Extended Abstract

Laboratory assessment of recycled bituminous mixtures with high RAP content

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Abstract

Due to the ageing of the road infrastructure and to ensure the safety of its users, the required maintenance operations generate a considerable amount of by-products. Among those, one can find the milled material from the bituminous layers, known as Reclaimed Asphalt Pavement (RAP), which is composed of aggregates and bitumen.

Even though both components of RAP are 100% recyclable materials, RAP has been recycled only as aggregate, downgrading its use and disregarding the bitumen's value. Indeed, the bitumen is aged after a pavement's service life, yet some of its properties can be recovered with the addition of a rejuvenator in the recycled mixture.

This dissertation aimed to evaluate the performance of a surface dense graded hot bituminous mixture that incorporated a high percentage of RAP (75%), treated with a rejuvenator. Its capacity of being re-recycled into another 75% RAP content mixture after enduring a service life was also evaluated.

An experimental laboratory study was carried out, encompassing the formulation of a recycled bituminous mixture, subjecting it to an oven-ageing procedure, the laboratory production of RAP, the production of a new mixture with that RAP and the assessment of both mixtures' mechanical and surface characteristics performance.

The results have shown that the mechanical performance of the recycled mixtures was better or on par with the reference mixture, while the superficial characteristics were slightly below the limits set in the Portuguese specifications.

Keywords: Reclaimed asphalt pavement, bituminous mixtures, circular economy, recycling, ageing

1. Introduction

The road infrastructure network is indispensable for society, enabling the functioning and development of a country by providing mobility and accessibility of people and goods. The maintenance required to be kept in such conditions that ensure the safety and comfort of its users generates a considerable amount of by-products.

Growing environmental concerns push for the transition to a circular economy, whose aim is to decrease waste production and natural resource depletion by reintroducing products at their end-of-life stage in the cycle, rather than disposing of them. In fact, in 2015, the EU has implemented the Action Plan for the Circular Economy, which advocates for a more efficient use of resources and for turning waste into secondary raw materials (European Commission, 2015).

In Europe, bituminous mixtures are the predominant construction material of the bound layers of a pavement and are 100% recyclable (EAPA, 2014). However, the reclaimed bituminous mixtures - or reclaimed asphalt pavement (RAP) as it is widely known - are recycled mostly in unbound layers as aggregates or in small percentages (5-20%) in new bituminous mixtures, which is not an efficient use of this resource, as the bitumen's properties are not being taken advantage of, thus downgrading the RAP (Zaumanis et al., 2016).

Furthermore, the exposure of the binder to the climate during its service life is an important aspect to be considered in recycled bituminous mixtures, especially when the RAP incorporation rate is high (>25%), as it has an ageing effect that changes the binder's properties. This ageing process makes the binder stiffer and influences the mixture's performance, therefore, when producing new mixtures with a high RAP content, it is recommended to use a softer binder or rejuvenator which improve the aged binder's properties (EAPA, 2018).

Indeed, in order to be viewed as a viable alternative to a traditional mixture, a recycled one and its materials should perform as well as the first, or better. Up to the present time, the performance of recycled mixtures has been evaluated in different conditions: with different percentages of RAP incorporation, with or without rejuvenator and different types of it and with or without fractionation of the RAP.

In general, those evaluations verify that increasing RAP content on recycled bituminous mixtures results in increasing stiffness, thus lowering cracking resistance and workability but increasing resistance to permanent deformation. The addition of a rejuvenator or a softer binder can enhance the workability, as they reduce the bitumen's/mixture's viscosity and stiffness, and, in the case of the rejuvenated mixtures, still keeping a high permanent deformation resistance (Mogawer et al., 2012; Zaumanis et al., 2015).

In spite of the positive results in those evaluations, the RAP recycling practice has been limited mostly due to the lack of confidence in the recycled pavement's performance, the increased complexity of the operation, the variability of the material and the unknown degree of mobilization of the aged binder (EAPA, 2014; Karlsson and Isacsson, 2006; Lo Presti et al., 2016; Zaumanis et al., 2016; Zaumanis and Mallick, 2015).

In essence, it is fundamental to deepen the knowledge on recycled bituminous mixtures in order to overcome the previously listed challenges and maximize the utility of RAP, bringing a contribution to the transition to a circular economy. As such, the main objectives of this study were to analyse the performance of a recycled bituminous mixture incorporating high RAP content after going through an ageing process, as well as the re-recycling capacity of RAP in new bituminous mixtures. Therefore, performance tests were carried out on:

(i) a recycled mixture incorporating 75% RAP before and after going through an ageing process.
(ii) a recycled mixture incorporating 75% RAP, whose aggregates and bitumen had already completed their second life cycle.
(iii) a reference mixture produced only with virgin materials, whose performance results were used as a benchmark.

2. Methodology and materials

2.1. Materials

For this study, the recycled mixtures were designed and produced in the laboratory. They included the following components:

(i) RAP milled from a Portuguese high trafficked road, whose aggregates and bitumen are of unknown origin and nature.
(ii) Basalt aggregates in the 10/16 mm, 4/12 mm and 0/4 mm fractions and limestone aggregates in the 0/4 mm fraction.
(iii) Bitumen with a penetration grade of 35/50.
(iv) Commercial rejuvenator derived from crude tall oil (a by-product of the paper industry).

Since the studied mixture incorporated a high percentage of RAP, an adequate characterization of its components (bitumen and aggregates) was essential. The tests used for the characterisation are identified in Table 1.

The RAP was characterised through the particle size distribution (EN 933-1), and was divided into four fractions: 19/25 mm; 12.5/19 mm; 4.75/12.5 mm; 0/4.75 mm. Each RAP fraction was individually characterized by its bitumen content (determined by the Soluble binder content - EN 12697-1) and particle size distribution (carried out on the aggregates left from the binder extraction procedure - EN 933-1).

In order to characterise the RAP binder, it was first recovered from each fraction using the rotary evaporator method (EN 12697-3). Then, the consistency and softening point were assessed by needle penetration (EN 1426) and the ring and ball method (EN 1427).

Regarding the percentage of rejuvenator to mix with the aged bitumen to recover its properties, it was defined through the assessment of the penetrations and softening temperatures of 3 %, 4.5 % and 7 % dosages (per weight of aged binder). After comparing those results to the desired properties of a 35/50 grade bitumen, defined in EN 12591, it was set that the percentage of rejuvenator to use was 4.5 %.

Table 1: Laboratory tests used to characterise the RAP

RAP characterisation		
EN 933-1	Particle size distribution	Characterisation of the aggregates
EN 12697-1	Soluble binder content	Determination of the bitumen content
EN 12697-3	Rotary Evaporator method	Recovery of the RAP binder
EN 1426	Determination of needle penetration	Characterisation of the binder
EN 1427	Determination of the softening point	Characterisation of the binder

2.2. Effect of production temperature and rejuvenator use in recycled mixtures

The unknown extent to which the aged binder is mobilized when producing a recycled mixture has been presented as an obstacle to the recycling practice. It is known, however, that it lies between total and no mobilization and also that it is dependent on the mixture production conditions (Nguyen, 2009).

Therefore, a set of blue Marshall specimens were produced to visually assess the extent to which the bitumen in the RAP is mobilized, the effect of the rejuvenator in the mixture and that of the heating temperatures of the various materials. The specimen components and respective production conditions are presented in Table 2.

Table 2: Production conditions for each blue specimen

	Components					
Specimens	Virgin Aggregates		RAP		Bitumen	Rejuvenator
	Percentage [%] per total weight of aggregates	Heating Temp. [°C]	Percentage [%] per total weight of aggregates	Heating Temp. [°C]	Percentage [%] per weight of specimen	Percentage [%] per weight of aged binder
0 RAP H	100	165	0	-	4	0
75 RAP H	25	165	75	165	4	0
75 RAP L	25	195	75	120	4	0
75 RAP LR	25	205	75	130	4	4.5

The H samples followed the mixing procedure described in EN 12697-35. The L sample differed in the heating temperatures of the virgin aggregates and the RAP. The LR sample was prepared following the rejuvenator's manufacturer guidelines (which are based on EN 12697-35).

Upon visual inspection of the blue Marshall specimens (depicted in Figure 1 and Figure 2) it was observed that the specimens were homogenous and did not exhibit aged binder film surrounding the aggregates, independently of the aggregate and RAP heating temperatures or the presence of the rejuvenator. Nevertheless, the mixing procedure that was adopted to continue this study was the one described in the rejuvenator's guidelines.

Figure 1: Blue specimens - top view

Figure 2: Blue specimens - half-cut view

From the top: 0 RAP H, 75 RAP H, 75 RAP L, 75 RAP LR

2.3. Bituminous mixture production and ageing

In order to approach the performance analysis of a recycled bituminous mixture incorporating high RAP content after going through an ageing process, two mixtures were produced and compacted in the laboratory: a reference mixture produced only with virgin materials and a mixture including 75 % of RAP and a rejuvenator. The reference mixture was a dense graded asphalt concrete with a maximum aggregate dimension of 14 mm and a bitumen with a nominal penetration grade 35/50: AC 14 surf 35/50.

The 75% RAP recycled mixture was designed using the Marshall method. It was set that the mixture would be composed of 25 % of virgin aggregates and 75 % of RAP and the amount of each fraction was determined accordingly, through a trial and error process, in which the gradation curve was fit between the upper and lower limits for the aggregate gradation of an AC 14 surf mixture, defined in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014a). The gradation curve, along with the upper and lower limits for the aggregate gradation of an AC 14 surf mixture, defined in specifications, is presented in Figure 3.

After determining the volumetric and Marshall properties of five sets of Marshall specimens (with varying the bitumen percentage between 4 % and 5.5 %, relative to the total mass of the specimen) , through the tests discriminated in Table 3, and comparing them to those set in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014a), the determined optimum binder content was 4.3 %.

Table 3: Laboratory tests used to determine the Marshall properties

Mix design		
EN 12697-5	Maximum density	Determination of the volumetric properties
EN 12697-6	Bulk density	Determination of the volumetric properties
EN 12697-34	Marshall test	Determination of the Marshall properties

This mixtures' performance was evaluated through stiffness, fatigue resistance, permanent deformation, water sensitivity and surface characteristics (macro and micro-texture). The tests used for the evaluation are identified in Table 4.

Table 4: Laboratory tests used to determine the mixtures' performance

Performance evaluation		
EN 12697-26	Stiffness	Characterisation of the stiffness
EN 12697-24	Resistance to fatigue	Characterisation of the fatigue behaviour
EN 12697-12	Water sensitivity	Determination of the effect of moisture
EN 12697-22	Wheel tracking	Determination of the resistance to permanent deformation
EN 13036-1	Volumetric patch technique	Determination of the average macro-texture depth
EN 13036-4	Pendulum test	Determination of the skid resistance (micro-texture)

Furthermore, to analyse this mixture's long-term performance, test specimens were produced integrating short-term oven conditioning in the production stage and further ageing them with long-term oven conditioning. The laboratory ageing procedure was based on the AASHTO R30 Standard, which consists of the short term conditioning, which accounts for the ageing that occurs during the mixing, storage, transportation and compaction of the mixture until it cools down; and the long term conditioning, which aims to simulate the ageing that occurs during the bituminous mixture's service life.

2.4. Re-recycling

In order to approach the re-recycling capacity of RAP in new bituminous mixtures, a mixture that incorporated RAP whose aggregates and bitumen had already completed their second life cycle was produced and its performance evaluated (according to the parameters discriminated in Table 4).

The required RAP was produced in the laboratory through the ageing of slabs from the 75% RAP mixture and their manual separation into bitumen coated aggregates.

Additionally, some hypotheses were assumed regarding this mixture's production parameters so that it was possible to carry out performance tests on the mixture in a timely manner. Those were:

(i) the particle size distribution of the laboratory produced RAP was the same as the mix design aggregate gradation obtained for the first phase's mixture – it was assumed that the laboratory RAP production process did not affect it.
(ii) the optimum bitumen content was the same as the 75% RAP mixture (4.3 %).
(iii) the optimum rejuvenator content was the same as the 75% RAP mixture (4.5 %).
(iv) the mixture's maximum density was the same as the 75% RAP mixture.

For this mixture, the aggregate gradation was also obtained through a trial and error process, similar to the previous one, and included 25 % of virgin aggregates and 75 % of the laboratory produced RAP. The gradation of all the produced mixtures for this study is shown in Figure 3.

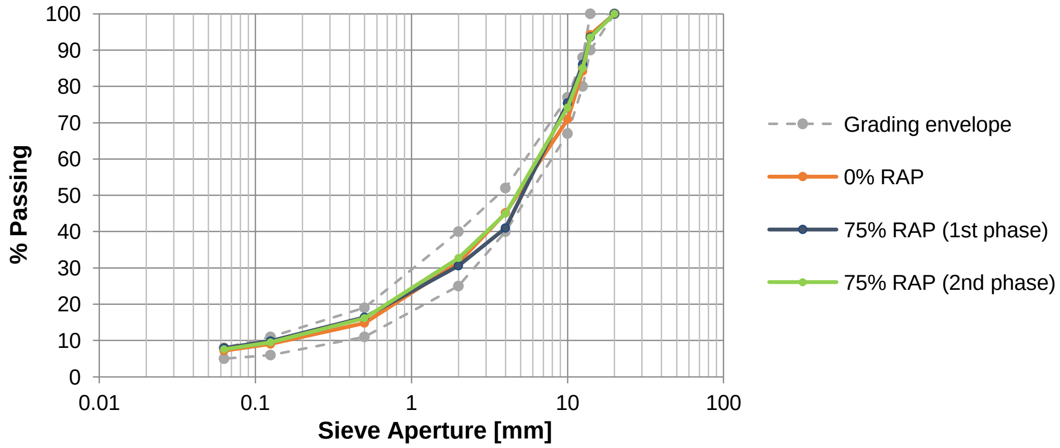

Figure 3: Reference and recycled mixtures' (1st and 2nd phase) gradation curve

3. Results and discussion

This section presents the results from the performance tests identified in Table 4. The analysed mixtures' designations are the following:

0% RAP: Virgin mixture;

75% RAP: Recycled mixture;

75% RAP (Aged): Recycled mixture after going through the ageing procedure;

75% RAP (2nd phase): Recycled mixture that incorporated RAP whose aggregates and bitumen had already completed their second life cycle.

In every parameter evaluated through the stiffness test, presented in Figure 4 to Figure 7, all the mixture's curves have similar development with the increase in frequency.

The 0% RAP mixture exhibited the lowest stiffness and elastic behaviour; and the 75% RAP (Aged) mixture was the opposite, exhibiting the highest stiffness and a predominantly elastic behaviour.

The 75% RAP mixture's performance was situated above the 0% RAP mixture, but below the 75% RAP (Aged) one, evidencing that the recycled mixture was stiffer than the virgin one and showing that the ageing process also had a stiffening effect in the mixture.

The 75% RAP (2nd phase) mixture had a close performance to the 75% RAP one and it is possible to observe the effects of the rejuvenator: the mixture was softened, and its elastic properties were restored almost to the 75% RAP mixture level.

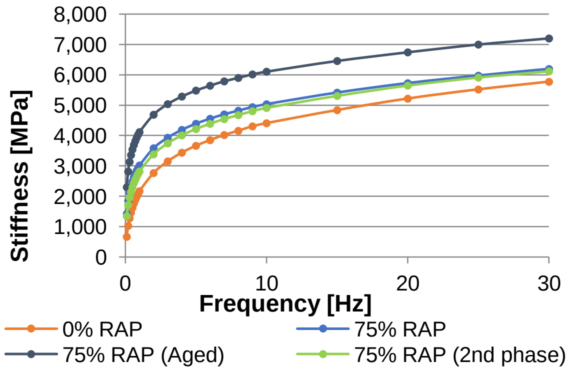

Figure 4: Stiffness vs. Frequency

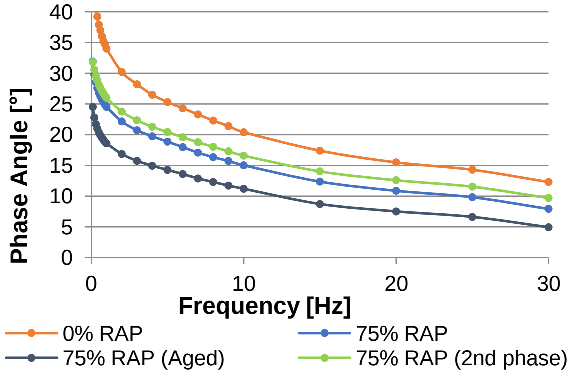

Figure 5: Phase angle vs. Frequency

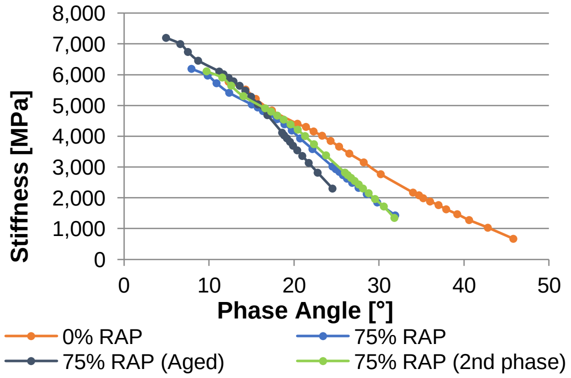

Figure 6: Black diagram

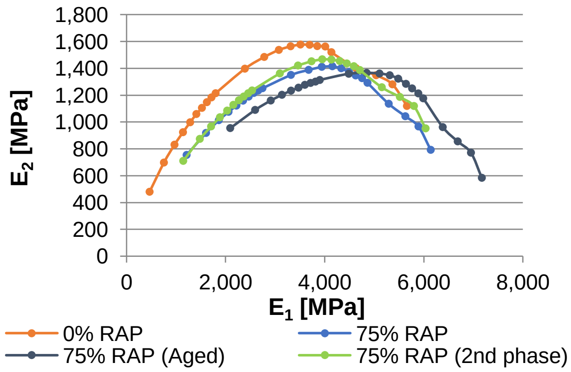

Figure 7: Cole-Cole diagram

The fatigue laws of the mixtures that did not go through the ageing process (0% RAP, 75% RAP and 75% RAP (Aged)), presented in Figure 8, have a similar slope, thus a very similar fatigue behaviour. The 75% RAP (Aged) mixture has a slightly lower slope, exhibiting the worst fatigue behaviour (as was expected from a mixture with a stiffened binder).

The 75% RAP (2nd phase) mixture, in terms of fatigue behaviour, is almost identical to the virgin one and the effect of the rejuvenator was also evident, as this mixture's fatigue line was situated between the 75% RAP mixtures (non-aged and aged).

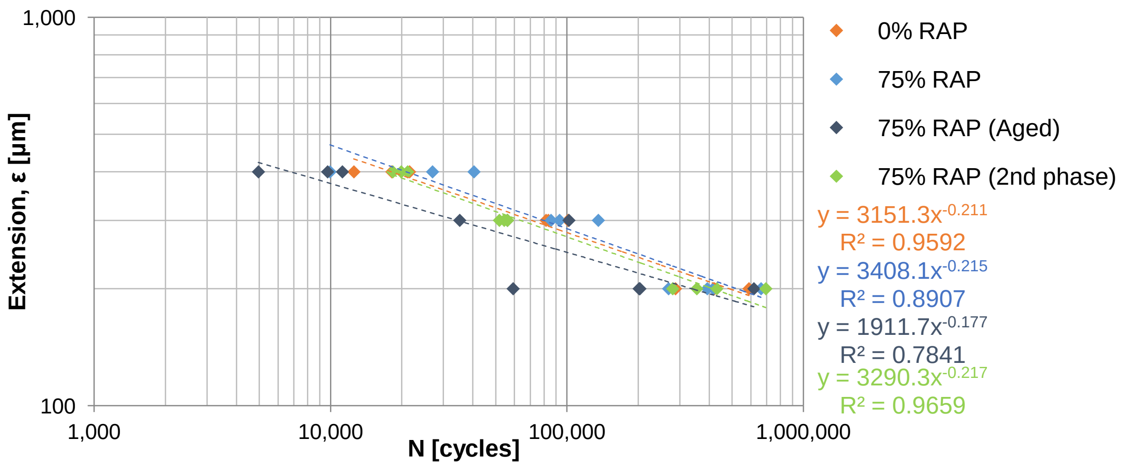

Figure 8: Fatigue laws

The rut depth progression of the mixtures is presented in Figure 9. The recycled mixtures had similar rut depth progression, while the virgin mixture had a noticeably higher slope. The 75% RAP (Aged) mixture has the lowest rut depth, followed by the 75% RAP and the 75% RAP (2nd phase).

These results clearly demonstrate that the recycled mixture is stiffer than the virgin one, making it less susceptible to rutting: an expected behaviour due to the presence of aged binder in the recycled mixtures. The further lowering of the rut depth from the 75% RAP mixture to the 75% RAP (Aged) also demonstrates the stiffening effect of the ageing process.

Regarding the 75% RAP (2nd phase) mixture, it had worse behaviour when compared to the other mixtures, which could be attributed to excess bitumen and/or overly softening of the mixture caused by excess rejuvenator.

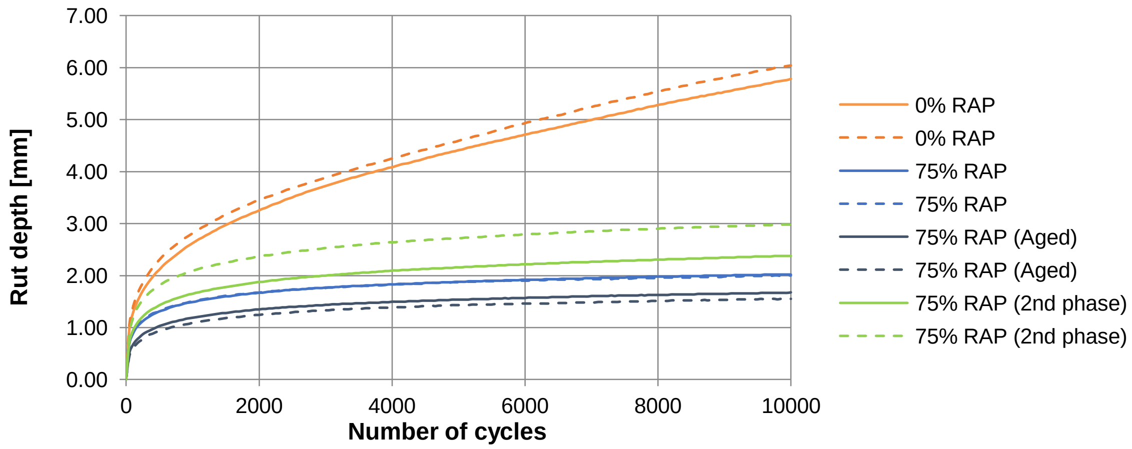

Figure 9: Progression of the rut depth

Regarding the water sensitivity results, presented in Figure 10, the mixture with the highest ITS (both on dry, ITS_d, and wet conditions, ITS_w) was the aged 75% RAP. However, that was not the mixture with the highest ITSR; those were the 0% RAP and the 75% RAP mixtures, showing similar performance between them, yet in the individual ITS values, the 75% RAP one presented higher strength. Even though the 75% RAP (2nd phase) mixture presents an ITSR on par with 75% RAP (Aged) one, its ITS values were the lowest.

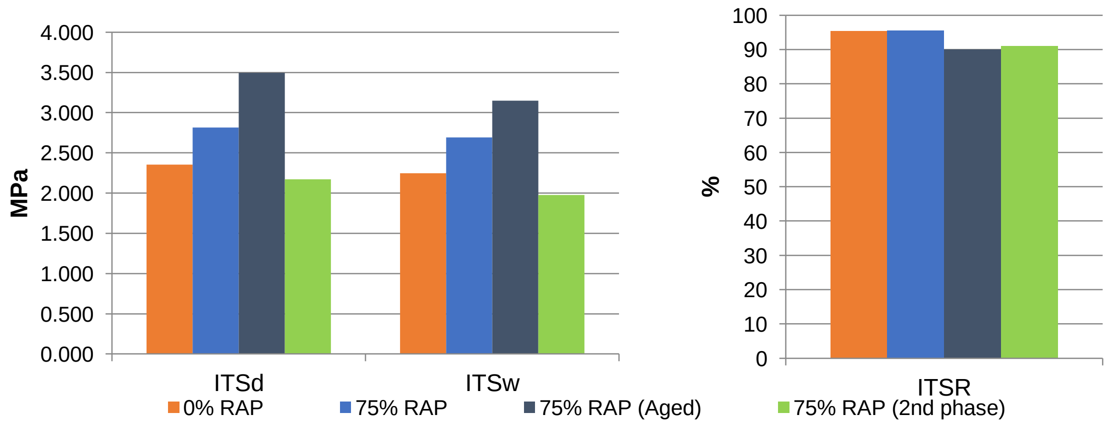

Figure 10: Indirect tensile strengths and indirect tensile strength ratio of the mixtures

Figure 11 presents a side by side comparison of the slabs from each 75% RAP phase. The macro-texture and micro-texture tests results are presented in Figure 12 and Figure 13, respectively. In those figures, the red dashed lines represent the minimum value set in the Portuguese Road authorities' specifications (EP - Estradas de Portugal, 2014b) for each parameter.

Figure 11: Surface texture comparison between 75% RAP (2nd phase) (left) and 75% RAP (right)

The 0% RAP mixture has the highest MTD, while the 75% RAP (2nd phase) has the lowest, which could be attributed to the fact that the aged bitumen was not evaluated, thus the rejuvenator dosage used might not have been the most suitable. In Figure 11 it is visible that the surface texture from the 2nd phase's slab is smoother overall and it even has several patches of flushing that might be caused either by excess bitumen/rejuvenator or by lower air voids content.

Among the 75% RAP mixtures from the first phase, it is noticeable that the oven ageing process has no significant effect on a mixture's macro-texture. When it comes to the minimum MTD set in the specifications, only the 0% RAP mixture was in compliance. However, that mixture has a minimum value in line with those from the 75% RAP mixtures from the first phase.

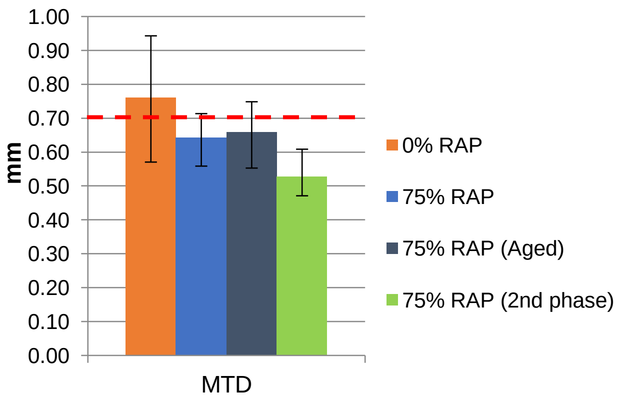

Figure 12: Mean texture depth for every mixture

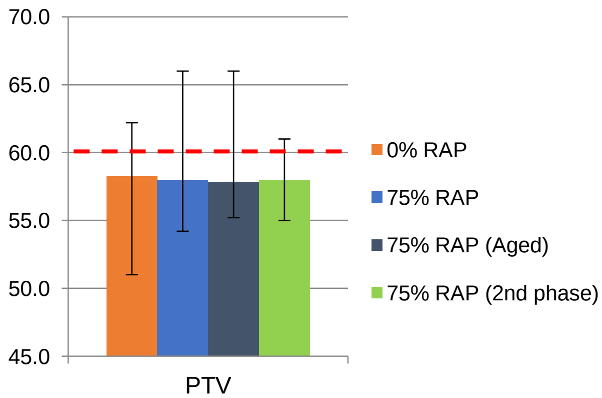

Figure 13: Mean pendulum test value for every mixture

The PTV values displayed insignificant differences between the mixtures. Akin to the macro-texture parameter, the oven ageing process had no significant effect on a mixture's micro-texture. And, although close, none of the mixtures met the minimum PTV set in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014b).

In spite of that, it has been documented (Chen et al., 2016; Do et al., 2014; Kane et al., 2013, 2010) that after construction there is an increase in a pavement's skid-resistance due to the removal of the binder coating the aggregate's surface by the action of traffic. After peaking, the skid-resistance decreases until it reaches an equilibrium phase, in a rate that is dependent mainly on the aggregate's properties, but also on the bitumen, traffic intensity and environmental conditions.

4. Conclusions

The main objectives of this study were to analyse the performance of a recycled bituminous mixture incorporating high RAP content after going through an ageing process, as well as the re-recycling capacity of RAP in new bituminous mixtures. These were assessed through stiffness, fatigue resistance, water sensitivity and permanent deformation tests, for the mechanical behaviour, and macro and micro-texture tests, for the surface characteristics. These tests were carried out on:

(i) a recycled mixture incorporating 75% RAP before and after going through an ageing process.
(ii) a recycled mixture incorporating 75% RAP, whose aggregates and bitumen had already completed their second life cycle.
(iii) a reference mixture produced only with virgin materials, whose performance results were used as a benchmark.

The following points present a summary of the results of the performance tests carried out on the aforementioned mixtures:

- All the mixtures' stiffness and phase angle curves had similar development with the increase in frequency. All the recycled mixtures exhibited higher stiffness than the virgin one and had a predominantly elastic behaviour, being the aged 75% RAP mixture the one with the highest stiffness.
- All the non-aged mixtures had a similar fatigue law, being the aged 75% RAP mixture had the worst performing in this parameter.
- The aged 75% RAP mixture exhibited the highest permanent deformation resistance, followed by the 75%RAP mixture, then the 75% RAP (2nd phase), being the virgin mixture the one with the worst performance.
- Regarding the water sensitivity, the mixtures that exhibited the highest ITSR were the virgin and the 75% RAP mixtures, showing similar performance between them. The lowest ITSR was exhibited by the aged 75% RAP mixture and the 75% RAP (2nd phase) mixture, however their ITS values on both wet and dry conditions were opposite: the aged 75% RAP mixture exhibited the highest ITS values, while the 75% RAP (2nd phase) mixture exhibited the lowest.
- The virgin mixture had the highest macro-texture and the lowest MTD was exhibited by the 75% RAP (2nd phase) mixture. As to the macro-texture for the 75% RAP mixture, it was similar between the evaluated ageing stages.
- All the mixtures' micro-texture surrounded the same value.

Through the analysis and comparison of the performance tests, it was possible to conclude that:

- The recycled mixtures presented higher stiffness than the virgin one, which was reflected in the stiffness and permanent deformation tests results. However, the expected lowering of the fatigue resistance was not observed for the non-aged recycled mixtures.
- The ageing process had a stiffening effect on the 75% RAP mixture, reflected on the highest stiffness and permanent deformation resistance and lowest fatigue resistance. However, it did not affect the surface characteristics of the mixture.
- The effect of the rejuvenator on the 75% RAP (2nd phase) mixture was evident: this mixture's stiffness and fatigue resistance were on par with that of the 75% RAP mixture.

All in all, the better mechanical performance in most of the parameters of the recycled mixtures in comparison with the virgin mixture demonstrates the viability of this recycled mixture to be used by the paving industry. Despite the surface characteristics not being in compliance with the Portuguese Road authority's specifications, and given the importance they have in the safety of the users, they might be improved either with the tuning of the gradation curve or via a surface treatment.

Finally, given the inferior performance demonstrated by the 75% RAP (2nd phase) mixture in the permanent deformation, water sensitivity and macro-texture tests, the importance of RAP characterisation and fractionation and the characterisation of the aged bitumen, in order to determine the optimum rejuvenator content, followed by a mixture design procedure to determine the optimum bitumen dosage, should be emphasized, as those are paramount steps to optimize a recycled mixture's performance.

The performance results obtained from this dissertation contribute to the demonstration of the viability of RAP recycling and the introduction of this type of mixture. Yet, as the laboratory mixture production and ageing process do not simulate all the exact conditions of mixture production in a plant, compaction on-site and ageing throughout its service life, a full-scale trial would be the only way to assess this type of mixture's performance in real circumstances.

Regarding the capacity of re-recycling RAP, the performance of a mixture whose aggregates and bitumen have already completed their second life cycle should be further studied, as the hypotheses assumed for this mixture's production would not guarantee the best performance results that could be achieved but would provide an insight into what they could be. Therefore, it is strongly recommended to begin such studies with the RAP characterisation and fractionation and the characterisation of the aged bitumen, in order to determine the optimum rejuvenator content, followed by a mixture design procedure to determine the optimum bitumen dosage.

Finally, with the intent to fully transition to a circular economy, it would be constructive to deepen the knowledge on the capacity of multi-recycling bituminous mixtures, evaluating the viability of the same RAP to endure multiple service lives while maintaining better or equivalent performance levels as virgin mixtures.

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