Maintenance and Rehabilitation

Evaluation of multi-recycling capacity of bituminous mixtures

Vitor Antunes[1,2], José Neves[1,3], Ana Cristina Freire[2]
[1]Instituto Superior Técnico, Universidade de Lisboa, [2]National Laboratory for Civil Engineering, [3]Ceris - Instituto Superior Técnico, Universidade de Lisboa

Abstract

Bituminous mixtures have a key attribute that they can be 100% recycled without downgrading its functionality. This represents the highest value application and has significant economic and environmental benefits. Every year billions of dollars are spent on road construction and maintenance globally. These operations produce a considerable amount of reclaimed asphalt pavement (RAP), which is a valuable waste. Its re-use reduces the depletion of quality resources in landfilled. RAP recycling is a step forward in the direction of sustainable approaches as defended by the recent policies yearns. RAP incorporation in new bituminous mixtures can be associated with different techniques, rejuvenators and additives. This incorporation represents the first cycle of the material’s life. The circular economy presupposes that materials have several cycles during them life. Therefore, the multi-recycle capacity of the bituminous mixtures need to be evaluated. The main objective of the paper is to analyse the multi-recycled capacity of RAP in new mixtures. For that, a laboratory study involving a surface dense bituminous mixture will be described. A RAP incorporation percentage of 25% was evaluated and to take advantage of the binder properties a commercial vegetable rejuvenator was used. The long-term oven ageing protocol was used to simulate the ageing of the mixtures. The stiffness modulus, resistance to fatigue, water sensitivity and permanent deformation resistance were assessed for different compositions. The study showed that bituminous mixtures have potential to be multi-recycled. Test results confirmed that multi-recycled bituminous mixtures had at least an equivalent performance over the primary material.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

The construction is still the sector that contributes the most to waste production each year; accounting for about 34 % of the total waste produced [1]. The transportation infrastructure sector, namely the road construction, has a significant impact on this percentage. It must be recalled that asphalt roads represent more than 80 % of European road network, with around 950 billion tonnes of asphalt being currently incorporated in the European road network [2]. In order to maintain the quality of road infrastructures, each year, huge amounts of money are allocated to Road Authorities to road construction and maintenance actions. The maintenance actions produce a considerable amount of Reclaimed Asphalt Pavement (RAP), which is a valuable waste.

Asphalt mixtures have a key attribute that they can be 100% recycled without downgrading its functionality. This represents the highest value application and has significant economic and environmental benefits.

RAP recycling in new asphalt presents environmental and economic benefits [2–6]. The main RAP recycling advantages highlighted in the bibliography are the following: (a) less emissions, (b) reduced usage of raw materials and consequent reduction in their exploration, (c) lower costs associated with transportation and operation of raw materials, (d) less energy consumption and fuel usage in transportation, (e) and less landfill disposals. RAP recycling is a step forward in the direction of sustainable approaches as defended by the recent policies yearns [7,8].

The applications of this material in pavement industry has become a standard practice in many countries. This is the most recycled construction waste product. However, its application in asphalt mixtures is still limited due to specifications requirements [9–17].

Despite this, with the increase of RAP incorporation in new asphalt mixtures and considering the need of periodic maintenance actions on the pavement structures the RAP materials can suffer multiple recycle actions. In this way, the evaluation of multi-recycling capacity of the mixtures presents the major importance [18].

Multi-recycling is the capacity of the materials in being subject to several recycling processes without losing their properties. During the recycling processes some valorisation actions can be performed, such as crushing and grading. These allow guaranteeing the properties of the materials and consequently having a greater control on mixture formulation [4,9,11,15].

The main objective of the paper is to analyse the multi-recycling capacity of RAP in new asphalt mixtures. For this purpose, a laboratory study involving a surface dense asphalt mixture was carried out. A RAP incorporation of 25 % was evaluated and to take advantage of the bitumen properties a commercial vegetable rejuvenator was used. The long-term oven ageing protocol was used to simulate the ageing of the asphalt mixtures. In this way, three mixtures were evaluated: two incorporating 25 % of RAP and one reference asphalt mixture only with virgin materials. One mixture with RAP was aged.

2. METHODOLOGY AND MATERIALS

2.1. Materials

For this study, two types of mineral aggregate with different fractions were selected given the materials that are applied in surface layer. These were: basaltic aggregates with the fractions 0/4, 4/12 and 10/16 mm, limestone aggregates with the fraction 0/4 and a commercial limestone filler. The RAP was produced in the maintenance actions of a motorway. The surface layer was milled and replaced by a new one.

The RAP material was also selected and its characterisation performed. Firstly, was characterized the grading of the RAP sample, representative of the stock pile, was characterized according to the EN 933-1. After the RAP was divided in fractions using a high capacity sieve shaker, in order to represent the typical values for of aggregates fractions that are used in Portuguese paving industry. The 3 used fractions were designated as RAP 1, having particles dimensions between 0 mm and 4.75 mm, RAP 2 having particles dimensions between 4.75 mm and 12.5 mm and RAP 3 which particles dimensions varies between 12.5 mm and 19 mm. In Figure 1 are presented the three fractions used in this study. Moreover, for the mixture formulation will be used the grading curves of the aggregates recovered from RAP.

A standard road bitumen (bitumen pen 35/50) according to the standard EN 12591 was used [19]. The rejuvenating agent is a pine chemical derived from the renewable raw material, Crude Tall Oil (CTO), a by-product of the paper industry.

RAP1 (0/4.75 mm)

RAP2 (4.75/12.5 mm)

RAP3 (12.5/19 mm)

Figure 1: RAP fractions in use in the study

2.2. Testing methods

The volumetric and mechanical characteristics of the asphalt mixtures were tested according to the standards presented in Table 1. To evaluate the mixtures' performance stiffness modulus, fatigue behaviour and permanent deformation characteristics were assessed. Bitumen content, penetration and softening point were evaluated on the recovered bitumen of the RAP fractions. These tests were also performed in order to determine the optimum content of rejuvenator to be added in the mixture.

The stiffness modulus and fatigue behaviour were assessed on beams, which were sawed from a slab prepared on the roller compactor equipment, and the tests were carried according to the procedures described in the European Standards presented in Table 1.

Table 1. Overview of test methods

Material	Test method	European standard
RAP	Soluble binder content (difference between mass of mix and aggregates)	EN 12697-1
	Aggregate size distribution (wet sieving)	EN 12697-2
Recovered bitumen	Binder recovery (rotary evaporator)	EN 12697-3
	Penetration	EN 1426
	Softening point ring and ball	EN 1427
	Penetration index IP	EN 12591
Aggregates	Aggregate size distribution (wet sieving)	EN 933-1
Asphalt mixture	Maximum density	EN 12697-5
	Bulk density (saturated surface dry)	EN 12697-6
	Void content	EN 12697-8
	Marshall stability and flow	EN 12697-34
	Stiffness modulus	EN 12697-26
	Fatigue life	EN 12697-24
	Wheel tracking (permanent deformation)	EN 12697-22

2.3. HMA production and artificial ageing

The hot mix asphalt (HMA) AC14 surf used in the study was a typical dense graded asphalt for surface layers in Portugal with maximum aggregate size of 14 mm. A reference mixture (0%RAP) was produced with natural aggregates and a penetration grade 35/50 bitumen. The formulation of the recycling mixes containing 25% RAP (25%RAP), a rejuvenator dosage, 35/50 bitumen and virgin aggregate. The mixtures were produced in 10-20 kg batches with a large laboratory mixer and a mixing temperature of 155-165 ºC.

Figure 2 shows the grading curves of the reference and recycled mixtures, as well as, the grading envelope for an AC14 surf mixture. In terms of gradation both mixtures presented similar aggregates dimension distribution, which allows to have similar aggregates skeleton.

The mixture with 25 % of RAP obtained from milling was the starting point of the repeated recycling experiments. The 25 % recycled hot bituminous mixture was considered as the stage 1 of the recycling process. This mixture was produced and divided in two parts: one was taken to performance characterization without ageing process and the other part was taken to performance characterization after the ageing process.

The defined ageing conditions take in consideration the short-term ageing (STA) and long-term ageing (LTA) of an asphalt mixture during its life period. To simulate the STA, the loose asphalt was placed in a pan and spread to a thickness ranging between 25 mm to 50 mm. The pan with the mixture was placed in a ventilated oven at 155 ºC for 2 h according to the standard AASHTO R30-02 [20].

After the STA process, the mixture was compacted using the roller compactor. The produced slabs were aged for more 5 days at 85ºC, in order to simulate the ageing that occurs over the service life of a pavement [20–22]. After they were sawed to produce specimens to the mechanical evolution characterization. The recycled aged mixture was designated as 25%RAP_A.

For the recycling mixtures 25RAP and 25%RAP_A the aggregates were overheated to 195 ºC a to compensate the lower RAP temperature of 120 ºC.

All mixtures were assessed after the production in order to evaluate the composition using standard volumetric and mechanical test methods (Table 1).

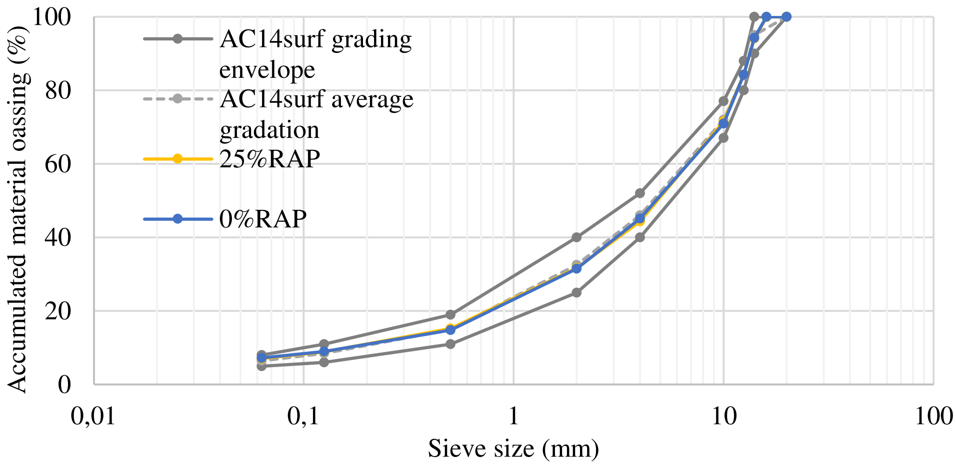

Figure 2: Mixture's gradation

3. RESULTS AND DISCUSSION

3.1. RAP characterization

Figure 3 shows the grading curves of RAP and RAP fractions as well as the curves of the recovered aggregates from each fraction. As expected, it is possible to observe that the recovered aggregates curves present a deviation when compared with the respective RAP fraction curve. The grading of recovered aggregates from RAP fractions were smaller than the grading of RAP lumps from the fractions.

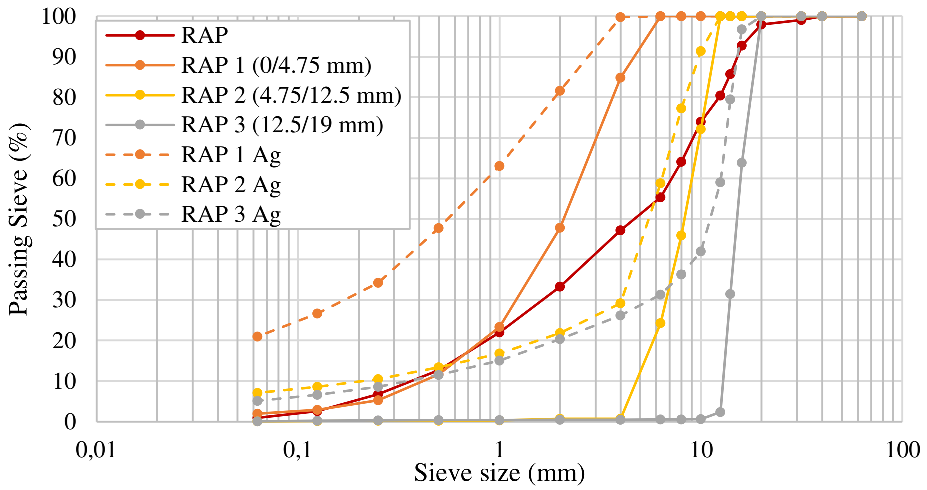

Figure 3: Gradation of RAP fractions and recovered aggregates from RAP fractions

The needle penetration test was performed according to the EN 1426 in order to evaluate the penetration value of the recovered bitumen from each RAP fraction and the optimum percentage of rejuvenator to be used. In Figure 4 are presented the results of penetration values determined at 25 ºC temperature. It was evaluated the penetration value of recovered bitumen from two of three fractions of RAP (2 and 3). For the finest fraction this value was not determined, due to the high content of fine material that can have influence the penetration value obtained for the fraction 1. It was observed that the 2 fraction presented an average penetration value of $19x10^{-1}$ mm.

In order to determine the optimum dosage of rejuvenator 3 percentages of rejuvenator incorporation were tested. The tests were performed in samples of recovered bitumen treated with different percentages of rejuvenator in evaluation. The blending protocol was the following:

- Place the bitumen to be treated in oven at 130 ºC for 30 min to 1 h;
- Once the bitumen is liquid enough, stir to homogenize and remove any bubble;
- Weigh the bitumen and place the container on a hot plate at 100 to 135 ºC;
- Add the additive in the right amount and stir by hand using a glass rod for about 30 s;
- Place the container back with the sample in an oven at 135 ºC for 10 min and stir for 30 s at 5 min intervals.

After the treating process the preserved recovered bitumen samples were tested. According to the rejuvenator supplier the optimum dosage is the one that meet the desired properties for the bitumen. As the reference asphalt mixture is an AC14 surf BB 35/50, in this way the desired properties for the bitumen are similar to the 35/50 virgin bitumen, that should vary between $35x10^{-1}$ and $50x10^{-1}$ mm at 25 ºC. For rejuvenator the optimum dosage determined was 4.5 % per weigh of aged bitumen in new mixture.

Figure 4 shows the softening temperature determined by the Ring and Ball method according to EN 1427. As well as performed in penetration tests, it was determined the softening temperatures of the aged binder recovered from 2 different fractions of RAP and the softening temperatures of the aged bitumen samples treated with different rejuvenator dosages. For the 4.5 % of rejuvenator dosage the softening temperature obtained was 61 ºC. The typical values for the softening temperature for a 35/50 traditional bitumen varies between 50 ºC and 58 ºC, this was only obtained for a 7 % rejuvenator dosage. However, taking into consideration the obtained results, it was considered as an optimum dosage the value of 4.5 % of rejuvenator percentage.

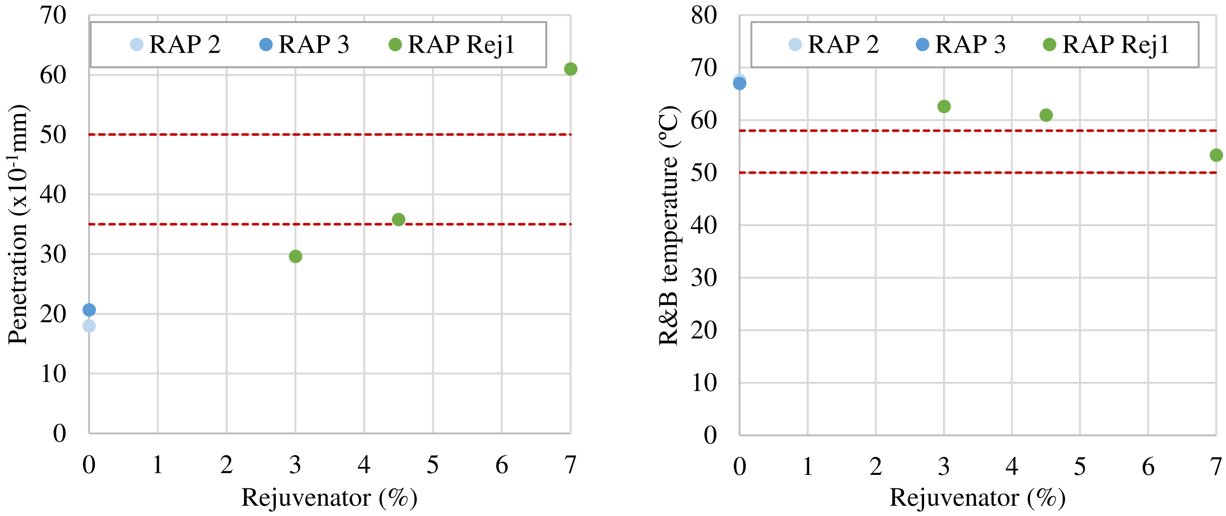

Figure 4: Bitumen RAP fraction characterization and optimum rejuvenator percentage: (left) Penetration value; (right) softening temperature determined by R&B test

3.2. Mixtures characterization

The total bitumen content of mix 25%RAP and 25%RAP_A is 0.8 % lower when compared with the reference mixture, which has a direct influence on the void content that is higher in recycled mixtures. Is possible to observe in Table 2 the mechanical characteristics of the asphalt mixtures. The Marshall stability of the recycled mixture is greater than the reference mixtures, despite the Marshall flow did not show significant changes. This growth in Marshall stability is related with the lower bitumen content. Additionally, this increase can also have some contribution from the RAP aged bitumen.

Table 2. Mechanical characteristics of the hot mixtures

Hot mix asphalt		Unit	0%RAP	25%RAP	25%RAP_A
Bitumen content	New	%	5	3	3
	Recovered	%	0	1.2	1.2
	Total	%	5	4.2	4.2
Void content		%	3.2	3.7	3.7
Marshall	stability	kN	14.8	18	-
	flow	mm	3.0	2.7	-
	coefficient	kN/mm	4.9	6.7	-
Permanent deformation	RD_{air}	mm	5.9	2.4	1.8
	WTS_{air}	mm/10^3	0.28	0.05	0.04
	PRD_{air}	%	11.7	4.7	3.5
Fatigue	ε_6	µm/m	170.8	151.2	164.4

From Table 2 and Figure 5 is possible to observe a considerable reduction in terms of permanent deformation behaviour. The 25%RAP mixture shows a reduction greater than 50 % in terms of the final rut depth when compared with the reference mixture. The ageing methodology in use shows a clear effect in terms of the resistance to permanent deformation when comparing the aged recycled mixture with the non-aged recycled mixture. Figure 5 chart shows also that the recycled mixture presented a tendency to a limit value, while the reference mixture presents a tendency to continue increasing the value of maximum rut depth. The 25%RAP_A mixture presents the best results for the 3 parameters measured by the wheel tracking test.

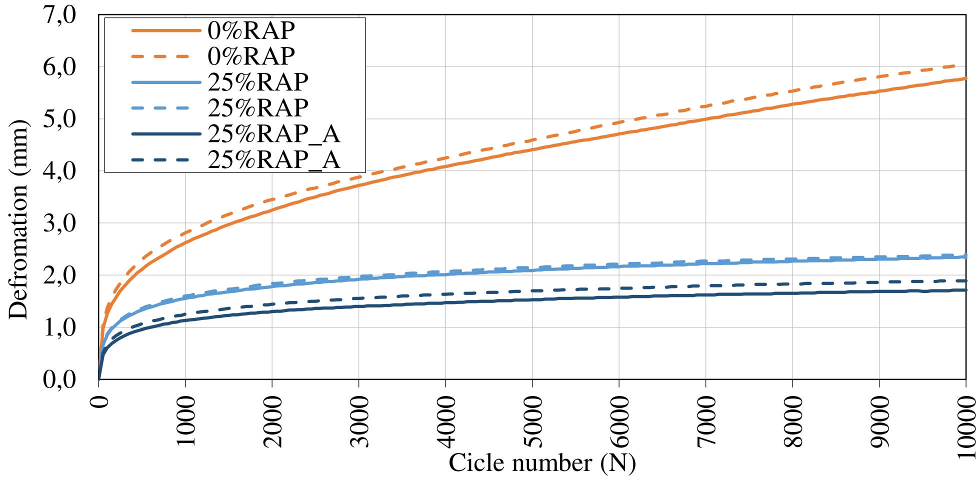

Figure 5: Permanent deformation

From the dynamic modulus measurement obtained by 4-point bending test method (4PBT) is obtained a result comprising two components: complex modulus (E*) and phase angle (δ). Depending of these two values the real part of the complex modulus can be calculated (E1), which represents the elastic properties of the material; and the imaginary part of the complex modulus (E2), which represents the viscous properties of the material.

The stiffness modulus was strongly affected by ageing (Figure 6). The recycled aged mixture showed a great increase in terms of stiffness modulus and a decrease in terms of phase angle. This higher stiffness of 25%RAP_A may result to lower resistance to fatigue cracking of the asphalt mixture during the in-service period.

Conversely to the expected, according to the results obtained by other authors [23–28], the stiffness modulus of 25%RAP mixture did not show significant differences when compared with the stiffness modulus obtained for the reference mixture. However, for the same testing conditions the results show a higher variation for the 25%RAP mixtures than for the reference mixture. This could be a consequence of incomplete blending between the aged binder of the RAP and new added bitumen. On other hand, the 25%RAP_A showed a decrease in terms of variability of results when compared with 25%RAP mixture, which can be related also with the blending degree between the aged binder and the new binder. The applied ageing methodology with the combination of short-term oven ageing with the long-term oven ageing can have contributed to the blending between both binders and the effect of rejuvenator. In terms of phase angle the 25%RAP mixture showed a reduction when compared with the 0%RAP mixture.

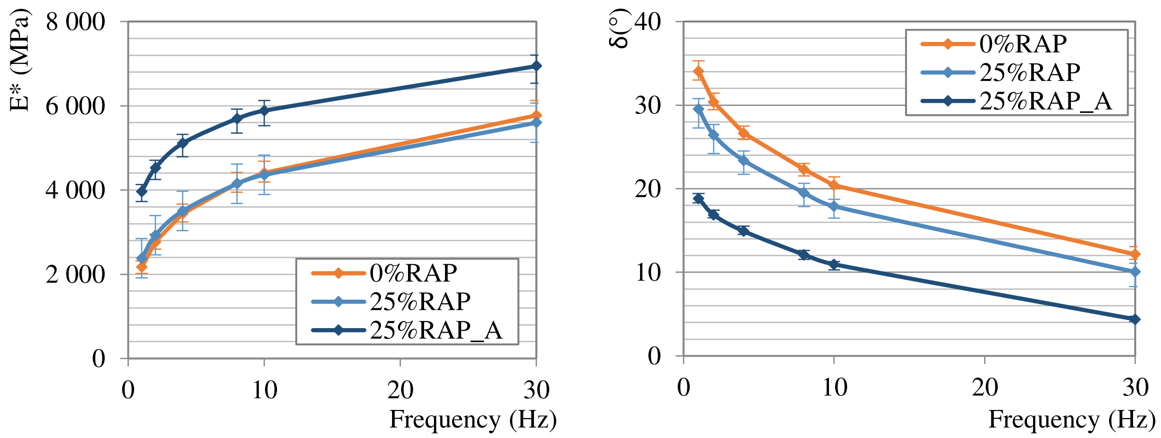

Figure 6: (left) Stiffness modulus curves at 20 ºC; (right) Phase angle curves at 20 ºC

In order to characterize the rheological properties of asphalt mixtures the results present the relation of complex modulus as a function of the phase angle (Figure 7). Lower values of phase angle indicate the prevalence of the elastic properties of the material. The phase angle increase reflects the participation of the viscous behaviour. The reduction of phase angle observed in Figure 6 and Figure 7 is related with the differences in type of binder. Both asphalt mixtures with RAP have a contribution of aged bitumen, as well as, the rejuvenator that reduce bitumen viscosity.

As the mineral skeleton in all mixtures is similar, the differences observed in stiffness and phase angle are due to the variations in bitumen content and the presence of aged bitumen and rejuvenator.

From the Black diagram presented in Figure 7 is possible observe a reduction in terms of phase angle for both mixtures with RAP. It is also evident the effect of laboratorial ageing process on recycled asphalt mixtures behaviour. This process allowed a reduction in terms of phase angle and an increase in terms of complex modulus, which is related with the contribution of elastic part of the mixture.

The previous considerations can be confirmed in the Cole-Cole diagram presented in Figure 7. By the analysis of the results presented in the Cole-Cole diagram is possible observe the increase of the elastic component in the aged recycled asphalt mixture (25%RAP_A) with a reduction of the viscous part for the same load, temperature and frequency conditions. It is possible to evaluate the laboratorial ageing effect on rheological properties of the asphalt mixtures. In general, the reference mixture (0%RAP) showed highest values for the elastic part (E1) and viscous part (E2) for the same loading and temperature conditions.

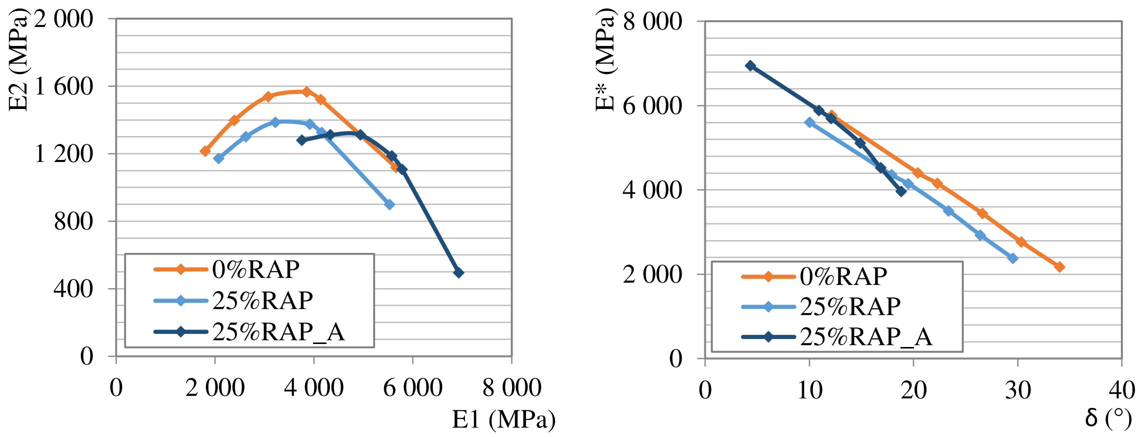

Figure 7: (left) Mixtures' Cole-Cole diagram; (right) Mixtures' Black diagram

Figure 8 presents the fatigue laws from the tests carried out. Although the results in Figure 8 reveal that fatigue behaviour of the asphalt mixtures 0%RAP and 25%RAP is somehow similar, is observed that the slope for the reference mixture is quite higher than the 25%RAP. This finding can be analysed in more detail by calculating ε_4, ε_5 and ε_6, which represent the strain values to induce specimens' failure after $1x10^4$, $1x10^5$ and $1x10^6$ loading cycles, respectively (Figure 9).

Figure 9 confirms different rankings for the tested blends depending on the number of loading cycles applied. For the 3 loading cycles levels the reference mixture presents the greatest strain value. The 25%RAP asphalt mixture obtained the second best value for the ε_4, ε_5. However, for the ε_6 the 25%RAP_A presented a value higher than 25%RAP and closer to the reference mixture.

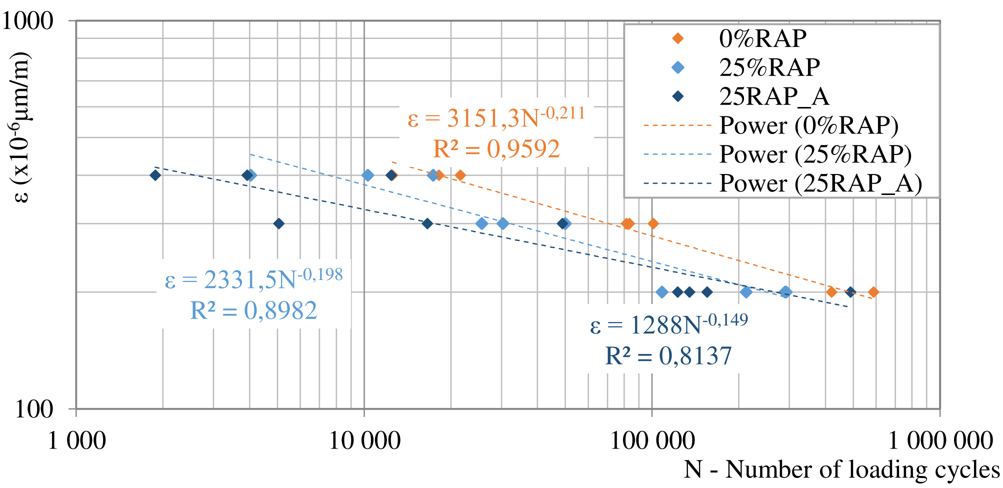

Figure 8: Fatigue curves of recycling mixes

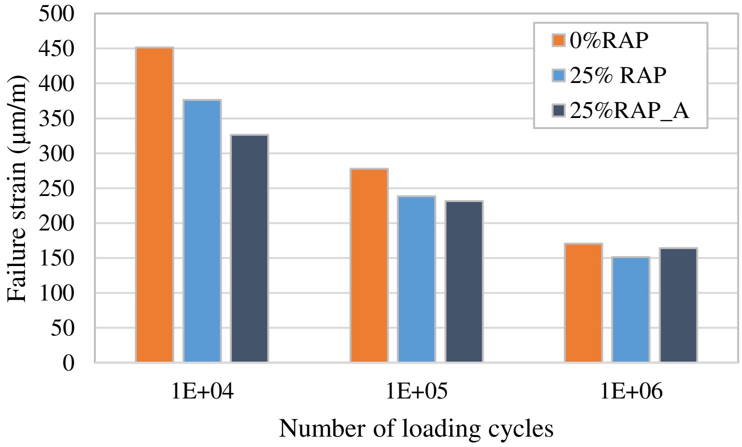

Figure 9: Fatigue performance in terms of strain needed to specimen's failure

Taking into account that evaluation of fatigue resistance aims to anticipate which mixtures will behave better under a high number of loading cycles, ε_6 is the parameter to assess the fatigue resistance of asphalt mixtures.

The ε_6 value shows that 25%RAP_A, the aged recycled mixture, has the best performance (only 4% less than reference mixture, 0%RAP). Adding RAP in asphalt mixtures slightly decreased resistance to fatigue when compared to the reference mixture – 11 % to 25%RAP mixture and the 4 % to the 25RAP_A mixture. Recording that both mixtures with RAP are the same mixture and the only difference between them is the induced ageing, is possible to observe a positive variation. The ε_6 value of aged recycled mixture (25%RAP_A) presented an increase of 9 % when compared with non-aged recycled mixture.

4. CONCLUSIONS

The multi-recycling capacity of RAP in new asphalt mixtures was the main focus of this study aiming to verify, on the one hand, the behaviour of the mixture with the incorporation of 25 % of RAP and, in the other hand the long-term performance of the recycled mixture.

The results produced in this study as well as the information gathered from the literature led to the following conclusions:

- The general performance of mixtures with 25 % RAP incorporation was very good when compared with reference mixture. The recycled mixture presented a slightly decrease in terms of fatigue resistance.
- The stiffness was not strongly affected by the RAP recycling in new asphalt mixture; 25%RAP and 0%RAP mixtures presented similar stiffness for the same loading conditions. The ageing introduces a great increase in stiffness.
- The introduction of RAP strongly affected the rutting resistance of the mixtures. Both mixtures with RAP presented lower values of rut depth, maximum wheel tracking rate and maximum wheel tracking slope. This can be related with the lower total bitumen content in the mixture and the presence of aged binder from RAP. The aged mixture presented the higher rutting resistance, which is related with the hardening of binder during the ageing period.
- Despite the strong effect of ageing on stiffness of the mixture, the aged recycled mixture (25%RAP_A) did not showed a considerable reduction in terms of fatigue resistance; the strain value for 1 million of cycles only presented a reduction of 4 % when compared with the reference mixture.

Concluding, it can be stated that RAP has potential to be multi-recycled in new asphalt mixtures. This material can be considered as a secondary raw material, however some tests must be performed in order to characterize its properties as well as a fractioning to be possible to control the grading curve to fit in grading envelope.

The performance of recycled mixtures showed good results even after ageing allowing to stablish that the mixtures with incorporation of RAP can present good long-term performance. In this way, since a convenient evaluation is carried out, solutions that incorporate RAP combined with a rejuvenator in order to take advantage of the aged bitumen are suitable alternatives to conventional hot mix asphalt.

It must also be emphasized that the use of RAP as part of aggregates and bitumen in new asphalt fulfil the European goals of increasing circular economy, reducing the landfill deposition and increasing the valorisation of by-products that can be treated as a secondary raw material.

ACKNOWLEDGEMENTS

The authors are grateful to the Fundação para a Ciência e a Tecnologia, IP for the financial support provided through grant SFRH/ BD/114715/2016 financed by the Portuguese Government budget. The authors also want to thank to the companies that provide the materials for this study.

REFERENCES

[1] Eurostat, Eurostat - Data Explorer, (2015). available: http://appsso.eurostat.ec.europa.eu/nui/show.do. (accessed April 11, 2018).
[2] EAPA, Asphalt the 100% recyclable construction product EAPA Position paper, Brussels, Belgium, 2014.
[3] M. Zaumanis, R.B. Mallick, R. Frank, 100% recycled hot mix asphalt: A review and analysis, Resour. Conserv. Recycl. 92 (2014) 230–245. doi:10.1016/j.resconrec.2014.07.007.
[4] R. West, J.R. Willis, M. Marasteanu, Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content - NCHRP Report 752, Washington, D.C., 2013. doi:10.17226/22554.
[5] Y. Zhang, D. Goulias, A. Aydilek, Sustainability evaluation of pavements using recycled materials, in: A. Loizos, I. Al-Qadi, T. Scarpas (Eds.), Conf. 10th Int. Conf. Bear. Capacit. Roads, Railw. Airfields - BCRRA 2017, CRC Press - Taylor & Francis Group, London, UK, 2017: pp. 1283–1291. doi:10.1201/9781315100333-185.
[6] M. Zaumanis, R.B. Mallick, R. Frank, 100% Hot Mix Asphalt Recycling: Challenges and Benefits, Transp. Res. Procedia. 14 (2016) 3493–3502. doi:10.1016/j.trpro.2016.05.315.
[7] COM 21, A resource-efficient Europe - flagship initiative under the Europe 2020 Strategy, 2011. Communication from the commision to the European Parliament, the council, the European economic and social committee and the committee of the regions., (2011).
[8] E. Comission, EUR 18906 - COST 333 - Development of New Bituminous Pavement Design Method, Office for Official Publications of the European Communities, Brussels, Belgium, 1999.
[9] R.C. West, QIP 129 - Best Practices for RAP and RAS Management, Lanham, USA, 2015.
[10] EP, Construction specifications book. 15.03 - Constructive methods (in Portuguese), Almada, Portugal, 2014.
[11] J. Don Brock, L. Richmond, Technical Paper T-127. Milling and recycling, Chattanooga, USA, 2016.
[12] EP, Construction specifications book. 14.03 - Materials (in Portuguese), (2012).
[13] LNEC, LNEC E 472 - Guide for the production of recycled hot mix asphalt (in Portuguese), (2009).
[14] EAPA, Asphalt in figures 2016, 2018. http://www.eapa.org/userfiles/2/Asphalt in Figures/2016/AIF_2016.pdf.
[15] Austroads, Maximising the Re-use of Reclaimed Asphalt Pavement Outcomes of Year Two : RAP Mix Design, 2015. www.austroads.com.au.
[16] R. McDaniel, R. Michael Anderson, NCHRP REPORT 452 - Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual TRANSPORTATION, 2001. http://www.national-academies.org/trb/bookstore.
[17] CEN, EN 13108-8: Bituminous mixtures - Material specifications - Part 8: Reclaimed asphalt, European Committee for Standardization, Brussels, Belgium, 2005.
[18] V. Antunes, A.C. Freire, J. Neves, A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling, Constr. Build. Mater. 211 (2019) 453–469. doi:10.1016/j.conbuildmat.2019.03.258.
[19] IPQ, NP EN 12591:2011 - Bitumen and bituminous binders. Specification for paving grade bitumens., (2011).
[20] AASHTO, AASHTO R 30-02: Mixture Conditioning of Hot Mix Asphalt (HMA), (2006).
[21] C.A. Bell, D. Sonsnovske, Aging: Binder Validation, 1994.
[22] A.J. Wieder, M.J. Fellin, Laboratory Aging of Mixtures : Field Validation, Washington, D.C., 1994.
[23] J.S. Daniel, A. Lachance, Mechanistic and volumetric properties of asphalt mixtures with recycled asphalt pavement, Bitum. Paving Mix. 2005. (2005) 28–36. doi:10.3141/1929-04.
[24] G. Valdés, F. Pérez-Jiménez, R. Miró, A. Martínez, R. Botella, Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP), Constr. Build. Mater. 25 (2011) 1289–1297. doi:10.1016/j.conbuildmat.2010.09.016.
[25] P.A.A. Pereira, J.R.M. Oliveira, L.G. Picado-Santos, Mechanical characterisation of hot mix recycled materials, Int. J. Pavement Eng. 5 (2004) 211–220. doi:10.1080/10298430412331333668.
[26] V.H. Nguyen, Effects of laboratory mixing methods and RAP materials on performance of hot recycled asphalt mixtures [PhD Thesis], University of Nottingham, 2009. http://etheses.nottingham.ac.uk/863/.
[27] M. Zaumanis, R.B. Mallick, R. Frank, Use of Rejuvenators for Production of Sustainable High Content Rap Hot Mix Asphalt, in: XXVIII Int. Balt. Road Conf., 2013: pp. 1–10.
[28] E. Bocci, A. Grilli, M. Bocci, V. Gomes, Recycling of high percentages of reclaimed asphalt using a bio-rejuvenator – a case study, in: Proc. 6th Eurasphalt Eurobitume Congr., 2016. doi:10.14311/EE.2016.334.