Recycled asphalt mixtures produced with high percentage of different waste materials

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ABSTRACT

The use of sustainable solutions in construction is not just an option, but is increasingly becoming a need of the Society. Thus, nowadays the recycling of waste materials is a growing technology that needs to be continuously improved, namely by researching new solutions for waste valorisation and by increasing the amount of wastes reused. In the paving industry, the reuse of reclaimed asphalt (RA) is becoming common practice, but needs further research work. Thus, this study aims to increase the incorporation of RA and other waste materials in the production of recycled asphalt mixtures in order to improve their mechanical, environmental and economic performance. Recycled mixtures with 50% RA were analysed in this study, including: i) RA selection, preparation and characterization; ii) incorporation of other waste materials as binder additives or modifiers, like used motor oil (UMO) and waste high-density polyethylene (HDPE); iii) production of different mixtures (without additives; with UMO; with UMO and HDPE) and comparison of their performance in order to assess the main advantages of each solution. With this study it was concluded that up to 7.5 % of UMO and 4.0 % of HDPE can be used in a new modified binder for asphalt mixtures with 50 % of RA, which have excellent properties concerning the rutting with WTS = 0.02 mm/10^3 cycles, the fatigue resistance with ε6 = 160.4, and water sensitivity with an ITSR of 81.9 %.

Keywords: Pavement recycling; Reclaimed asphalt (RA); High-density Polyethylene (HDPE); Rejuvenator; Used motor oil; Waste materials; Mixture performance.

1. Introduction

A common issue in which the Society is focused nowadays is the recycling of used materials, based on their economic and environmental value. The constant population growth and of the higher standard of living cause an increase on the production of waste. Therefore, developed countries have taken conscience that waste management is a fundamental key to solve this emergent and serious problem. Not only urban waste, as bottles, paper, organic waste, but also industrial waste and construction and demolition waste must be carefully processed in order to reduce their environmental impact and maximize their valorisation. The specific area of road paving industry is also addressing that topic, where recycling of reclaimed asphalt (RA) materials [1] and the incorporation of other wastes and by-products [2] in road pavements have been tested and applied in recent years.

In fact, a large number of studies are presently concentrated on the use of RA. Several techniques are amply developed to incorporate this type of materials and their selection depends on the country and on the materials and methods available [3-6]. The technological evolution observed in the last years has resulted in an increase of the amount of RA incorporated in the production of new/recycled asphalt mixtures, being possible to include RA percentages in the order of 50% [7-9]. Other studies [10, 11] also assessed the possibility of incorporating 100% of RA in “new” totally recycled mixtures, which were able to show characteristics similar to those of a conventional asphalt mixture.

The incorporation of RA in new mixtures is a way to reuse materials, decrease the quantity of waste placed in landfills and decrease the need of new materials, preserving the natural resources. The bitumen of RA materials is normally aged, and thus it is necessary to add some sort of rejuvenating agent to improve the workability and flexibility of the recycled mixtures incorporating RA materials. The use of commercial rejuvenators is a way to solve the problem, but it increases the cost of the final mixture [12, 13]. Despite the cost of the rejuvenators, their influence on the properties of the final mixtures is usually enough to justify their use. However, in order to reduce the cost of the rejuvenator and incorporate higher amounts of waste in new asphalt mixtures, a previous study [10] tried to apply used motor oil (UMO) as a different type of bitumen rejuvenator. The results obtained in that study were very promising, since UMO effect on aged bitumen was similar to that of a commercial rejuvenator.

The amount of rejuvenator to be included in a recycled asphalt mixture is limited in order to avoid rutting problems, but the use of polymers can be a solution for this restriction. In fact, polymers have been traditionally used as additives to modify the properties of asphalt binders, in order to improve the mechanical properties of the asphalt mixtures. Virgin elastomers and plastomers have been successfully studied and used as asphalt modifiers. The most commonly used are the styrene–butadiene–styrene (SBS) block copolymers [14], although other polymer types have also been tested. Al-Hadidy and Yi-qiu [15] have also used low density polyethylene (LDPE), with very positive results. Polacco et al. [16] also obtained positive results, especially with linear low-density polyethylene (LLDPE). Other polyethylene-based polymers were tested in that study, but in all cases the obtained polymer-modified asphalt had a heterogeneous structure and showed storage instability. High-density polyethylene (HDPE) was also studied as asphalt modifier [17], and it was possible to observe that more economic pavements with higher performance and durability can be obtained by using 5% HDPE for bitumen modification. The good results obtained in these studies led to more recent studies with waste plastics (polymers) for bitumen modification [18]. In this context, plastic package waste [19] and plastic bottles waste [20] were both used in asphalt mixtures with encouraging results, allowing to conclude that the use of new or recycled polymers could ultimately give similar results, highlighting the more efficient use of waste plastic in environmental terms.

Taking the abovementioned into account, the main aim of the present study is to use higher amounts of different reclaimed materials in the production of new asphalt mixtures with a performance at least as good as that of conventional mixtures. The maximum percentage of RA incorporation is usually imposed by technical limitations of the asphalt plants. In this study, a percentage of 50% RA incorporation was defined, since that recycling rate can presently be used in some asphalt plants without significantly compromising their production rates. In order to increase the use of reclaimed materials in the asphalt mixtures, a recycled rejuvenator (UMO) and a recycled bitumen modifier (waste HDPE) were also used to improve the properties of the final binder, thus assuring an adequate performance of the new asphalt mixture.

2. Materials and methods

2.1. Materials

The present study has been carried out using a series of different materials. Taking into account the objective of maximising the recycling rate, 50% of reclaimed asphalt (RA) was added to the final mixture, reducing the use of raw materials to less than 50%. In order to improve the properties of the final mixture, other waste materials were also used, which were chosen with the objective of increasing the amount of reclaimed materials incorporated in the mixture. Thus, used motor oil (UMO) and waste high-density polyethylene (HDPE) have been used for bitumen modification.

In order to fulfil the European specification requirements (EN 13108-1 and 13108-8), the final mixture must present adequate characteristics in terms of aggregates particle size distribution, binder content, air voids content and mechanical properties. Thus, it was necessary to characterise the individual materials used prior to the production of the mixture, as described in the following subsections.

2.1.1. Reclaimed asphalt material

The RA used in this study was obtained from a motorway pavement in Portugal, by milling the thickness of the pavement corresponding to a single layer (surface course) in order to obtain a homogeneous material. After fifteen years in service, the pavement presented fatigue cracking, and thus the RA binder would be expected to be very hard after being exposed to such long term aging.

2.1.2. Waste materials used for bitumen rejuvenation/modification

Regarding the wastes used as additives to modify the bitumen, used motor oil and HDPE, these have different functions. The UMO was used to rejuvenate the aged bitumen of the RA. Actually, the addition of UMO to the aged bitumen is expect to increase its penetration grade and decrease its softening point [21].

The use of waste plastics/polymers to modify the binder is actually a current practice in scientific studies and most of these conclude that the use of these materials improve the performance of the asphalt mixtures [19, 20]. Based on the number of studies in this area, on the quantity of plastic wastes generated and collected, and on the alternative processes for their reuse, a waste HDPE was selected as being the option with higher potential of valorisation. This material has been obtained from a company that collects and treats waste polymers in the North of Portugal. After collection, the polymers undergo a visual separation process and a mechanical treatment to reduce the size of the particles for dimensions smaller than 4 mm. The HDPE used in this study was mainly obtained from waste plastic packaging.

2.1.3. New materials

With respect to the virgin aggregates used to fulfil the grading curve of the mixture, they are granite igneous rocks and the filler is limestone. These types of aggregates were chosen based on their availability in the region, and on the type of layer where they are expected to be used (surface course). Table 1 shows the main properties of the natural aggregates used in the study.

Table 1 Main properties of the natural aggregates

Property	6/14 mm agg.	4/6 mm agg.	0/4 mm agg.
Density (EN 1097-6), Mg/m3	2.66	2.65	2.66
Water absorption (EN 1097-6), %	< 1	< 1	< 1
LA Abrasion Coef. (EN1097-2), %	28	28	28

Taking into consideration a previous study carried out with the chosen RA [10], it was possible to conclude that the fine particles of that RA are excessive. For this reason, a maximum value for the percentage of fines to be introduced in the new mixture was imposed.

The virgin bitumen used was a 35/50 pen grade bitumen, because it is the most commonly used bitumen in Portugal.

2.2. Methods

2.2.1. RA characterization

The technological challenge of using high rates of RA in new asphalt mixtures has been difficult to overcome due to the reduction in the production rates and the potential additional damage induced in the aged binder during the production stage. Thus, in order to minimize these problems, a separation process has been adopted, where the RA material was divided into two fractions that would be subjected to different heating procedures. Oliveira, Silva [22] have tested the influence of different separation processes, and concluded that the best process would be to disaggregate the RA material lumps, after which, it would be separated into two fractions at an intermediate sieve (#8 mm).

The coarse RA fraction was then heated up with the virgin aggregates while the fine RA fraction (fraction with dimension below 8 mm), which is richer in bitumen, is protected from severe heating by being directly introduced in the mixer, at room temperature, during the mixing operation.

In order to study the best composition of the final asphalt mixture, it was necessary to carefully characterize each fraction of RA, namely their binder properties and their particle size distribution. The percentage of bitumen of each RA fraction was obtained by the ignition method (EN 12697-39). Different samples of each fraction were tested and the results showed low variation, which confirmed a good homogeneity of the different RA material samples. These results were essential to define the quantity of new bitumen to be added during the production of the final mixture. The bitumen of the different fractions of RA material was burnt during the incineration process (EN 12697-39), and then it is possible to evaluate the particle size distribution of their constituting aggregates, according to the EN 12697-2 standard. This information was then used during the mix design in order to determine the size and quantities of new aggregates to be used to fit within the grading envelope of a conventional surface course mixture.

In order to characterize the aged binder present in the RA, it was separated from the RA sample by dissolving it in toluene and, after removing all solid particles from the bitumen solution (using filter and tube centrifuges), the bitumen was recovered by vacuum distillation using a rotary evaporator, in accordance to the EN 12697-3 standard. For characterization of the bitumen, penetration (EN 1426), softening point (EN 1427) and dynamic viscosity (EN 13302) tests were used. The dynamic viscosity tests were performed at a range of temperatures (110-180 ºC), in order to study the viscosity at the mixing/compaction temperatures, using a rotating spindle apparatus, according to a predefined procedure [23].

2.2.2. Recycled HMA mix design

In order to assess the influence of each binder modifier (rejuvenator and polymer stabiliser), three asphalt mixtures were produced and characterised (Mixture A – without additives; Mixture B – with UMO; Mixture C – with UMO and HDPE). However, the mix design procedure was only carried out for the mixture without additives so that the effect of the additives could be analysed separately from that of having a different binder content in the final mixture. The best composition for the recycled HMA mixtures was thus obtained by means of using the empirical Marshall mix design method, as defined in the Portuguese specifications and in the EN 13108-1 standard.

Given that the empirical specifications are based on compositional recipes, the grading limits have to be strict and must be totally fulfilled, in order to enable the use of the mixtures in road pavements without premature distresses. Thus, the design grading curve of an AC 14 surf/bin was set for the recycled HMAs in order to fulfil the specification limits [24]. This type of mixture was selected because it can be used both in surface and binder courses, and because it would be easier to adjust this type of gradation to recycled mixtures with high RA contents.

In order to design the recycled AC 14 surf/bin mixtures and to evaluate their mechanical properties defined on the empirical specifications, five batches of mixture were prepared by using different percentages of bitumen between 4.0% and 6.0%, in intervals of 0.5%. For this mixture, the new aggregates, the coarse RA and the filler were batched and put in an oven at 200 ºC, while the fine RA was not heated and the new bitumen was heated at 150 ºC, except in the final mixture with HDPE where the process of bitumen modification imposes a temperature of 180 ºC . In order to achieve an adequate workability, the coarse RA and the new aggregates were both introduced in the mixer and blended for 1 minute. Then, the fine RA fraction was added and mixed for an additional minute, after which the new binder was added and the whole material was mixed during 2 minutes. After the mixing process, three specimens were compacted with 75 blows per face (EN 12697-30) for each percentage of bitumen and their bulk density was evaluated. The theoretical maximum density (TMD) of all the mixing batches was also assessed. The main volumetric characteristics (voids content and VMA) were calculated based on the previous results and on the binder content of the mixtures. Finally, all the specimens were tested by using the Marshall Test procedures (EN 12697-34), recording the load (stability) and deformation values.

According to the EN 13108-1 standard, the optimum binder content of the Marshall mix design method is the average value of the binder contents resulting from the maximum Marshall stability (EN 12697-34), the air voids content equal to 4% (for this AC 14 surf/bin mixture) and the maximum bulk density.

2.2.3. *Bitumen modification/rejuvenation*

Both additives used to modify the bitumen are considered waste. The objective is to assess if these waste materials can add extra value to the recycled asphalt mixture, with higher potential value than in other solutions. The first additive is used motor oil (UMO) and it should act as a rejuvenator, increasing the penetration and decreasing the softening point [21]. Presently, large quantities of UMO are still being used only for energy production (i.e., it is just burned). The second additive is high-density polyethylene (HDPE) and it should act as a stabilizer. This second additive will be especially used to stabilize the binder already modified with UMO, especially when using high amounts of oil that can originate permanent deformation problems.

The process of bitumen modification was different depending on the type of additive used. In the case of UMO, it is simply mixed with the bitumen at a temperature of 150 ºC with a digestion time of 5 minutes. The HDPE additive is solid, needing more time and heat to be molten into the bitumen. Thus, the digestion of the HDPE was made at a temperature of 180 ºC during 60 minutes. According to the RA properties and the mix design of the final mixture, the binder of the recycled mixture should be composed by 52% (2.6% out of 5.0%) of RA binder and 48% (2.4% out of 5.0%) of new 35/50 bitumen, referred in this article as base binder. Then, two percentages of UMO, 3% and 6%, were added to that base binder for rejuvenation. Finally, two percentages of HDPE, 3% and 6%, were added to the binder already modified with 6% of UMO in order to improve its stability. The choice for those percentages of additive/modifier has been taken based on information presented in the literature [16, 25]. In terms of production process, a low shear mixer and digestion times of 5 minutes (to blend the oil with the base bitumen) and 60 minutes (to digest the HDPE into the bitumen) were used. The properties of all these binders were finally compared with those of a conventional 35/50 pen binder.

2.2.4. HMA characterization and performance

The evaluation of the water sensitivity is determined in Europe by the EN 12697-12. According to this standard, two groups of three cylindrical specimens compacted with an impact compactor are tested for the indirect tensile strength (ITS) after a different conditioning period, in order to determine the influence of the water on the weakening of the bond between aggregates and binder and, consequently, on the strength of the mixture. During the conditioning period (between 68 and 72 hours), one group is kept dry (at ambient temperature) and the other is immersed in water at 40 °C, up to two hours before the tests. At that point, the specimens are moved to a different water bath and conditioned at 15 °C until the time of testing.

Following the determination of the ITS of each specimen, it is possible to calculate the average value of each group and the indirect tensile strength ratio (ITSR), which corresponds to the ratio between the ITS of the wet group (ITSw) and the dry group (ITSd) of specimens. The air voids content of the specimens were also assessed due to its great influence in the water sensitivity performance of the asphalt mixtures.

Different tests can be used to assess the rutting resistance of asphalt mixtures, based on static or rolling loads, in laboratory or real scale. For this study, the laboratory Wheel Tracking Test (WTT) was chosen, which is described in the EN 12697-22 standard (procedure B, in air). The test temperature of 50 ºC was defined based on the climatic conditions of the region and the other test conditions were established according to the mentioned standard (wheel load = 700 N, test frequency = 0.44 Hz and 10000 loading cycles. The main parameters that can be obtained from this test are the Wheel tracking slope (WTS_{AIR}) between the 5000th and the 10000th cycles, and the Proportional Rut Depth, (PRD_{AIR}) and the maximum Rut Depth (RD_{AIR}) at the end of the test.

Besides the rut resistance, one of the most important properties to assure an adequate performance of asphalt mixtures is the fatigue cracking resistance. The fatigue test carried out in the present work consists in supporting a prismatic specimen in four points and applying a sinusoidal load in the two central points, bending the specimen in a similar way of that imposed by the vehicles in a pavement layer. The four-point bending test was carried out according to the EN 12697-24, for the test temperature of 20 ºC and with a frequency of 10 Hz in controlled strain. Thus, the test would be concluded when the specimen's stiffness reached half of its initial value. In order to fully characterize the asphalt mixture in terms of fatigue resistance, a number of specimens are tested using different strain levels.

Another important property of asphalt mixtures is their stiffness modulus, namely because this parameter is used for pavement design. As in the fatigue resistance test, a four-point bending apparatus was used to determine the stiffness modulus of the mixtures. In this case, the specimens are not damaged during the test and are submitted to a frequency sweep load at 0.1, 0.2, 0.5, 1, 2, 5, 8 and 10 Hz, according to the EN 12697-26 standard. In order to obtain a characterization of the mixtures in a wider range of testing conditions, the tests were repeated for different temperatures, namely 0, 10, 20 and 30 ºC.

3. Results and discussion

3.1. RA characterization

Knowing the RA characteristics is crucial to design recycled asphalt mixtures correctly. Therefore, it is very important to spend some time analysing the RA. In this study, and based on the procedure suggested by Oliveira, Silva [22], the RA was submitted to a mechanical disaggregation, in order to reduce the amount of lumped particles present in the RA material. Figure 1 shows the particle size distribution of the RA material before and after the disaggregation process.

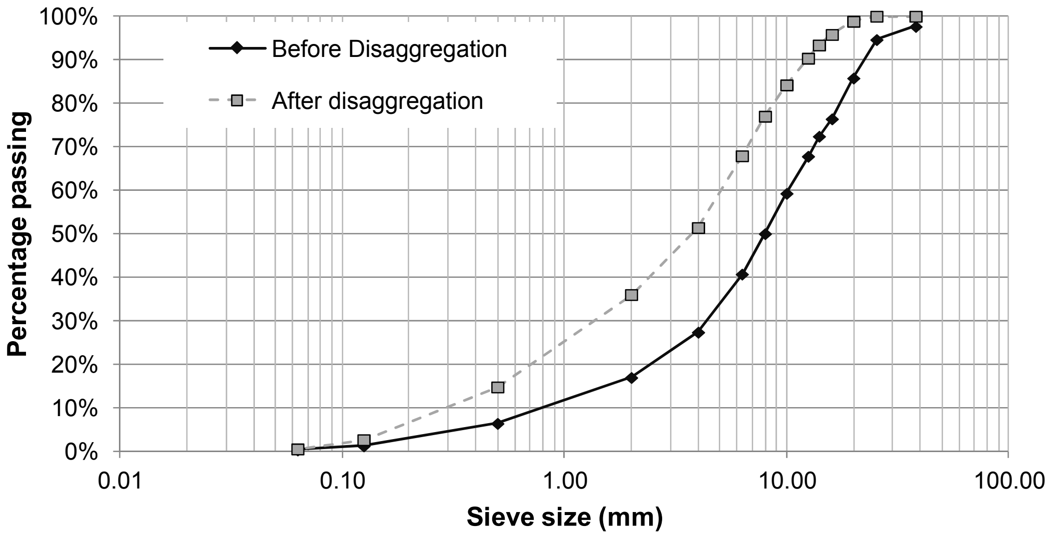
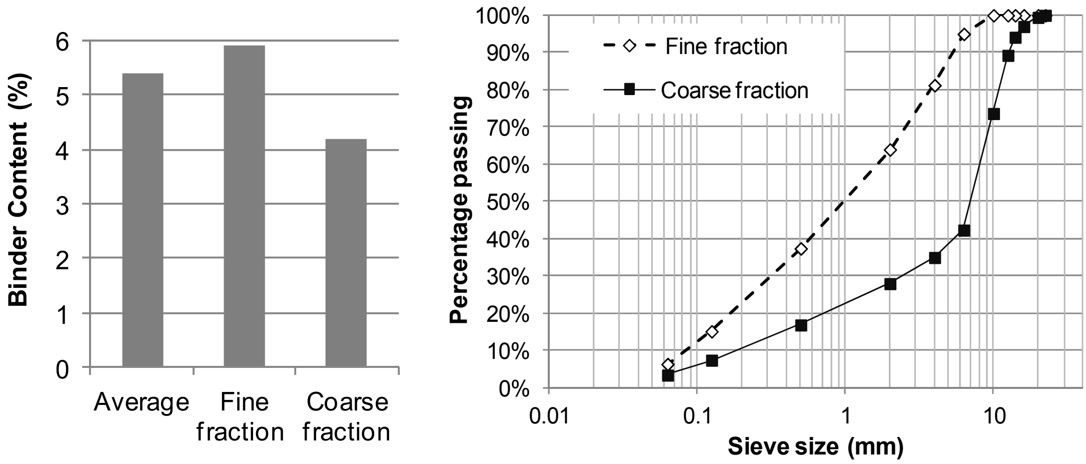


Figure 1 Gradation of the RA before and after disaggregation

In respect of the particles maximum size, it is possible to conclude that a considerable decrease was observed, which shows the efficiency and importance of this disaggregation process. Analysing the grading curve of the material after disaggregation, it can be seen that the percentage of fine RA passed in the sieve size of 8 mm greatly increases from 50% to 77%.

After the disaggregation process the RA material was separated into two different fractions (coarse RA and fine RA) and their characteristics had to be analysed separately. Firstly, the percentage of bitumen present in both fractions was determined (Figure 2a) and then the particle size distribution of their aggregates was assessed after burning the binder (Figure 2b). As expected, the binder content of the fine RA fraction is higher than that of the coarse RA fraction. Regarding the particle size distribution it is possible to see that the coarse RA fraction has nearly 40% of fine particles which are difficult to disaggregate and remained lumped in bigger particles bound by the bitumen. These fine particles were only visible after the process of removing the bitumen.

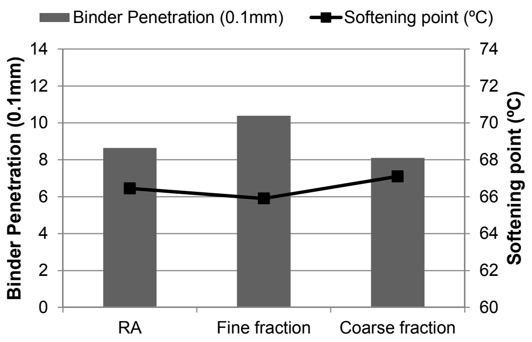


a) b)

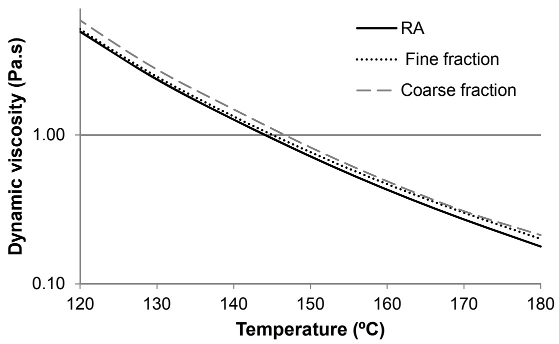
Figure 2 Binder content (a) and particle size distribution after incineration (b) of the different RA fractions

In order to finalize the characterization of the RA material it is important to determine the main characteristics of the aged bitumen. Thus, after extracting the bitumen from the RA material, three different samples were analysed: the first (named by RA) is the bitumen recovered from a sample of RA without separation; the second (fine fraction) and the third (coarse fraction) are the samples of bitumen recovered from each of the corresponding RA fractions. Figure 3 presents the results of this characterization, namely the penetration, softening point temperature and dynamic viscosity.

All the results presented in Figure 3 show a very hard binder with penetration values around 10 × 0.1 mm, although it is possible to observe that the coarse fraction sample is slightly harder (more aged) than the fine fraction sample. This can be explained by the higher exposure of the coarser aggregates to oxygen, while the fine aggregate particles and involved by a thicker and more impervious (to the air) layer of binder.



a)



b)

Figure 3 Penetration and softening point (a) and Dynamic Viscosity (b) results of the binders recovered from the RA before and after separation in two fractions

3.2. Recycled HMA mix design

As previously mentioned, the mix design of the asphalt mixtures was carried out according to the Marshall Test methodology. The aggregates' particle size distribution follows the specifications limits as can be seen in Table 2. This was obtained by imposing a relative amount of 30% fine RA fraction and 20% coarse RA fraction. The remaining composition of the aggregate fractions was as follows: 38% of 6/14 mm aggregate, 5% of 4/6 mm aggregate, 4% of 0/4 mm aggregate and 3% of filler.

Table 2 Aggregate gradation limits of the used mixture

Sieve size (mm)		20.0	14.0	10.0	4.0	2.0	0.50	0.125	0.063
Percentage passing	Max	100.0	100.0	77.0	52.0	40.0	19.0	11.0	8.0
	Min	100.0	90.0	67.0	40.0	25.0	11.0	6.0	5.0
Used mixture		99.9	97.7	76.3	42.7	31.2	17.6	10.2	6.3

From Table 3, it was found that the optimum binder content of the recycled mixture is 5%. With that amount of total binder, only 2.4% of new bitumen should be added, since 2.6% of aged bitumen is already present in the RA fractions. .

Table 3 Results of the Marshall Mix Design Method

Binder content (%)	MTD (kg/m^3)	Bulk density (kg/m^3)	Voids Content (%)	VMA (%)	Marshall Stability (kN)	Marshall Flow (mm)
4.0	2493.44	2231.53	10.50	19.17	15.76	3.93
4.5	2451.94	2248.73	8.29	18.11	16.56	3.97
5.0	2431.43	2346.51	3.49	14.88	17.72	4.17
5.5	2412.46	2333.61	3.27	15.73	15.03	5.13
6.0	2406.15	2331.02	3.12	15.31	15.02	5.21

As previously mentioned, the binder content of the mixtures produced with additives was kept constant so that the variation on the performance of the mixtures mainly depends on the effect of the additives (dependent variable). Nevertheless, the dosage of each additive/modifier had to be studied. This evaluation was carried out by adding different percentages of both additive/modifier (UMO and HDPE) to a sample of base binder (BB) composed by 52% of RA recovered binder and 48% of new 35/50 pen grade bitumen. The properties of these binders were analysed in order to obtain a binder that could be classified as a reference 35/50 pen binder typically used in Portugal. First, 3.0 and 6.0% of used motor oil were used to soften the BB. Then, as the sample of binder with 6.0% UMO was softer than expected, 3.0 and 6.0% of HDPE were added to stabilize the binder without reducing the amount of the other additive used. The results of the basic characterization of the several binders are presented in Figure 4, as well as the specification limits presented in EN 12591.

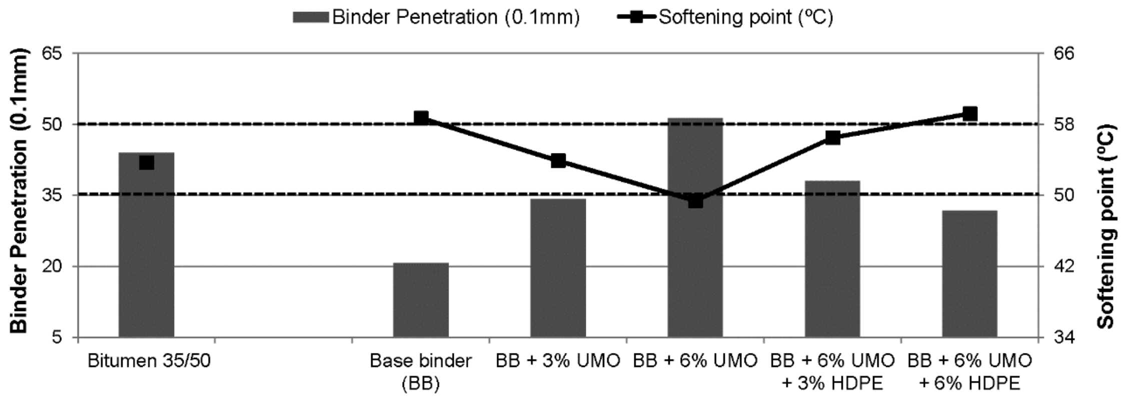


Figure 4 Penetration and softening point of the reference bitumen (35/50 pen), of the base bitumen and of the modified binders

As expected, it was observed that the base binder is very hard, due to the high quantity (52%) of aged bitumen of this material. The addition of UMO to this BB quickly increases the penetration value and reduces the softening point temperature. The target characteristics of the BB modified with UMO can be obtained by adding nearly 3 to 6% of UMO. HDPE has an opposite effect to that of UMO. In fact, the addition of HDPE decreases the penetration values and swiftly increases the softening point temperature.

Figure 5 was developed with the penetration results previously presented in order to facilitate the definition of the possible combinations of UMO and HDPE that would result in the reference 35/50 pen bitumen. The results of the BB before and after modification with UMO and HDPE (blue dots presented in Figure 5) allowed to obtain an oblique plane. The intersection of this plane with a front plane (corresponding to the target penetration value of the reference 35/50 pen bitumen) yielded a line with the possible combinations of UMO and HDPE.

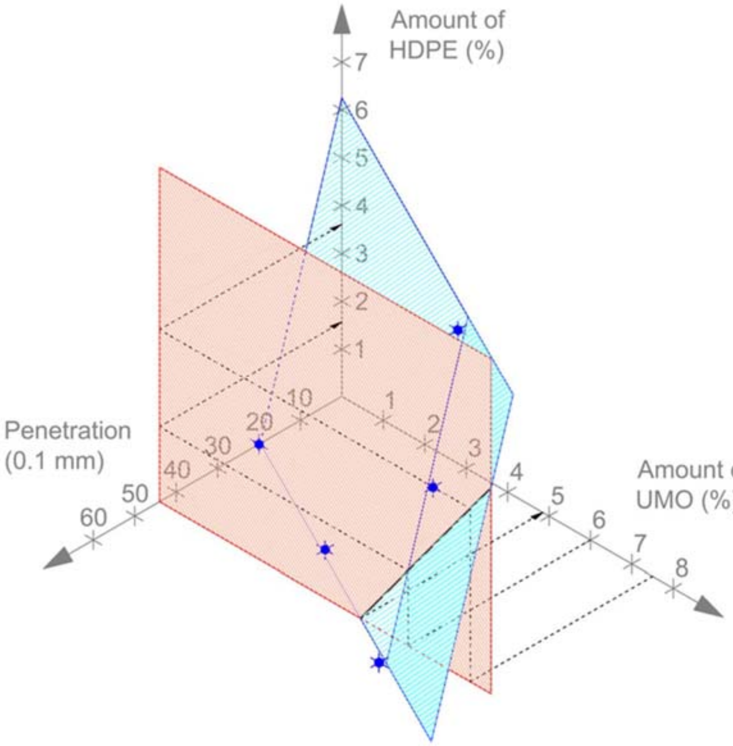


Figure 5 Evolution of the binder penetration (0.1 mm) with the increase in the percentage of additive/modifier added

Analysing the results presented in Figure 5, it is possible to observe that without using HDPE the optimum percentage of UMO is around 5.0%. This combination without HDPE was selected for HMA characterization (Mixture B). Moreover, for a binder with 6% of UMO, it was observed that the optimum amount of HDPE that would turn the binder into a 35/50 pen bitumen is very low (1.5%). Thus, in order to obtain a binder with a higher amount of reclaimed materials (UMO and HDPE), another mixture with 7.5% of UMO and 4.0% of HDPE was selected (Mixture C) to be produced and characterized in the following stages of this work.

3.3. HMA characterization and performance

As mentioned above, three different mixtures were produced in the lab to determine the effect of the additives in the performance of the mixtures. Mixture A was produced without additives, while Mixture B was produced with a binder modified with 5.0% UMO and Mixture C with a binder modified with 7.5% UMO and 4.0% HDPE.

3.3.1. Water sensitivity

Water sensitivity is a very important characteristic for asphalt mixtures, since it provides valuable information about how the mixture will behave in contact with water and is also a good indicator of the long term performance (durability) of the mixtures. If the mixture is not properly designed, its contact with water may potentially cause disaggregation of the mixture. Table 4 represents the water sensitivity and the indirect tensile strength results of the three mixtures and their relationship with the air voids content.

Table 4 Water sensitivity test results

Mixture	ITSR (%)	Air voids (%)	ITSd (kPa)
Mixture A	77.6	4.9	2254.7
Mixture B	81.5	3.7	1321.0
Mixture C	81.9	4.4	1256.1

It can be observed that the air voids content are different, but all of them fulfil the specification limits of 3 to 5% for this type of mixture. Mixtures A and C are those that show higher air voids contents that result from the harder binder present in mixture A (the base binder presented in Figure 4 before modification) and from the use of HDPE for bitumen modification in mixture C.

Observing the ITSR values of the mixtures it is possible to conclude that the mixtures with additives have a higher water sensitivity performance than that of the mixture without additives. In conventional asphalt mixtures, it is generally accepted that lower voids contents will result in higher ITSR values and, therefore, in an increased durability of the mixtures. This may justify the good ITSR result observed in mixture B. However, in the case of Mixture C, it is not exclusively related to the reduced air voids content, but also with an increased performance provided by the use of the HDPE.

Analysing the indirect tensile strength values of the dry specimens (ITSd), it can be observed that mixture A is significantly stiffer than Mixtures B and C, withstanding a tensile stress of about two times the stress of the other mixtures at failure. This can be associated to a higher brittleness of the mixture, which should indicate that the mixture may have a higher stiffness modulus and a lower fatigue cracking resistance. The softening effect of the used motor oil on the aged binder is also obvious from these results, as it is the main responsible for the reduction of the ITSd values of Mixtures B and C (in comparison with Mixture A).

3.3.2. Resistance to permanent deformation

The resistance to permanent deformation, also known as rut resistance, is one of the most important characteristics for asphalt mixtures in countries with high in service temperatures. In this study the evaluation of this characteristic was made by performing the standard WTT evaluation. Table 5 shows a summary of the WTT results obtained.

Analysing the results, it is possible to conclude that Mixture C has a significantly higher rut resistance than the others mixtures. In fact, the evolution of the deformation during the test (WTS) and the final rut depth of Mixture C are both very low, confirming the very good performance of this mixture at high temperatures.

Table 5 Wheel Tracking Test results

WTT characteristics	Mixture A	Mixture B	Mixture C
Average thickness (mm)	42.27	40.81	41.51
Wheel tracking slope (WTS_{AIR}) (mm/10^3 cycles)	0.15	0.17	0.02
Proportional rut depth, max. (PRD_{AIR}) (%)	8.49	10.74	4.07
Rut depth, max. (RD_{AIR}) (mm)	3.59	4.39	1.69

Figure 6 represents a graph where the deformation of the mixtures is plotted against the number of cycles, based on the average values measured in the WTT. Again, Mixture C presented the higher performance (lowest deformation) due to the effect of the HDPE on the modification of the final bitumen, reducing its temperature susceptibility and increasing the stability of the mixture at high temperatures. The performance of this mixture was even higher than that of the mixture without additives, which comprised a harder bitumen. As expected, Mixture B showed the lowest rut resistance performance as a consequence of the softening effect of the UMO. However, this result does not impede the use of Mixture B in road pavements since its performance is close to that observed in Mixture A.

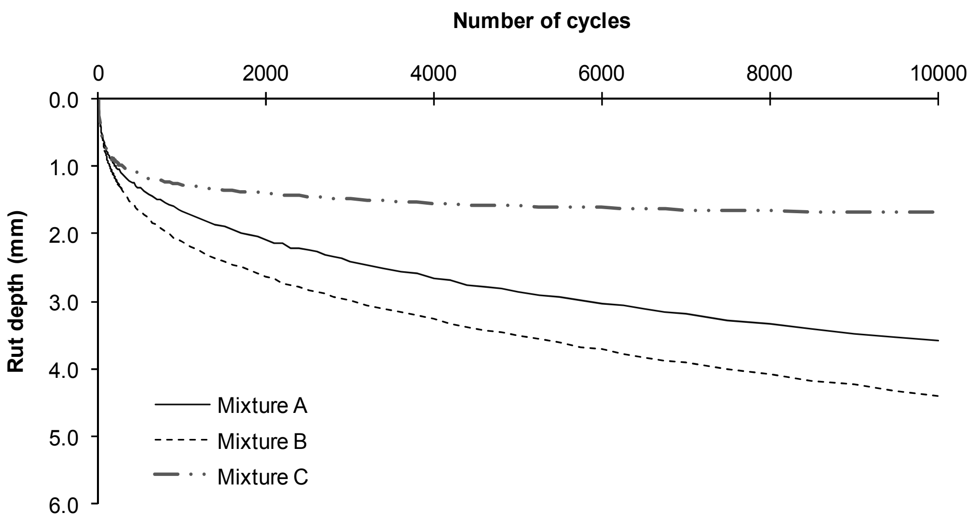


Figure 6 Rut depth evolution during wheel tracking tests

3.3.3. Fatigue cracking resistance

The fatigue cracking resistance is one of the characteristics of asphalt mixtures that most influence their performance under the effect of repeated traffic loads applied over a road pavement. The results obtained in the fatigue cracking resistance tests can be plotted in a graph and this property can be expressed by a fatigue life equation, as those represented in Figure 7.

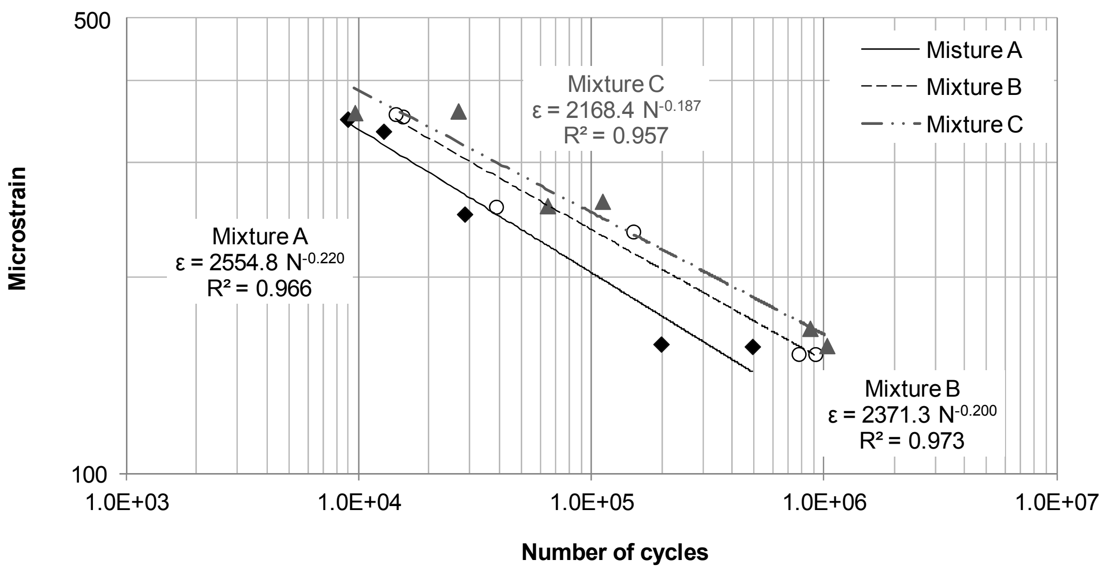


Figure 7 Fatigue life equations of the mixtures, tested at 20 °C

Based on these results, it is possible to conclude that the mixtures with modified bitumen present a longer fatigue life than that of the mixture produced without additives. Mixture C presented the best fatigue resistance performance.

The parameters specified in EN 12697-24 (N_{100} and ε_6) and presented in Table 6, which should be used to evaluate the fatigue performance of the studied mixtures, were estimated from the fatigue life equations presented in Figure 7.

Table 6 N_{100} and ε_6 parameters estimated from the fatigue life equations

Mixture	N_{100}	ε_6
Mixture A	2.18E+06	119.4
Mixture B	6.58E+06	147.4
Mixture C	11.23E+06	160.4

Both mixtures produced with the rejuvenating additive (UMO) showed higher values of N_{100} and ε_6 in comparison with those of the mixture without additives, but the influence of the HDPE on the modification of the final bitumen (Mixture C) is also significantly important in the improvement of the fatigue cracking resistance of mixtures with high reclaimed asphalt contents. Taking into consideration the N_{100} values presented in Table 6, the use of UMO and/or HDPE increased 3 (mixture B) to 5 (mixture C) times the fatigue life of the recycled mixtures in comparison with mixture A.

3.3.4. Stiffness Modulus

The stiffness test results were analyzed and represented by the use of Master Curves for a reference temperature of 20 °C. Based on the frequency-temperature superposition principle, namely by using the Arrhenius equation for a typical linear viscoelastic behavior of an asphalt material, it was possible to adjust and draw the master curves for stiffness modulus (E*), phase angle, storage modulus (E1) and loss modulus (E2) characteristics. These results are presented in Figure 8.

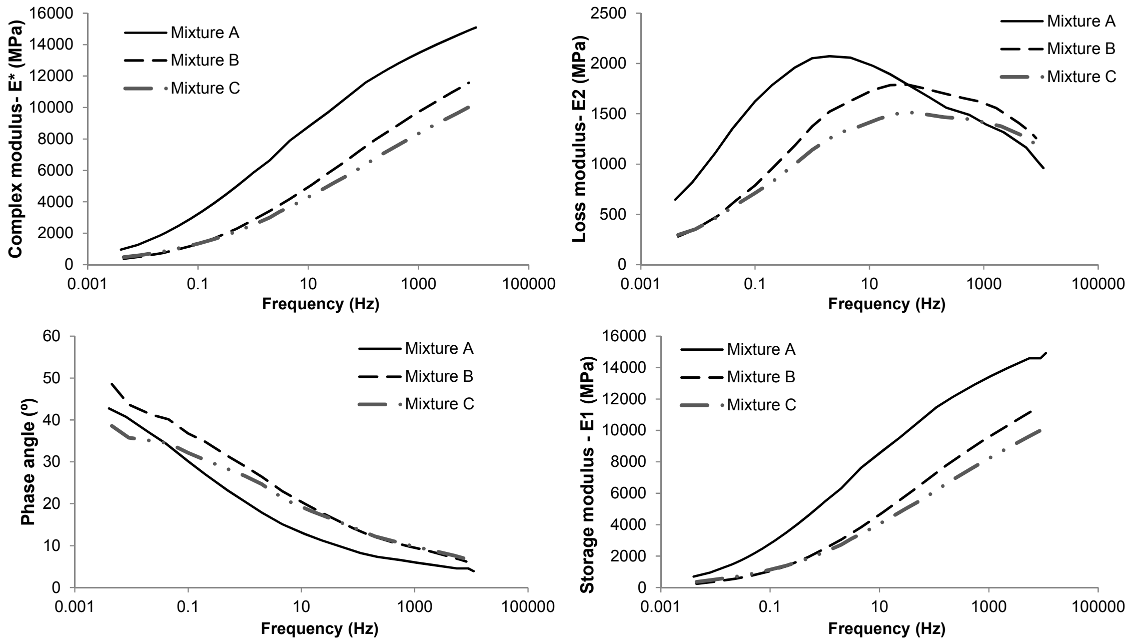


Figure 8 Stiffness master curves results obtained for a reference temperature of 20 °C

The different master curves confirm that mixture A (without additives) has the highest stiffness modulus and lowest phase angle at most frequencies. The incorporation of UMO decreased the stiffness modulus and increased the phase angle, as a consequence of the higher prevalence of the viscous component of the stiffness modulus (E2) at higher frequencies (or lower temperatures), thus improving the flexibility of mixtures B and C. This fact, together with the lower complex modulus of mixtures B and C, also justify the higher fatigue resistance of these mixtures previously presented. The positive stabilization influence of HDPE at higher temperatures (or lower frequencies) was also verified in the phase angle results, where mixture C presented the lowest phase angle at very low frequencies.

4. Conclusions

The results obtained in this study show that it is possible to increase the amount of reclaimed materials incorporated in asphalt mixtures while improving their performance, accomplishing the main objective of the paper. But other conclusions have also been achieved along of the study and they are presented below:

1. An adequate mix design of recycled asphalt mixtures can be obtained provided that the RA characterization is detailed and correctly carried out in order to obtain the best composition of the mixtures that result in an improved performance.
2. The bitumen present in the RA was of a low penetration grade, around 10×0.1 mm, which conditioned the selection of the optimum amount of additives that would turn this bitumen into a 35/50 pen binder.
3. A 35/50 pen bitumen was obtained by adding 5.0% of UMO (Mixture B) or 7.5% of UMO and 4.0% of HDPE (Mixture C) to the final mixture.
4. Mixture B presented some interesting characteristics in comparison with Mixture A, but Mixture C showed the best water sensitivity, rut resistance and fatigue cracking resistance results amongst the three mixtures.
5. The stiffness modulus of mixture C was not the highest, but it is still within the range of values normally expected for asphalt paving mixtures.

Thus, the combination of both additive/modifier (UMO and HDPE) that were obtained from waste materials proved to be a very good solution to increase the amount of recycled materials used in the production of asphalt mixtures while improving their performance. The UMO acted as a rejuvenator of the aged binder present in the RA material and the HDPE was used to stabilize the mixture, modifying the final binder and improving its performance.

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