Performance and Ageing Evaluation of Bituminous Mixtures with High RAP Content

C. Santos, V. Antunes, J. Neves, and A. C. Freire

Abstract The implementation of a circular economy implies turning waste into resources, avoiding its disposal in landfills and minimizing the extraction of raw materials. Every year, a considerable amount of Reclaimed Asphalt Pavement (RAP) is generated, as the road network requires pavement maintenance to ensure the safety and comfort of the users. RAP contains both constituents of a bituminous mixture (bitumen and aggregates), and is 100% recyclable, therefore being able to be re-introduced back into the cycle without its use being downgraded. However, RAP is currently being employed solely as an aggregate in unbound layers or in small percentages in new bituminous mixtures, rather than taking advantage of the aged bitumen. This paper presents a study which aimed to evaluate the performance of a surface dense-graded hot bituminous mixture before and after being subjected to an ageing procedure. The bituminous mixture containing a high RAP content—75%—was treated with a commercial vegetable rejuvenator. Short Term Oven Ageing (STOA) and Long Term Oven Ageing (LTOA) procedures were used to simulate the ageing that occurs during the mixture's production and service life, respectively. The evaluation of the recycled bituminous mixture's performance was based on stiffness, fatigue resistance, and permanent deformation tests carried out in the laboratory. In comparison with a conventional bituminous mixture, it was found that, in general, the recycled bituminous mixture, before and after ageing, showed higher stiffness and resistance to permanent deformation, yet had very similar fatigue resistance.

Keywords RAP · Bituminous mixture · Circular economy · Recycling · Ageing

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V. M. C. F. Cunha et al. (eds.), *Proceedings of the 3rd RILEM Spring Convention and Conference (RSCC 2020)*, RILEM Bookseries 35,
https://doi.org/10.1007/978-3-030-76543-9_4

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 pavement maintenance actions required to ensure an adequate quality level regarding user safety and comfort generates a considerable amount of by-products.

Environmental concerns push for the transition to a circular economy model, 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 European Union (EU) has implemented the Action Plan for the Circular Economy, which advocates for more efficient use of natural resources and for turning waste into secondary raw materials [1].

In Europe, bituminous mixtures are the predominant construction material of pavement bound layers and they are 100% recyclable [2]. However, the Reclaimed Asphalt Pavement (RAP) is mostly recycled as unbound granular material or in small percentages (5–20%) in new bituminous mixtures. This is not an efficient use of this resource since the bitumen's properties are not being taken advantage of, thus downgrading the RAP [3].

Furthermore, the exposure of the binder to the climate conditions during its service life is an important aspect to be considered in bituminous mixtures, in general. In the case of RAP use, especially in the case of high incorporation rates (> 25%), this ageing effect that changes the binder's properties becomes more important. In fact, the ageing process makes the binder stiffer and influences the mixture's performance, therefore, when producing new bituminous mixtures with high RAP content, it is recommended to use a softer binder or rejuvenator which improves the aged binder's properties [4].

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 even 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 different types of rejuvenator 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 mixture's 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 [5, 6].

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 [2, 3, 7–9].

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.

The main objective of this paper is to analyze the performance, in laboratory, of a recycled bituminous mixture incorporating high RAP content after going through an ageing process. This mixture contained 75% RAP content, treated with a commercial vegetable rejuvenator. The ageing process was simulated through Short Term Oven Ageing (STOA) and Long Term Oven Ageing (LTOA) procedures. The performance tests were carried out on two recycled mixtures incorporating RAP (before and after the ageing process), and one reference bituminous mixture produced only with virgin aggregates.

2 Methodology

2.1 Materials

The recycled bituminous mixtures that were produced in laboratory incorporated RAP milled from a high trafficked road, whose age was unknown as well as bitumen origin and nature. From the recovered RAP aggregates, it is possible observe that they have multiple origins as limestone, basalt and granitic. The RAP was treated with a commercial rejuvenator derived from crude tall oil, a by-product of the paper industry.

The virgin materials were basalt aggregates in the 10/16, 4/12 and 0/4 mm fractions, limestone aggregates in the 0/4 mm fraction and a virgin bitumen with a nominal penetration grade of 35/50.

2.2 Testing Methods

The tests performed throughout this study can be divided into three categories: (i) RAP characterization; (ii) mix design; and (iii) performance evaluation (Table 1).

An adequate characterization of the RAP and its components (bitumen and aggregates) was essential since the studied bituminous mixture incorporated a high percentage of RAP. The mix design tests included those used to determine the mixtures' volumetric and mechanical characteristics and its performance was evaluated through stiffness, fatigue resistance, and permanent deformation tests.

Table 1 Test methods

Standard	Test method	Scope	Cat
EN 933-1	Particle size distribution	Characterization of the aggregates	(i)
EN 12697-1	Soluble binder content	Determination of the RAP binder content	(i)
EN 12697-3	Rotary Evaporator method	Recovery of the RAP binder	(i)
EN 1426	Determination of needle penetration	Characterization of the binder	(i)
EN 1427	Determination of the softening point	Characterization of the binder	(i)
EN 12697-5	Maximum density	Determination of the volumetric properties	(ii)
EN 12697-6	Bulk density	Determination of the volumetric properties	(ii)
EN 12697-34	Marshall test	Determination of the Marshall properties	(ii)
EN 12697-26	Stiffness	Characterization of the stiffness	(iii)
EN 12697-24	Resistance to fatigue	Characterization of the fatigue behaviour	(iii)
EN 12697-22	Wheel tracking	Determination of the resistance to permanent deformation	(iii)

2.3 Bituminous Mixture Production and Ageing

The experimental study has concerned a dense graded hot bituminous mixture with a maximum aggregate dimension of 14 mm and a bitumen with a nominal penetration grade 35/50: AC 14 surf 35/50. Two mixtures of this type were analyzed in the laboratory and compared: a reference bituminous mixture containing only virgin materials and a mixture incorporating 75% of RAP and a rejuvenator, both produced and compacted in the laboratory.

The bituminous mixture for the specimens was prepared following the rejuvenator's manufacturer guidelines and compacted according to EN 12697-30 with a target temperature for compaction of 165 °C (specified by EN 12697-35 for a 35/50 penetration paving grade bitumen). The specimen production procedure was the following:

Step 1 All the materials were heated:

- The RAP was heated at 130 ºC for 2h30.
- The virgin aggregates were heated at 205 ºC for 4h00.
- The virgin bitumen was heated at 165 ºC for 3h00.

Step 2 The RAP and rejuvenator were added to the mixer and mixed for 30 s.
Step 3 The virgin binder and virgin aggregates were added to the mixing bowl and mixed for 2 min 30 s.
Step 4 The mixture was poured into the mold and compacted.

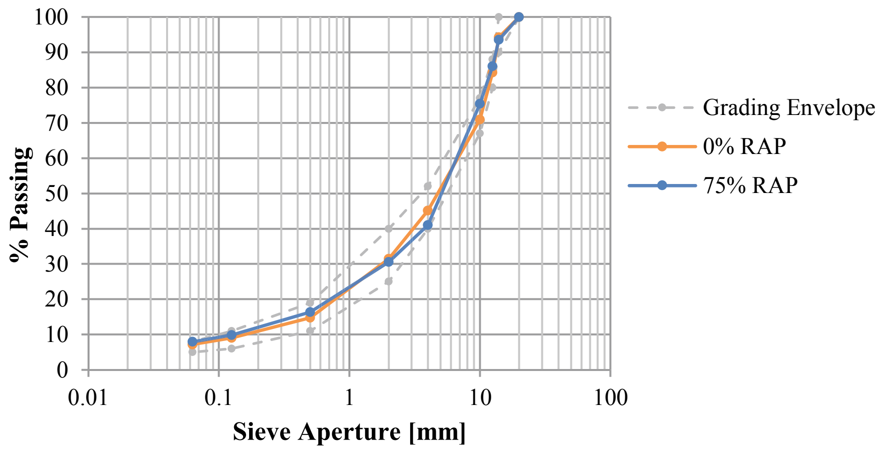


Fig. 1 Reference and recycled bituminous mixtures' gradation curve

The percentage of rejuvenator to mix with the aged bitumen to recover its properties was defined through the assessment of the penetrations and softening temperatures of bitumen samples mixed with different dosages of rejuvenator. The selected dosage was 4.5% of rejuvenator per weight of aged binder, whose sample properties were similar to those of a 35/50 grade bitumen, defined in EN 12591.

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, defined in the Portuguese Road authority's specifications [10]. The gradation curve, along with the upper and lower limits defined in the specifications, is presented in Fig. 1.

To analyze the performance of the recycled mixture after going through an ageing process, there were test specimens whose production integrated short-term oven ageing (STOA) and were further aged through long-term oven ageing (LTOA). This laboratory ageing procedures were based on AASHTO R30, which consists of the STOA, accounting for the ageing that occurs during the mixing, storage, transportation, and compaction of the mixture until it cools down; and the LTOA aiming to simulate the ageing that occurs during the bituminous mixture's service life.

3 Results and Discussion

This section presents the results of the performance tests identified in Table 1. The analyzed bituminous mixtures' designations are the following:

- 0% RAP: Virgin bituminous mixture.

- 75% RAP: Recycled bituminous mixture (unaged).
- 75% RAP (Aged): Recycled bituminous mixture after the ageing procedure.

The stiffness was evaluated through the 4-point bending test method (4PBT) and the results regarding the stiffness modulus and phase angle as a function of the loading frequency are presented in Figs. 2 and 3, respectively.

All the bituminous mixture's curves show similar behaviour depending on the test frequency: the 0% RAP bituminous mixture exhibited the lowest stiffness modulus and elastic behaviour; and the 75% RAP (Aged) bituminous mixture was the opposite, exhibiting the highest stiffness modulus and predominantly elastic behaviour. The 75% RAP bituminous mixture's stiffness modulus and phase angle were situated above the 0% RAP bituminous mixture, but below the 75% RAP (Aged) one, evidencing that the recycled bituminous mixture was stiffer than the virgin one and demonstrating that the ageing process also had a stiffening effect in the bituminous mixture.

The fatigue performance was analyzed by the strain values that induce specimens' failure after 10,000 (ε_4), 100,000 (ε_5) and 1,000,000 (ε_6) loading cycles, calculated

Fig. 2 Stiffness modulus versus frequency

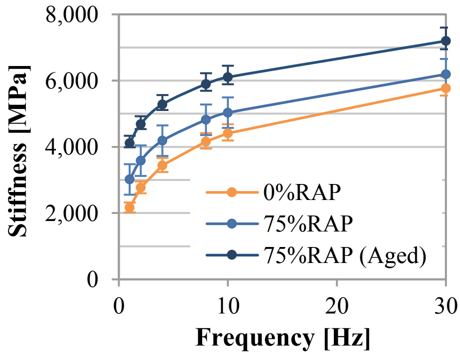
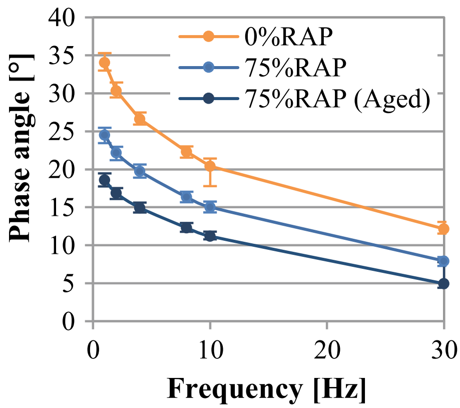


Fig. 3 Phase angle versus frequency



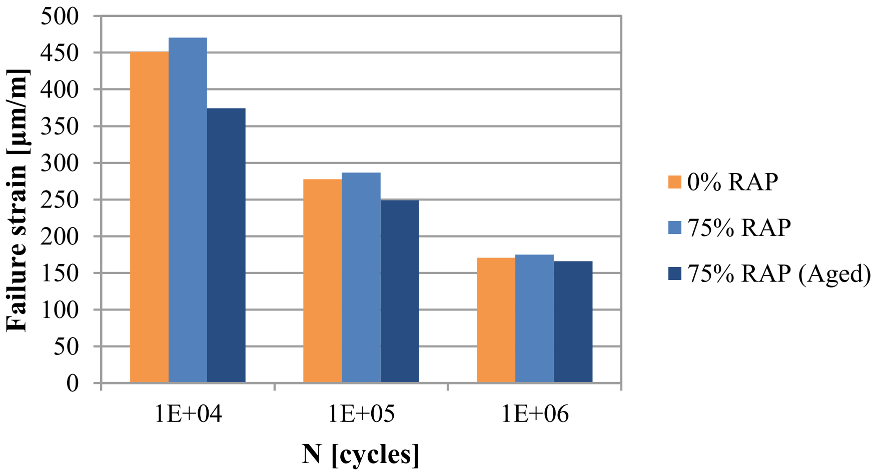


Fig. 4 Strain at fatigue failure

from each bituminous mixture's fatigue law. These parameters are represented in Fig. 4.

Overall, the 75% RAP bituminous mixture has the highest failure strain in all the parameters. Also, for the 10,000 and 100,000 loading cycles, the 75% RAP (Aged) bituminous mixture has a lower fatigue behaviour than the other bituminous mixtures. However, it is more relevant to evaluate the fatigue performance for a high number of loading cycles. As such, for the 1,000,000 cycles, the difference in failure strain between the bituminous mixtures is minimal: between the recycled bituminous mixtures, it is a difference of about 5%, while between the unaged bituminous mixtures it is of about 2%.

The rut depth progression of the bituminous mixtures is presented in Fig. 5. The recycled bituminous mixtures had similar rut depth progression, presenting a tendency to stabilize, while the virgin mixture had an increasingly higher value.

These results demonstrate that the recycled bituminous 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 material. The further lowering of the rut depth from the 75% RAP bituminous mixture to the 75% RAP (Aged) also demonstrates the stiffening effect of the ageing process.

4 Conclusions

The main objective of this study was to analyze the performance and ageing behaviour of a recycled bituminous mixture incorporating high RAP content (75%), whose age

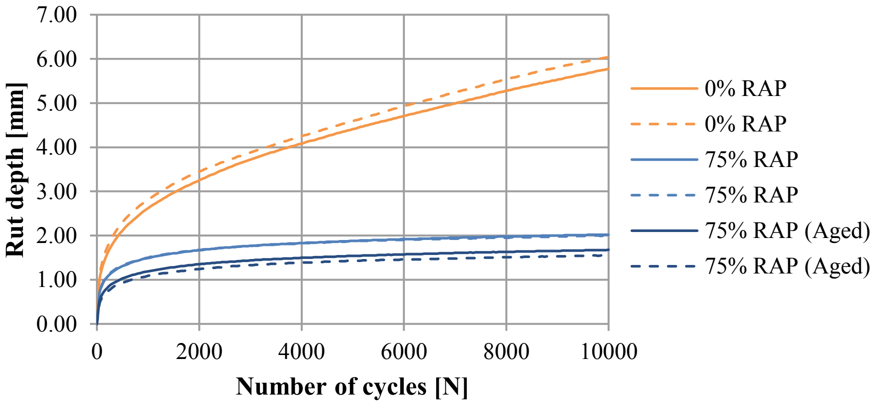


Fig. 5 Progression of the rut depth

was unknown. The performance was assessed in laboratory through stiffness, fatigue resistance, and permanent deformation tests.

The summary of the test results is:

- The stiffness modulus and phase angle had similar behaviour with the increase of loading frequency for all the bituminous mixtures. The recycled materials exhibited higher stiffness than the virgin one and had a predominantly elastic behaviour, being the 75% RAP (Aged) mixture the one with the highest stiffness.
- The 75% RAP bituminous mixture exhibited the highest failure strain in all of the parameters, yet, in the 1,000,000 cycles, the failure strain was similar in all the materials.
- The aged 75% RAP bituminous mixture exhibited the highest permanent deformation resistance, followed by the 75% RAP mixture, being the virgin bituminous mixture the one with the worst performance.

Through the analysis and comparison of the performance tests, it was possible to point out the following main conclusions:

- The recycled bituminous mixture presented higher stiffness than the virgin one, which was reflected in the stiffness and permanent deformation test results.
- The ageing process had a stiffening effect, reflected on the highest stiffness and permanent deformation resistance and lowest fatigue resistance.

The performance results obtained from this study contribute to the demonstration of the viability of RAP recycling and the introduction of this type of material in the paving industry. Yet, as the laboratory bituminous mixture production and ageing process do not simulate all the exact conditions of 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 bituminous mixture's performance in real circumstances.

Acknowledgements The authors are grateful to the Portuguese Foundation for Science and Technology, IP for the financial support provided through grant SFRH/BD/114715/2016 financed by the Portuguese Government budget. The authors also want to express their gratitude to the companies that provided the materials and respective technical information needed to develop this study.

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