22	Wheel-tracking	Slab: 300 × 400 × 40 mm^3
Water sensitivity	CEN EN 12697-12/23	Indirect tensile	Cylinder: diameter 101.6 and 63.5 height (mm)

The evaluation of stiffness and phase angle was performed under controlled strain conditions with a strain level of 50 µm/m at 20 °C and for frequencies of 30, 20, 10, 5, 3, and 1 Hz applied through a loading sine wave. Figure 5 displays the obtained results.

Fatigue resistance was evaluated at a frequency of 10 Hz by applying three different strain levels (200, 300, and 400 µm/m) at 20 °C and a failure criterion of 50% loss of initial stiffness. Based on the admissible number of load repetitions obtained, the derived value of ε_6 (strain that induces specimen decay after 1 million load cycles) was 252 µm/m.

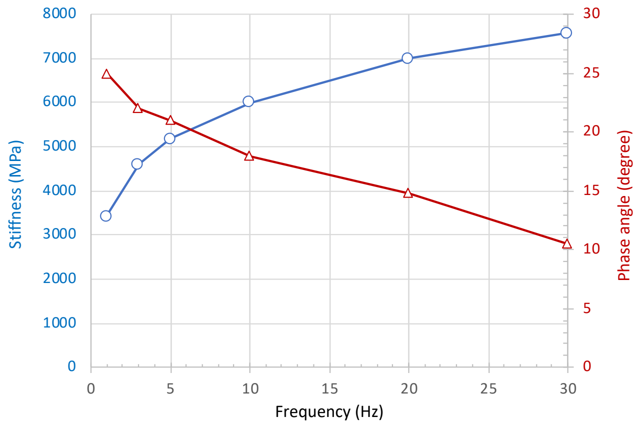

Figure 5. Stiffness and phase angle results at 20 °C [22].

Permanent deformation resistance was assessed in a small-sized device, tested in air, by applying 10,000 loading cycles at 60 °C, or a lower number of loads if a rut depth of 20 mm was reached beforehand. Table 3 summarizes the obtained results.

Table 3. Permanent deformation resistance results [22].

Parameter	Result
RD_{air} (mm)	7.6
PRD_{air} (%)	14.8
WTS_{air} (mm/10^3 cycles)	0.339

RD_{air}—rut depth for the material at the end of the test. PRD_{air}—proportional rut depth for the material at the end of the test. WTS_{air}—wheel-tracking slope: average rate at which the rut depth increases with repeated passes.

Regarding water sensitivity measured at 15 °C, the blend performed particularly well, with an ITSR—indirect tensile strength ratio—of 104.4%, i.e., showing practically the same resistance in dry (ITS_{dry} = 2392.2 kPa) and wet (ITS_{wet} = 2499.1 kPa) conditions.

A global analysis of the obtained results allowed the following conclusions in comparison to some results available for conventional AC without RAP [28,29]: (a) stiffness showed adequate values, about 25% higher than those of conventional AC; (b) phase angles were lower than for conventional AC, which was in agreement with the results of stiffness; (c) fatigue resistance presented a much higher value of ε_6 (252 µm/m) in comparison with a common AC, circa 50% higher, which allowed us to foresee a good potential of lifespan in terms of fatigue cracking; (d) permanent deformation resistance seemed to be a weak point of the rejuvenated mixture because all the deformation parameters measured were considerably above (three times higher) the typical results for a conventional AC; (e) no problems associated with water sensitivity were identified.

2.2.3. Stage 1: Compositions of AC with LDPE

The study published in 2020 by the research team [26] on the use of flakes of LDPE as a low-cost bitumen modifier showed some benefits of incorporating LDPE in a conventional *AC 14 surf 35/50* with 5% of binder.

Since LDPE was applied as a binder modifier, it was considered as part of the total binder. The best percentage of LDPE was determined based on Marshall tests and volumetric properties (EN 12697-5, -8, -9) of blends manufactured with five percentages of LDPE: 0% (control), 2%, 4%, 6%, and 8% by mass of bitumen. The selected asphalt mixture was the one with 6% of LDPE, taking into account the results for Marshall stability (20.8 kN) and flow (3.7 mm), even though the air voids content (1.9%) of this blend was below the requirements of the Portuguese specification for a typical AC for surface course (3–5%).

Workability of the blend was also assessed because the introduction of LDPE could be an issue to mix, transport, lay, and compact the studied AC. This evaluation was based on gyratory compactor testing (EN 12697-10). The results indicated that the AC with plastic was slightly more difficult to lay but also more resistant to in-service traffic compaction. Even so, the experience of handling the material in the laboratory revealed that workability was not an issue.

The tests carried out to evaluate mechanical performance were those indicated in Table 2. Additionally, an ageing protocol (AASHTO R 30-02: specimens placed in an oven at 85 °C for 120 h) was also considered to better understand its effect on the material's behaviour. Figure 6 shows a summary of the obtained results for stiffness and phase angle at 10 Hz and 20 °C. The addition of recycled LDPE increased the stiffness and reduced the phase angle of the conventional AC both in aged and unaged conditions.

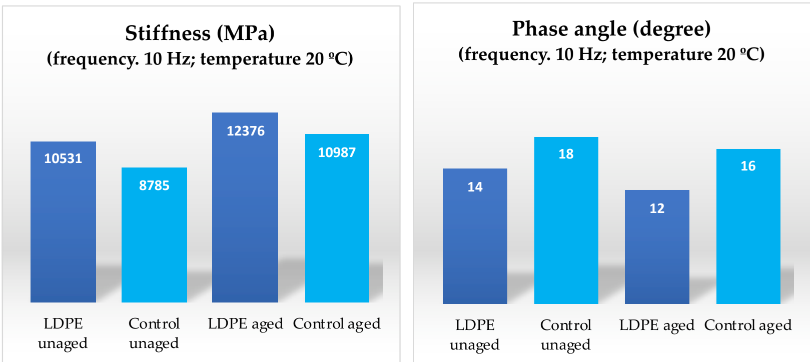

Figure 6. Stiffness and phase angle results for a frequency of 10 Hz at 20 °C [26].

Regarding resistance to moisture, measured at 25 °C, the blend with LDPE revealed lower resistance than the control AC. However, the modified blend performed rather well with an ITSR of 90%, i.e., higher than 80%, the usual required performance.

Although fatigue performance of the unaged AC with LDPE (ε_6 = 122 µm/m) was lower than that of control AC (ε_6 = 131 µm/m), when the ageing effect was considered the AC with LDPE performed better (with LDPE: ε_6 = 106 µm/m; control: ε_6 = 92 µm/m). Therefore, although the incorporation of LDPE generally increased the mixture stiffness, it was not significantly detrimental to cracking resistance. Moreover, part of the ageing effect on fatigue resistance was likely to be compensated by the use of LDPE.

Table 4 summarizes the results obtained for permanent deformation resistance of the tested blends. Adding LDPE to the control mixture considerably increased permanent deformation resistance of the conventional AC in both unaged and aged conditions. This was one of the most favourable contributions to mechanical performance revealed by the addition of LDPE.

Table 4. Permanent deformation resistance results [26].

Parameter	LDPE Unaged	Control Unaged	LDPE Aged	Control Aged
RD_{air} (mm)	3.5	10.3	2.5	5.0
PRD_{air} (%)	8.7	25.8	6.2	12.5
WTS_{air} (mm/10^3 cycles)	0.043	0.111	0.032	0.052

2.2.4. Stages 2 and 3: Composition of Blends and Testing Procedures

Considering the conclusions identified in Stage 1, the laboratory plan included the study of two blends with 5.5% of total binder (aged + virgin bitumen + LDPE) aiming at improving the permanent deformation resistance of AC when using a high percentage of RAP as well as WCO as a binder rejuvenator. One of the blends (designated 85RAP+WCO+P) was manufactured with a slight increase of aggregate skeleton by adding coarse aggregates (15% of quartzite 10/16), 1.5% of virgin bitumen, and 6% of LDPE (by mass of total bitumen), and the other with 1% of virgin bitumen and 6% of LDPE but without any adjustment of gradation (designated 100RAP+WCO+P), whose gradation is shown in Figure 1. Figure 7 shows the gradation of 85RAP+WCO+P and a view of a cross section of 100RAP+WCO+P and 85RAP+WCO+P specimens. This view reveals the improvement of aggregate skeleton in 85RAP+WCO+P, with 15% more of the 10/16 fraction, in comparison to 100RAP+WCO+P.

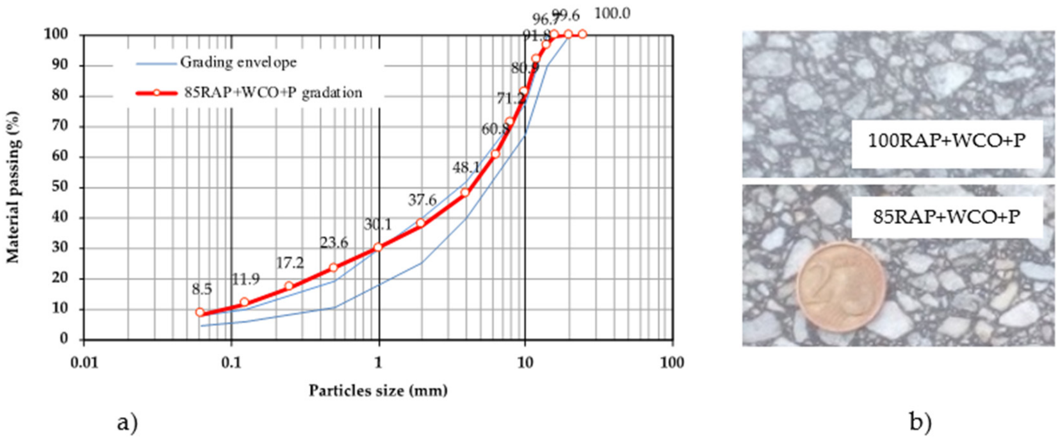

Figure 7. (**a**) Gradation of 85RAP+WCO+P and specification grading envelope; (**b**) view of 100RAP+WCO+P and 85RAP+WCO+P specimens.

The blends and cylindrical (Marshall) specimens were produced and moulded by applying the same procedures mentioned before for the study carried out by Fernandes et al. [22]. The LDPE flakes were at room temperature before they were added to the mixing process. After mixing, the blends stayed at 165 °C for 30 min to allow a better diffusion of the WCO and LDPE within the mixture.

For the uniaxial cyclic compression tests, cylindrical specimens (about 150 mm in diameter and 60 mm in height) were moulded in a CBR (California Bearing Ratio) mould with a vibrating hammer (Kango model 638 with an additional mass of 32 kg), which applied a loading frequency of 60 Hz. A tamping foot with a diameter slightly smaller than the top of each specimen produced compaction. Compaction was applied for 1.5 min on the top of each specimen.

Cyclic compression tests, carried out according to EN 12697-25, consisted of testing three cylindrical specimens of each blend by recording the accumulated vertical permanent deformation of specimens with the number of loading cycles. The tests were performed at a temperature of 60 °C by using a loading plate with a diameter of 100 mm in contact with the upper face of the specimen with 150 mm in diameter. These conditions matched those of the uniaxial cyclic compression test with confinement as described in EN 12697-25. The tests started with a pre-stress of 10 kPa applied for 10 min. After this, a cyclic block-pulse stress of 100 kPa was applied with a loading time of 1 s and a rest time of 1 s. The test finished after applying 3600 pulses on the sample subjected to the test.

Mechanical assessment of the blends followed throughout Stage 3 was the same testing protocol as indicated above in Table 2.

3. Results

3.1. Stage 2: Preliminary Evaluation of Blends with RAP, WCO and LDPE

3.1.1. Results of Marshall Compression Tests, Volumetric Properties, and Water Sensitivity

Four replicates of cylindrical specimens were tested in terms of porosity and voids in the mineral aggregate (VMA) as well as Marshall compression tests. Table 5 presents the average values obtained and usual requirements indicated in the Portuguese specification [27] as well as the results obtained by Fernandes et al. [22] for comparison.

Table 5. Results for Marshall tests and volumetric properties.

AC Mixture	Stability (kN)	Flow (mm)	Stability/Flow (kN/mm)	Density (kg/m^3)	Porosity (%)	VMA (%)
100RAP+WCO+P	24.8	3.5	7.1	2349.0	1.7	14.2
85RAP+WCO+P	19.1	3.3	5.8	2301.0	3.5	15.6
WCO-rejuvenated AC [22]	14.5	3.9	3.7	2208.3	NA	NA
Portuguese Specification	7.5–21	2–4	Min. 3	ND	3–5	Min. 14

NA—not available. ND—not defined. VMA—voids in the mineral aggregate.

Both mixtures (100RAP+WCO+P and 85RAP+WCO+P) achieved high stability, which is usual for mixtures that incorporate high RAP proportion. In terms of flow and stability/flow ratio the results fulfilled the usual requirements. When comparing 100RAP+WCO+P and 85RAP+WCO+P, the results revealed that the finer gradation of the first blend created lower voids content (1.7%) as well as lower VMA (14.2%). As expected, the results showed that improvement of 85RAP+WCO+P gradation was achieved by adding coarser particles that delivered volumetric properties within the specification range. However, because the gradation was particularly fine in the case of 100RAP+WCO+P the voids content was slightly below the usual range. Also, the Marshall stability of 100RAP+WCO+P was above the range defined in the specification.

Regarding water sensitivity both 100RAP+WCO+P and 85RAP+WCO+P revealed no weaknesses with ITSR values of 88.9% and 107.4%, respectively. However, it must be stressed that both ITS_{dry} and ITS_{wet} at 25 °C were much lower for 85RAP+WCO+P than for 100RAP+WCO+P (Table 6).

Table 6. Results for water sensitivity.

AC Mixture	Indirect Tensile Strength (ITS) (kPa)		ITSR (%)
	ITS_{dry}	ITS_{wet}	
100RAP+WCO+P	1314.3	1169.5	88.9
85RAP+WCO+P	600.7	645.0	107.4
WCO-rejuvenated AC [22]	2392.2	2499.1	104.4

3.1.2. Permanent Deformation Resistance in Cyclic Compression Tests

Figure 8 represents the variation of permanent deformation with the number of cycles for all the specimens subjected to testing.

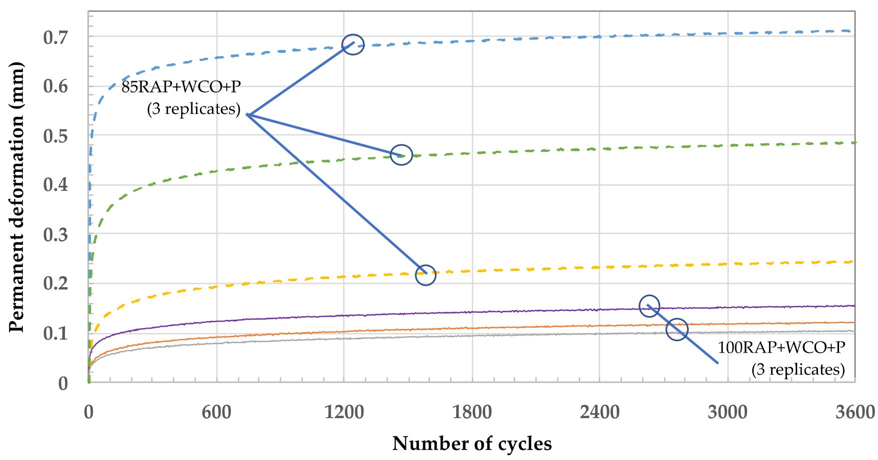

Figure 8. Accumulated permanent deformation recorded for 100RAP+WCO+P and 85RAP+WCO+P.

Although there was some scatter of accumulated vertical deformation, probably derived from the heterogeneity of the 85RAP+WCO+P specimens, which had a small percentage of virgin coarse aggregates and a low content of virgin binder, the mixing procedure may have been insufficient to homogenize the blend. Figure 8 shows that 100RAP+WCO+P (Δh—average of permanent deformation of 0.127 mm) performed better than 85RAP+WCO+P (average of Δh of 0.48 mm). The same conclusion can be observed if the parameter *fc* (creep rate) is considered (100RAP+WCO+P: 0.098 microstrain/cycle; 85RAP+WCO+P: 0.185 microstrain/cycle). Apparently, the higher the proportion of aged binder within the blend, the better the resistance to permanent deformation.

Furthermore, a comparison of these results with 0.37 mm for Δh and 0.32 microstrain/cycle for the creep rate obtained for the control AC studied in [26], not published in the paper, also confirmed the good performance of both 100RAP+WCO+P and 85RAP+WCO+P to permanent deformation.

3.2. Stage 3: Mechanical Performance Evaluation of Blends with RAP, WCO and LDPE

3.2.1. Stiffness and Phase Angle

Figure 9 displays the results of stiffness and phase angle measured for both 100RAP+WCO+P and 85RAP+WCO+P as well as the results obtained by Fernandes et al. [22].

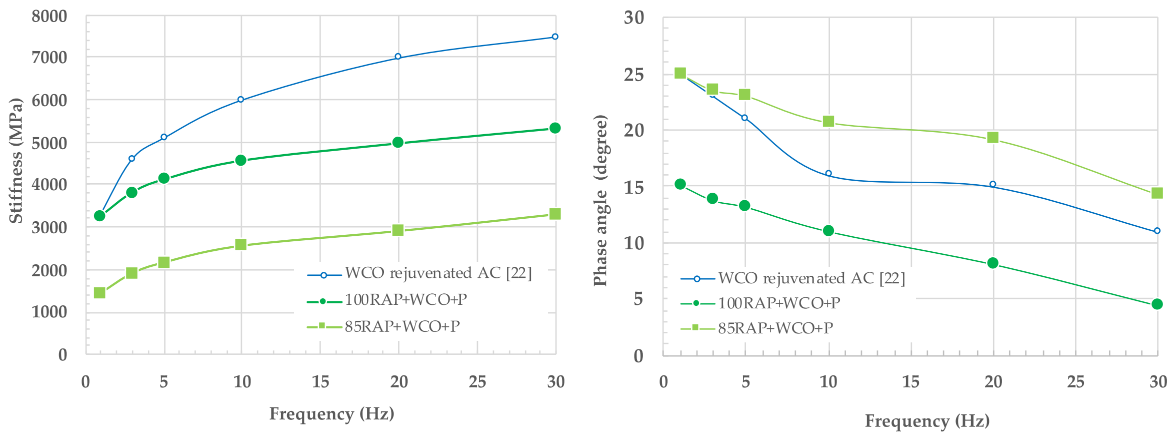

Figure 9. Results of stiffness and phase angle measured for 100RAP+WCO+P and 85RAP+WCO+P.

When comparing the 100RAP+WCO+P and 85RAP+WCO+P blends, it was apparent that stiffnesses were lower for the latter blend while the opposite occurred with phase angles. For instance, the stiffness at 10 Hz was about 80% higher for the 100RAP+WCO+P (4572 MPa) than for the 85RAP+WCO+P (2569 MPa). The stiffness of 100RAP+WCO+P was about 25% lower than that measured in [22] (without LDPE), which was about 6000 MPa for the same testing conditions. Nevertheless, the incorporation of LDPE changed the material deformability, giving it more elasticity, since phase angle values were lower for the blend with LDPE (100RAP+WCO+P).

3.2.2. Fatigue Resistance

Table 7 summarizes the fatigue laws (number of load repetitions, N, to failure as a function of the applied tensile strain, ε_t) derived from the four-point bending (4PB) test results after plotting them in a log–log scale. Figure 10 presents the strains corresponding to a fatigue life of 1 million cycles (ε_6) as well as the so-called ε_5 (strain for a life of 100,000 cycles) and ε_4 (strain for a life of 10,000 cycles).

Table 7. Fatigue resistance results for 100RAP+WCO+P and 85RAP+WCO+P.

AC Mixture	A	B	R^2 (%)
100RAP+WCO+P	1315.9	−0.127	92.3
85RAP+WCO+P	2038.3	−0.127	90.6
WCO-rejuvenated AC [22]	2441.8	−0.165	92.7

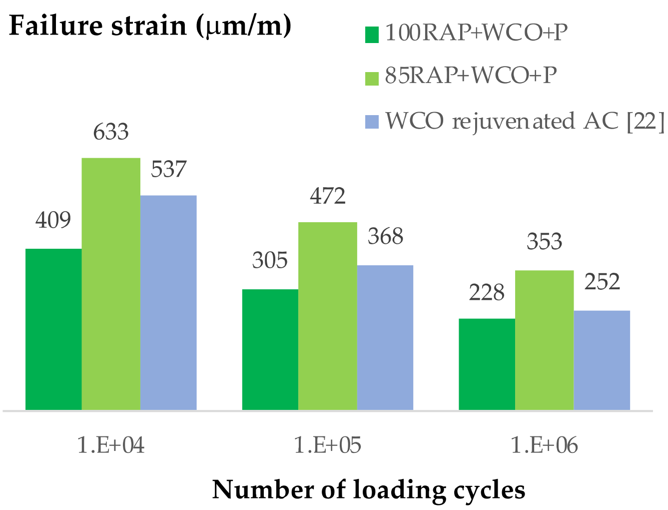

Figure 10. Fatigue performance in terms of strain necessary to specimen's failure.

The derived fatigue laws revealed the same slope (−0.127) for both 100RAP+WCO+P and 85RAP+WCO+P, both with LDPE. Because the slope of the fatigue line determined in [21] (without LDPE) was higher (−0.165), it was apparent that the incorporation of LDPE made the resistance of the AC to fatigue less sensitive to the level of tensile strain applied.

In addition, the obtained values of ε_6, ε_5, and ε_4 showed that the 100RAP+WCO+P had lower fatigue resistance than the 85RAP+WCO+P for all the strain levels. On the other hand, comparing the results of 100RAP+WCO+P with those collected from [22], they showed that the use of LDPE reduced the resistance to fatigue, which was more visible for higher strain levels. The lowest level of aged bitumen of the 85RAP+WCO+P compensated for the unfavourable effect of LDPE, so that this blend revealed the best fatigue performance amongst the blends under comparison.

Nevertheless, taking the usual values of ε_6 obtained for conventional AC into account, it must be highlighted that all the values of ε_6 revealed a very good behaviour of the rejuvenated AC with LDPE against fatigue cracking, with values above 200 μm/m (10 Hz, 20 °C).

3.2.3. Permanent Deformation Resistance

Figure 11 illustrates the variation of rut depth formed on the slabs after wheel-tracking tests.

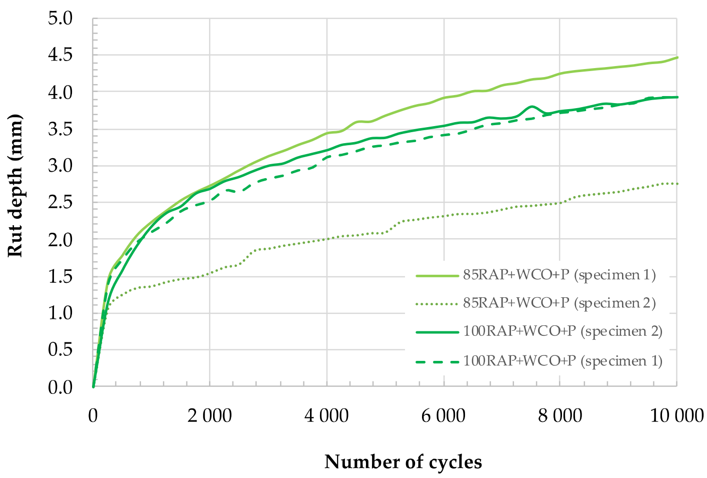

Figure 11. Rut depth recorded in wheel-tracking tests.

According to EN 12697-22, the evaluation of asphalt concrete is based on two testing replicates. In this case, the results of rut depth for 85RAP+WCO+P revealed some scatter, which may be related to some heterogeneity of the material. On the contrary, the slopes of the curve rut depth vs. number of cycles revealed much less dispersion for this blend. Table 8 summarises all the parameters derived from wheel-tracking tests.

Table 8. Permanent deformation resistance results.

Parameter	RD_{air} (mm)	PRD_{air} (%)	WTS_{air} (mm/10^3 cycles)
100RAP+WCO+P	3.93	9.50	0.120
85RAP+WCO+P	3.64	9.03	0.145
WCO-rejuvenated AC [22]	7.60	14.80	0.339

The results of 100RAP+WCO+P showed that the incorporation of LDPE increased significantly the resistance to permanent deformation in comparison to the performance measured in [22] (without LDPE). Although the combined effect of using LDPE and adjusting the 85RAP+WCO+P gradation improved the permanent deformation resistance, the results were below expectations because the proportion of aged binder was lower in this blend.

4. Discussion

Figure 12 compares the relative performance of the tested blends to others used for comparison regarding resistance to permanent deformation (PRD_{air} and WTS_{air}), stiffness, phase angle, fatigue resistance, and water sensitivity. For a specific parameter, the best performant mixture is represented by a relative performance of 100%. The other blends have a lower percentage, which represents the relative performance of each blend in comparison with the best performant one.

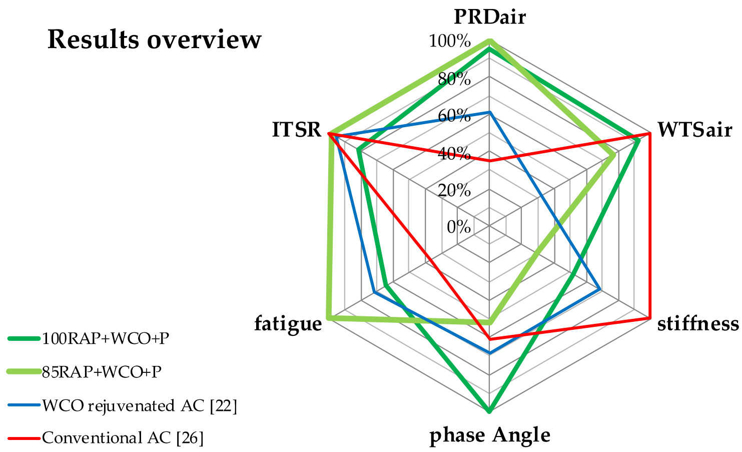

Figure 12. Relative performance of blends.

The analysis of results confirms that all the studied blends have good performance regarding resistance against moisture. Indeed, the ITSR values are close for all the blends and, as mentioned before, higher than 80%. Consequently, the achieved level of adhesion between the aggregate and the binder (aged + virgin + WCO + LDPE) seems to be satisfactory.

Another highlight from Figure 12 is that the permanent deformation resistance was considerably improved with the incorporation of LDPE in the blends. This finding is more obvious when the PRD_{air} values are considered. However, the performance level in comparison with that of the conventional hot-mix AC studied in [26] is clearly better for both PRD_{air} and $WTS_{air.}$ These results clearly show that the use of LDPE as a binder modifier improved the weakness of the rejuvenated blend studied by Fernandes et al. [22]. Even so, the level of performance did not reach the permanent deformation resistance of the AC with LDPE (without RAP) evaluated by Almeida et al. [26], as presented in Table 4.

In terms of fatigue resistance, the use of LDPE in 100RAP+WCO+P reduced the blend's performance in comparison with the mixture studied by Fernandes et al. [22]. On the contrary, this effect was absent in the 85RAP+WCO+P because the proportion of virgin binder was higher and, thus, there was a larger proportion of rejuvenated bitumen within the blend, resulting in a better fatigue resistance. Moreover, it must be stressed that all the rejuvenated mixtures performed better as far as fatigue cracking than the conventional AC.

It was expected that the addition of LDPE would increase the stiffness values of 100RAP+WCO+P in comparison to those measured by Fernandes et al. [22], but the opposite occurred. Although the authors do not have a definitive explanation for this, it may be attributed to the gradation of RAP. In fact, the beams made to perform four-point bending tests were produced with RAP from the same source as the RAP used by Fernandes et al. [22], but from a different batch, which was slightly finer, below the size of 4 mm. Because finer fractions usually contain higher binder content, this may have produced a richer mastic and, thus, lower values for stiffness. Also, apparently, this effect was greater than the stiffening effect of LDPE. This issue requires further research to try to better understand the tendency observed.

For 85RAP+WCO+P the effect described above was accompanied by a higher percentage of virgin bitumen in this blend, which may have contributed to a better rejuvenation of the RAP's aged binder and, thus, resulted in greater reduction of stiffness and increase of phase angle in comparison to the results obtained by Fernandes et al. [22].

Even so, the stiffness levels achieved, particularly for 100RAP+WCO+P, were great enough to use these rejuvenated blends as a pavement asphalt concrete. Moreover, the values measured for phase angles of 100RAP+WCO+P were lower than those measured by Fernandes et al. [22]. This result reveals the contribution of LDPE to a more elastic behaviour of the rejuvenated AC, as illustrated in Figure 13, considering the lower values of phase angle for similar values of stiffness. This was not observed for the 85RAP+WCO+P, since this blend had a higher proportion of virgin bitumen, which led to a less elastic behaviour.

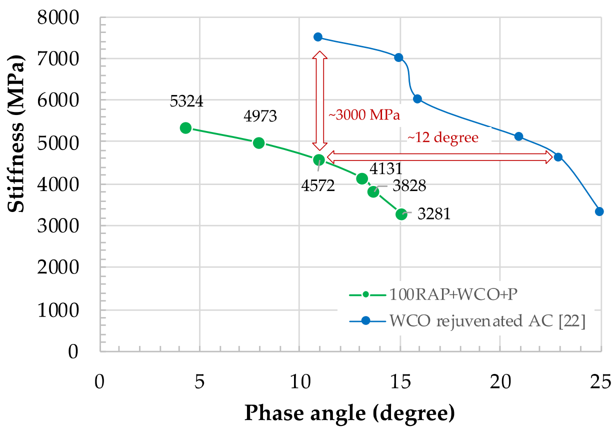

Figure 13. Results of stiffness as a function of phase angle (Black diagram).

A more detailed analysis of the stiffness and phase angle results (Figure 9) reveals that the rejuvenated asphalt mixture studied in [22] (without LDPE) was much more sensitive to the testing frequency (i.e. the speed of vehicles) than 100RAP+WCO+P and 85RAP+WCO+P. So, if the speed of vehicles reduces, the capacity of spreading loads will be lower for the rejuvenated asphalt mixtures with LDPE. For instance, by reducing the frequency from 20 Hz (approx. 126 km/h) to 5 Hz (approx. 31 km/h) the variation of stiffness and phase angle will be 127 MPa/Hz and 0.4 degree/Hz, respectively, for the blends studied in [22], whereas those rates will be 56 MPa/Hz and 0.33 degree/Hz for the 100RAP+WCO+P.

Figure 14 shows the result of applying a technique to rank the blends previously used by the authors elsewhere [6]. This ranking procedure uses six parameters from results to calculate a single score. These parameters are RD_{air}, WTS_{air}, stiffness, and phase angle at 10 Hz and 20 °C, ε_6 and ITSR. The first step consists in normalising these parameters to allow expressing them in a scale from 0% to 100%. This is done by dividing each individual value by the maximum of them, except for RD_{air}, WTS_{air} and ITSR, which are divided by the minimum. The global score is the sum of all the normalized parameter by applying the following weights to each one: RD_{air} 15%; WTS_{air} 15%; stiffness 20%; phase angle 5%; ε_6 40%; ITSR 5%. Values closer to 100% signify a better global performance than lower scores.

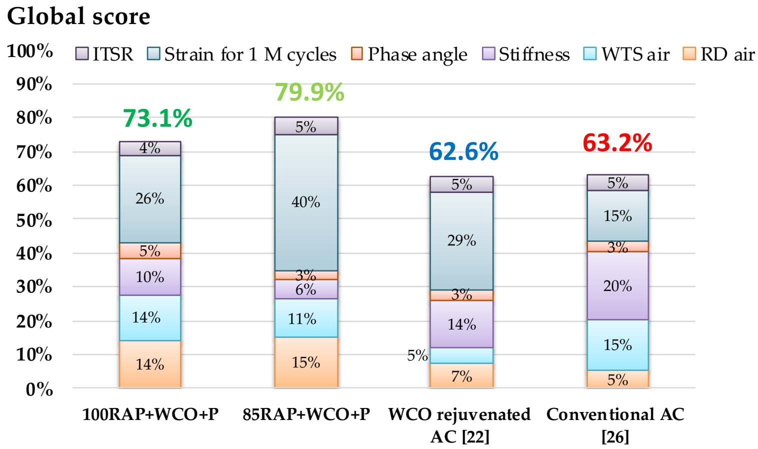

Figure 14. Ranking of the blends based on a global score for performance.

The global analysis presented in Figure 14 shows that 85RAP+WCO+P was the best performant blend. Nevertheless, this score was achieved particularly because this blend revealed a superior fatigue performance, which was derived from the higher amount of virgin binder within the mixture. Comparing the score of 100RAP+WCO+P to that of 85RAP+WCO+P for the remaining parameters, the first one performed better. Furthermore, itwas apparent that the incorporation of LDPE as a binder modifier improved the global performance of the WCO-rejuvenated AC studied by Fernandes et al. [22], achieving a higher score than the conventional AC.

5. Conclusions

The study described in this paper focused on the evaluation of the mechanical performance of asphalt concrete to be applied in surface or binder layers of road pavements mostly formed by full recycled RAP, WCO, and flakes of LDPE. Gathering information about blends previously studied by the authors' research team, mainly on either asphalt concrete with full recycled RAP rejuvenated with WCO or asphalt concrete with flakes of LDPE used as a binder modifier, allowed the authors to define the base to develop the blends studied in this paper. The evaluation of the blends' volumetric properties and Marshall stability and flow were performed to find out if the results fulfilled the usual requirements. Although the raw materials and the produced asphalt concrete had not satisfied a number of empirical parameters defined in the Portuguese specifications, the study proceeded to a performance-oriented stage in which fundamental properties of the studied blends were evaluated in a testing laboratory plan.

The information gathered and the laboratory evaluation of the blends produced with very high percentage of RAP, WCO as binder rejuvenator, and LDPE as bitumen modifier allowed for the conclusions presented below:

- The Marshall study showed high stability values for both 100RAP+WCO+P and 85RAP+WCO+P since these blends incorporated a high RAP proportion. The flow and stability/flow ratio met the usual specifications. For the sake of economy, the gradation of 100RAP+WCO+P was kept as it was, i.e., with a high percentage of fine particles resulting from milling. As gradation did not meet the grading envelope usually used for AC blends for surface layers, the porosity of 100RAP+WCO+P resulted in values slightly below the usual range.

- The water sensitivity measured by indirect tensile strength was quite satisfactory for both mixtures, but the 85RAP+WCO+P performed better because the quantity of virgin binder was higher in this blend.
- Using LDPE as binder modifier changed the deformability of 100RAP+WCO+P in comparison to the similar blend without LDPE previously studied, giving it higher elasticity, visible by the lower phase angle values measured. The stiffness values were also considerably lower for the studied blends, which were not expected, taking into account that LDPE was included as a binder modifier. A possible reason for this is that the 100RAP+WCO+P was produced from a different batch of RAP (slightly finer), thus richer in aged bitumen, than that applied to manufacture the blend without LDPE used for comparison. This issue requires additional study to try to clarify these results. Even so, the stiffness moduli values attained, particularly for 100RAP+WCO+P, are adequate to use these rejuvenated blends with WCO and LDPE to build asphalt concrete pavements.
- The increase of elastic behaviour was also observed for the studied blends with LDPE by showing lower sensitivity of stiffness and phase angle to the speed of loading, allowing the material to spread stresses with lower change for a larger range of loading conditions.
- Regarding permanent deformation resistance, the wheel-tracking tests showed a good performance for both 100RAP+WCO+P and 85RAP+WCO+P. The uniaxial cyclic tests carried out to evaluate resistance to permanent deformation also captured that good performance but ranked those blends in differently. The heterogeneity of the specimens resulting from the mixing method in a planetary mixer and compaction by vibro-compression were likely to have produced some scatter for 85RAP+WCO+P results.
- Using LDPE reduced fatigue resistance of blend 100RAP+WCO+P in comparison to the mixture previously studied without LDPE. Nevertheless, this effect disappeared for the 85RAP+WCO+P, which had a higher proportion of virgin binder and, consequently, a larger proportion of rejuvenated bitumen. Nevertheless, the most important conclusion is that the rejuvenated mixtures with WCO and LDPE performed better with regard to fatigue cracking than the conventional AC.

A global analysis of the rejuvenated blends with WCO and LDPE as binder modifier, carried out by using six calculated performance indicators, showed that those blends performed better than a conventional mixture used as reference. In addition, that global study also revealed that the incorporation of 6% of LDPE (by mass of bitumen) had a favourable effect on the permanent deformation resistance, while keeping a very good performance in terms of resistance to fatigue cracking.

Finally, the actions performed in this study showed that full recycling of RAP, rejuvenated with WCO and LDPE flakes as a bitumen modifier, is feasible and has a great potential as a paving material, particularly for low and intermediate traffic roads. Furthermore, this type of material can contribute to reducing inadequate deposition of WCO and waste of LDPE in nature, as well as to reducing energy consumption and CO_2 emissions. The authors are aware that the studies on this type of asphalt concrete must continue to fully understand its long-term behaviour, especially after aging, and the life cycle analysis.

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

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