Extended Abstract

Total recycling of RAP mixtures using waste cooking oil as a rejuvenating agent

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Abstract

The purpose of this thesis is to analyze the viability of the use of reclaimed asphalt pavement (RAP) rejuvenated using waste cooking oil (WCO). In this case, the studied mixture contains 100% RAP materials in which were added 18% of WCO and 1% virgin bitumen, by weight of existent bitumen. The correspondent mixture was tested for stiffness, fatigue resistance, permanent deformation, and water sensitivity. Finally, the economic viability of the mixture was further evaluated.

The performance results showed that the rejuvenated mixture presents itself as a viable and cheaper alternative to the current pavement solutions. The rejuvenation with WCO achieved slightly higher stiffness modulus and longer fatigue life. Regarding the permanent deformation, the obtained results showed a greater rut depth when compared to the reference mixtures.

Considering the obtained results, it can be said that the rejuvenated mixture appears to be a very interesting solution for low to medium traffic pavements, however, a more in-depth study is required. The formulation on the “recipe” should be optimized so that the problems with permanent deformation can be attenuated. All of this to achieve a validation plan for this type of solution so that rejuvenated mixtures can become a reality, contributing to a circular economy in road pavements rehabilitation.

Keywords: Reclaimed asphalt pavement (RAP), rejuvenation, waste cooking oil (WCO), performance results, circular economy

1. Introduction

Asphalt bitumen as we know it today has acquired a high importance in society since it is a material widely used in road pavement worldwide. It is an oil residue, which is obtained in the final stage of its distillation and has the function of binder agent when mixed with crushed or natural aggregate. To the set of asphalt bitumen and aggregate, we called it bituminous mixtures.

In Portugal, these bituminous mixtures are principally used in flexible pavements, mainly as base and/or regularization layer and as wearing layer. The thickness of these layers isn't fixed, considering the road in question, the existing climatic conditions, and the traffic to which they will be subjected, the thickness is established for each layer to obtain an acceptable useful lifetime.

Like any other structure, road pavements also have their weaknesses. In this case, these are particularly visible in the upper layers, which over time start to show some pathologies, the most frequent being the cracking and the rut deformation. When advanced stages of degradation are reached these pathologies become irreversible and most often impose a replacement of the affected layers.

During the last few years, the strategy used by the different operators to requalify the affected roads has been the reconstruction of the same with new materials. It is a technologically simpler option (since the techniques are very well known, and the materials are generally available) but not very sustainable as it doesn't recycle the existing materials and, therefore, certainly more expensive, especially for secondary networks, less demanding structurally. Consequently, the reuse of existing materials (recycling) should be considered.

One of the problems associated with recycling is the reactivation of the functions of the existing binder so that it can play an important role in the final layers. It is in this sense that the rejuvenating agents of asphalt bitumen arise and among them, those that allow the reuse/recovery of waste such as waste cooking oil (WCO). It is expected that WCO when mixed with the aged bitumen present in reclaimed asphalt pavement (RAP), allows to restore or even improve its initial properties, giving the resulting mixture properties that allow its direct use in layers of pavement. Thus, the need to resort to new materials is reduced and the economic and environmental impact of pavement rehabilitation is diminished.

However, in Portugal, and as in other developed countries, the use of rejuvenating agents such as WCO in recycled mixtures is still reduced. Therefore, it seems important to carry out a laboratory work that seeks to evaluate its advantages and disadvantages.

2. Experimental study

The purpose of this study is to analyze the viability of the use of reclaimed asphalt pavement (RAP) rejuvenated by the use of waste cooking oil (WCO). The correspondent studied mixture contains 100% RAP materials to which were added a percentage of 18% of WCO and 1% virgin bitumen.

The performed laboratory work was divided into two distinct phases. The first one held in the Laboratory of road pavements of Instituto Superior de Engenharia de Coimbra (ISEC), whose objective was to formulate the correspondent "recipe" of production, that is, to define the quantities of WCO and virgin bitumen to be introduced into the RAP mixture to simulate the conditions of a standard mixture. The second phase was carried out in the Laboratory of transport infrastructures of Instituto Superior Técnico (IST), whose objective was to evaluate the viability of the rejuvenated mixture.

2.1 First phase – formulation of the "recipe"

Regarding the definition of the "recipe" itself, an iterative process of trial and error was carried out, in which were tested a total of seven different combinations of WCO and virgin bitumen. The work plan carried out in each of the attempts was performed based on the Marshall methodology, according to the standard EN 12697-34 (CEN 2004a), for the formulation of bituminous mixtures.

Table 2.1 illustrates a summary of the attempts, which ultimately led to the attainment of the final formulation. It should be noted that the percentages of bitumen presented are related to the total mass of the sample and the percentages of WCO are related to the total mass of bitumen present in the sample.

Table 2.1 - “Recipes" used in each one of the attempts

Attempt	%RAP bitumen	%virgin bitumen	%total bitumen	%WCO
1	4,7	0,3	5	4
2	4,7	1,3	6	8
3	4,7	0,8	5,5	8
4	4,5	1,5	6,0	8
5	4,5	0,5	5	16
6	4,5	1	5,5	16
7	4,5	0,5	5,0	18
Final formulation	**4,5**	**1**	**5,5**	**18**

2.2 Second phase – Characterization of the defined mixture

After the formulation of the mixture was chosen, the second phase of the experimental work was initiated. The work plan to be carried out at this stage can be described in two distinct stages, divided over a period of two weeks. In the first week, all the necessary specimens were manufactured, and in the second week, the correspondent specimens were submitted to the performance tests.

Since the tests carried out did not require a single type of specimen, it was necessary to manufacture three different types, each with the respective dimensions intended for the test in question. Figure 2.1 summarizes the entire manufacturing process, which results in a total of 30 specimens, divided over 2 slabs, 20 prismatic beams, and 8 cylindrical specimens.

To evaluate the performance of the rejuvenated mixture, a series of tests were conducted to determine its stiffness, fatigue resistance, permanent deformation, and even water sensitivity. All the performed tests are summarized in Table 2.2, accompanied by the correspondent standard and the method used in each of them.

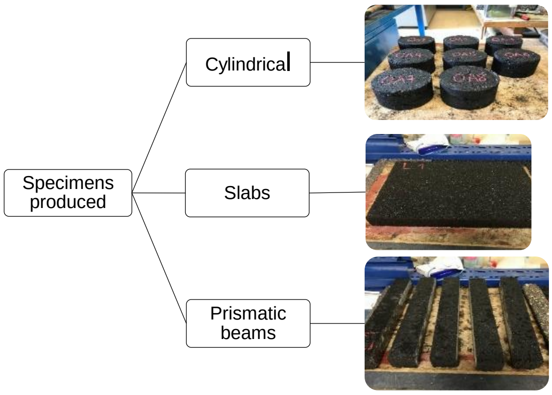


Figure *2.1* – Specimens produced to evaluate the performance of the mixture (adapted from Crucho, 2018)

Table 2.2 – Tests used for characterization of the mixture (adapted from Crucho, 2018)

Test	Standard	Method
Stiffness	CEN EN 12697-26	Four-point bending
Fatigues resistance	CEN EN 12697-24	Four-point bending
Permanent deformation	CEN EN 12697-22	Wheel-tracking small size device – in air
Water sensitivity	CEN EN 12697-12	Method A - ITSR
(indirect tensile strength)	(CEN EN 12697-23)	(diametral compression)

3. Presentation and discussion of results

It is important to mention that in the second phase of the laboratory work no reference mixture was manufactured and so the obtained results had to be compared with equivalent AC14 surf mixtures from external studies. In case of the stiffness modulus and fatigue resistance, the results were compared with the studies of Crucho 2018 and Silva 2016. The resistance to permanent deformation and water sensitivity, were also compared with the results provided by the company (JJR Construções) responsible for producing the virgin mixture that originated the used RAP material.

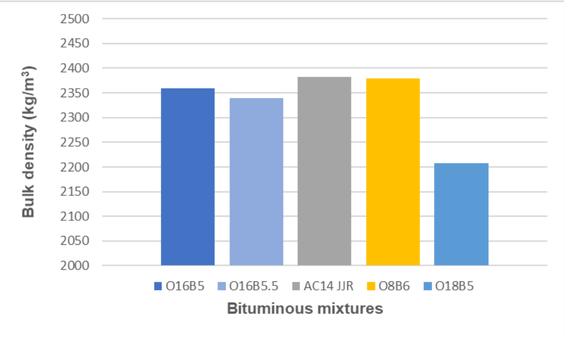
3.1 Mixture formulation

Among the tested mixtures, it is important to show the results obtained for the last four to be performed which served as the basis for the final formulation. The combinations used in these mixtures corresponded to a percentage of 8%, 16% and 18% of WCO with 5%, 5.5% and 6% of virgin bitumen, which were named "O16B5", "O16B5.5", "O8B6" and "O18B5" respectively.

For the formulation of the mixture, the values of bulk density and Marshall compression test were used, since those could be comparable with the available reference values. These reference values were referenced by the IP (Infraestruturas de Portugal) specifications and by the company responsible to produce the original bituminous mixture.

Figure 2.2 shows the values of the bulk density for each mixture. As it is possible to observe the obtained values are very close to the original value (AC14 JJR). This was due to the addition of WCO, which tends to produce a rejuvenating effect on the RAP mixture.

Figure 2.2 – Bulk density of the rejuvenated mixtures



Regarding the results of the Marshall compression test, this includes the stability and flow value. Table 3.1 shows the obtained values for each mixture, as well as the reference values presented by the IP specifications. The presented values for each mixture correspond to the average of the obtained values.

Table 3.1 – Marshall values for each mixture

Mixture	Stability (kN)	Flow (mm)
IP specifications	7,5 – 15	2 – 4
O8B6	17,5	4,3
O16B5	18	3,5
O16B5.5	14,5	3,9
O18B5	13,6	3,

Considering the observed results, the assessment of the mechanical performance of the final mixture was done with 18% of WCO and 5.5% of total bitumen. This binder percentage is 0.5% higher than that of the original mixture. However, given that a small part of the residual bitumen of the RAP material is likely to act as "Black Rock", it was decided to use a slightly higher percentage (5.5% instead of 5%).

3.2 Characterization of the rejuvenated mixture

3.2.1 Stiffness

The stiffness test was performed according to EN 12697-26 (CEN 2004b). A sinusoidal load was applied using a strain amplitude of 50 µm/m with the frequencies of 1 Hz, 3 Hz, 5 Hz, 10 Hz, 20 Hz, and 30 Hz. The temperature of 20 ºC was also chosen for the conduction of the test.

A total of 18 specimens were tested and the respective stiffness modulus and phase angle were determined for each of them. Figures 3.1 and 3.2 show the stiffness modulus and phase angle of the rejuvenated mixture when compared to the reference mixtures.

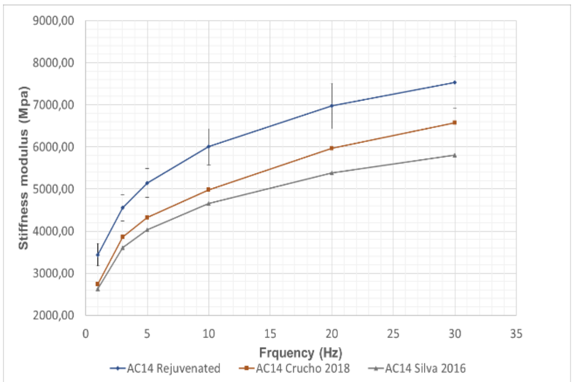


Figure 3.1 – Stiffness modulus of rejuvenated and reference mixtures

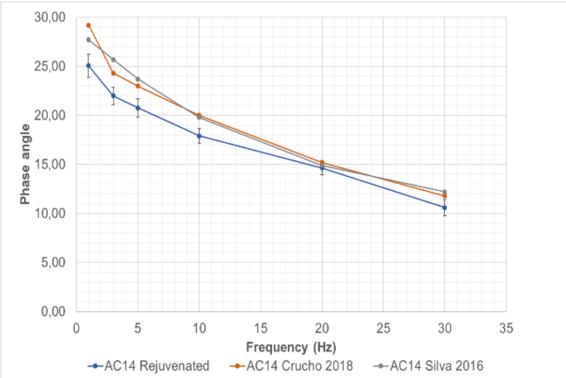


Figure 3.2 – Phase angle of rejuvenated modulus and reference mixture

Considering the mixture in question, the obtained results were within the expected values. The rejuvenated mixture presented an increase of 14% to 24% in the stiffness modulus and a decrease of 2% to 17% in the phase angle.

However, the obtained variations were not significant, proving that the mixture does not seem to exhibit a fragile behavior that could lead to cracking.

3.2.2 Fatigue resistance

The fatigue resistance test was performed according to EN 12697-24 (CEN 2004c) under strain-controlled conditions. In this case, three levels of strain were chosen: 200, 300, and 400 µm/m. The strain was applied by a sinusoidal load at a frequency of 10 Hz and the selected temperature for the test was 20 º C. For this study the failure criterion was specified by the correspondent standard, corresponding to the number of cycles required for the initial stiffness modulus to be reduced by 50%.

Once the test was performed on all the chosen specimens, it was possible to calculate the fatigue line for the rejuvenated mixture. Figure 3.3 illustrates the obtained fatigue line, as well as the fatigue lines of the reference mixtures.

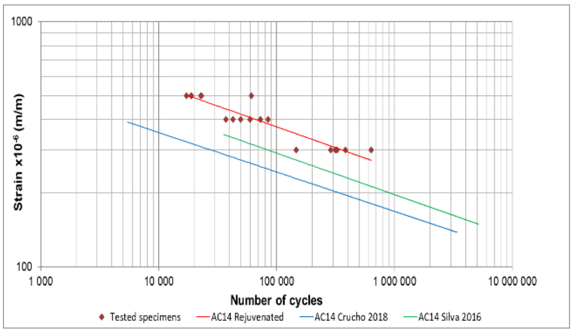


Figure 3.3 – Fatigue lines of the rejuvenated and reference mixtures

The results showed that the rejuvenated mixture presents a value of ε_6 much higher than both of reference mixtures and a similar slope, which means that for the same induced strain it supports a greater number of repetitions, translating into a better behavior to fatigue.

3.2.3 Permanent deformation

The permanent deformation of the rejuvenated mixture was evaluated by the wheel-tracking test. The test was performed according to the standard EN 12697-22 (CEN 2003a), small size device, procedure B, tested in air. A 700 ± 10 N load was applied at the top of the slab by a standardized wheel. This load was applied continuously at a temperature of 60 º C until the stopping criterion was reached. According to the mentioned standard, this stopping criterion is defined by the limit of 10,000 cycles or the maximum deformation of 20 mm.

Table 4.8 presents the results for both slabs and the values of the reference mixtures. The obtained results for the rejuvenated mixture were expected, all indicators of the permanent deformation test are higher than the reference mixtures, which proves its inferior performance at medium to high temperatures.

Table 3.2 – Wheel-tracking results of the rejuvenated and reference mixtures (adapted from Crucho, 2018)

Mixture	RD_{air} (mm)	PRD_{air} (%)	WTS_{air} (mm/10^3cycles)
AC14 Rejuvenated	7,60	14,80	0.339
AC14 Crucho 2018	2,62	4,33	0,091
AC14 Silva 2016	2,39	3,90	0,052
AC14 JJR	4,9	12,1	0,200

Nevertheless, it is important to note that the obtained values for the rejuvenated mixture are acceptable when compared to its original mixture (AC14 JJR). Most likely a correction of the final mixture gradation with coarse aggregate (reduced cost intervention) would provide the necessary resistance to permanent deformation to overcome this gap.

3.2.4 Water sensitivity

The last test to be performed was the evaluation of the water sensitivity of the mixture, one of the most critical pavement distresses. The procedure to evaluate water sensitivity was conducted by the standard EN 12697-12 (CEN 2008) and the indirect tensile strength (ITS) test method as described in EN 12697-23 (CEN 2003b).

The evaluation of the water sensitivity of the mixture is based on the ITSR value which is the ratio between the ITS values of the two specimen groups, "ITS_{Wet}" and ITS_{Dry}", respectively. Table 3.3 presents all the values obtained for the rejuvenated mixture and the provided values of the reference mixtures.

Table 3.3 – ISTR values of the rejuvenated and reference mixtures

Mixture	ITS_{Dry} (kPa)	ITS_{Wet} (kPa)	ITSR (%)
AC14 Rejuvenated	2392,2	2499,1	104
AC14 Crucho 2018	1287,3	739,4	57
AC14 Silva 2016	-	-	86

From the value of the ITSR of each mixture, it was possible to verify that the rejuvenated mixture shows improvements to water sensitivity. The ITS value for the "Wet" group has even increased slightly, which makes it possible to affirm that the resistance of the mixture is not affected by water.

3.4.5 Mixture costs

Even though mixture performance is an important factor and demonstrates the possibility of the application of this type of mixtures in pavement layers, it is necessary to verify that the costs involved are cheaper than current solutions, so that they effectively can be used.

In order to simulate the paving cost of the studied mixture, a thickness of 5 cm of wearing layer was assumed and the costs for all the operations that run until its final placement were taken into consideration. Table 3.4 shows all the considered operations and the final cost obtained for the correspondent mixture expressed in € per ton of BM (bituminous mixture)

Table 3.4 – Operation costs associated to the rejuvenated mixture

Operation	€/ton of BM
Milling	0,47
Transport + screening process	4,73
1% virgin bitumen	3,00
18% WCO	0,50
Production	3,00
Paving	5,04
Total cost	**16,74**

Once the paving cost of the rejuvenated mixture was obtained, the corresponding value was determined in €/m^2. Considering the value of the average bulk density of the mixture and the assumed thickness for the wearing layer, a cost of **€2/m^2** was obtained. Therefore, it was possible to verify that the rejuvenated mixture presented itself as a viable alternative to the equivalent AC14 solution which current pricing is admitted being at €5/m^2. Figure 3.4 shows the costs difference between both solutions, where the rejuvenated mixture represents a reduction of **60%**.

In addition to the operations presented previously, there are also costs associated with the deposition of RAP materials that were not considered. However, since the rejuvenated mixture promotes the reuse of RAP material, the quantities to be sent to deposition are also reduced. This means that the possible costs incurred by this operation were not counted and therefore the cost reduction associated with the use of a rejuvenated mixture would possibly be greater than 60%.

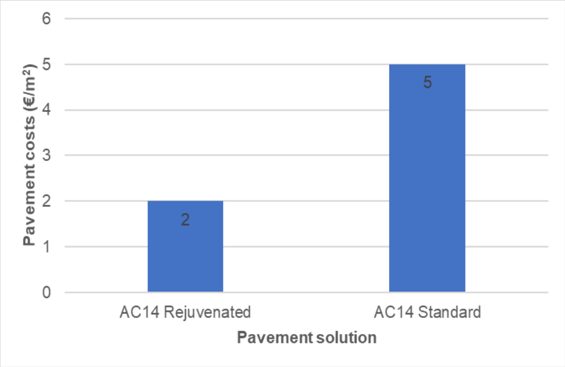


Figure 3.4 – Costs difference per m^2 between both pavement solutions

4. Conclusions

Once completed all the laboratory work and obtained all the results, it can be affirmed that the objectives to which this thesis was proposed were fulfilled. The rejuvenated mixture was manufactured and the technical and economic viability for its reapplication in low to medium-traffic pavements was evaluated.

When compared to the reference mixtures the rejuvenated mixture exhibited higher stiffness modulus, translating into a maximum increase of 24%. This can be explained by the presence of aged bitumen in the mixture, which possibly was not completely rejuvenated by the inclusion of the WCO making it slightly more rigid. This possibility was observed simultaneously with the obtained values for the phase angle which were inferior to the reference mixtures. This decrease in values is in agreement with the results obtained for the stiffness modulus and increases the option of the presence of aged bitumen in the mixture since the approximations of the phase angle values to zero translate a more resistance behavior of the mixture to the induced deformation.

Through the analysis of the mixture behavior to fatigue resistance, it was found that the rejuvenated mixture presented a much higher value of ε_6 (252 μm/m), which translates into higher fatigue resistance and therefore longer lifetime. This behavior may be explained by the aggregate gradation of the mixture that presented more fine aggregate than the reference mixtures. As we know, a higher percentage of fine aggregate may indicate the presence of higher mastic (fine aggregate plus binder) in the mixture, which makes it more resistant to fatigue assessment conditions. This is also corroborated by the obtained low porosities of the rejuvenated mixture.

Regarding the mixture behavior to permanent deformation, it was found that the rejuvenated mixture showed lower performance than the reference mixtures, presenting an average rut depth of 7.6 mm. The same results were obtained for the other parameters evaluated, namely the proportional rut depth in air (PRD_{AIR}) and the wheel-tracking slope in air (WTS_{AIR}). In both parameters, the rejuvenated mixture presented higher values than the reference mixtures, which demonstrates its greater propensity to deform. This decrease in the performance should be associated with the higher amount of mastic and low porosity already mentioned. In addition, the greater susceptibility of the rejuvenated bitumen to medium to high temperatures may also condition the results, since the test was carried out at 60 º C. However, the obtained results weren't necessarily bad, it can be said that the mixture it is suitable for less demanding pavements as was intended with this study.

The analysis of water sensitivity verified once again the superior performance of the rejuvenated mixture when compared with the reference mixtures. The value of the ITSR presented by the studied mixture was 104%, which translates its superior water resistance. Such occurrence may be explained by the low porosity of the mixture. Nevertheless, the presented ITSR values were obtained under different test conditions when compared to the other studies and so the higher performance exhibited by the rejuvenated mixture could not be totally accurate.

After the evaluation of the rejuvenated mixture performance, the economic viability of its the application in a wearing layer 5 cm was also evaluated. A paving cost of **2 €/m²** was obtained, which compared to a standard AC14 surf, represents a cost reduction of around 60% for a low to medium traffic pavement.

On this basis, it can be concluded that bituminous mixtures obtained by RAP materials and rejuvenated by WCO, may present itself as a viable alternative to the current paving solutions for wearing layers. The evaluation of the performance through the various tests indicates that they can perform quite satisfactorily. In addition, these are mixtures that reuse the entire materials that were applied in other pavements, strongly contributing to a circular economy in road paving.

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