

Performance of warm recycling mixtures and their influence on the design of asphalt layer

Desempenho de misturas asfálticas recicladas mornas e sua influência no dimensionamento do revestimento asfáltico

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Abstract

The main purpose is to evaluate the performance of asphalt regarding resilient modulus and fatigue curve. The asphalt was produced with two wastes, reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA), using the technique of warm mixtures. The evaluation includes, based on these parameters, the thickness differences in the design of asphalt layer for each mixture. Five asphalt mixtures were produced with incorporation of RAP and RCA, in different gradation fractions (fine and/or course), without adding any natural aggregate. In view of the aim of the article, the mixtures were evaluated through tests of resilient modulus and fatigue life, in order to support the design, establishing the necessary thickness to meet traffic demands of each mixture. The design was performed using MeDiNa software. Among all results, it is highlighted that asphalt binder content is the component that exerts the greatest influence on the resilient modulus of the mixtures. As for fatigue, in addition to the binder content, the possible anchoring of the asphalt binder in the pores of the RCA may have favored the performance of the GARC_MRAP mixture. Still, all mixtures with RAP, both in fine or course fraction, resulted in lower coating thicknesses compared to the REF, for the same load request, with better performance of the GARC_MRAP mixture produced with 100 % waste material and incorporation of only 3.1 % neat binder.

Keywords: Reclaimed asphalt pavement. Recycled concrete aggregate. Resilient modulus. Fatigue life. Mechanistic analysis.

Resumo

O objetivo geral foi avaliar o desempenho das misturas asfálticas no que diz respeito ao módulo de resiliência e à curva de fadiga, confeccionadas com o emprego de dois resíduos, revestimento asfáltico fresado (RAP) e agregado reciclado de concreto (ARC) utilizando a técnica das misturas mornas. A avaliação engloba, a partir desses parâmetros, as diferenças de espessura no dimensionamento do revestimento asfáltico para cada uma das misturas. Foram produzidas cinco misturas asfálticas com incorporação de RAP e ARC, em diferentes frações granulométricas (graúda e/ou miúda), sem adição de qualquer agregado natural. Diante do objetivo do artigo, as misturas foram avaliadas através dos ensaios de módulo de resiliência e vida de fadiga, a fim de possibilitar o dimensionamento, estabelecendo a espessura necessária para atendimento as solicitações de tráfego de cada uma delas. O dimensionamento foi realizado no software MeDiNa. Diante dos resultados, destaca-se que teor de ligante asfáltico é o componente que exerce maior influência no módulo de resiliência das misturas. Quanto à fadiga, além do teor de ligante, a possível ancoragem do ligante asfáltico nos poros do ARC pode ter favorecido o desempenho da mistura GARC_MRAP. Ainda, todas as misturas com RAP, tanto na fração graúda como miúda, resultaram em menores espessuras de revestimento em comparação a mistura REF para uma mesma solicitação de carga, com melhor desempenho da mistura GARC_MRAP produzida com 100 % de resíduos e incorporação de ligante novo de apenas 3,1 %.

Palavras-chave: Revestimento asfáltico fresado. Agregado de resíduo de concreto. Módulo de resiliência. Vida de fadiga. Análise mecanicista.

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Introduction

The use of recycled materials in the construction of highways has become an increasing practice. The main objective is to reduce the environmental impact, in this case, seeking alternatives that minimize the exploitation of natural resources, such as mineral aggregates and binders. The concept of sustainability of pavement structures is usually based on the selection of materials and, therefore, seeking alternative sources of aggregates is a key factor in minimizing the environmental impact caused by the sector (PLATI, 2019). Therefore, the use of by-products or wastes with characteristics suitable for use in asphalt mixtures has been frequent (RODRÍGUEZ-FERNÁNDEZ *et al.*, 2019) and one of the most studied alternatives is the Reclaimed Asphalt Pavement, also very well known in the technical and academic environment as RAP.

Freire *et al.* (2014), analyzing the state of the art on the use of RAP, concluded that the works performed attest to the technical feasibility for producing asphalt mixtures using this waste, however, there is still fear in the use of mixtures with high levels of this material, due to the greater disparity between the results of mechanical tests. As far as the RAP application feasibility is concerned, Motta (2011) indicates that the temperature influences the rheological characteristics of the binder and, when recycled asphalt mixtures are processed, the ideal is that the milled material is not subjected to high temperatures (such as conventional mixtures), in order to prevent an even greater aging of the asphalt contained in the milled content and the early deterioration of the mixture. Therefore, the use of warm and semi-warm mixtures may favor the addition of greater amounts of RAP in the production of hot recycled mixtures (OLARD, 2008; PROWELL; HURLEY, 2007).

In addition to RAP, another residue mentioned in recent scientific research, for use in asphalt mixtures, is the Recycled Concrete Aggregate (RCA). According to Pasandín and Pérez (2015), in particular, construction and demolition waste are the most notable recyclable materials in the construction industry. According to the studies carried out by Motter, Miranda and Bernucci (2015), the porosity of the aggregates of concrete waste is related to the increase in binder consumption, a hypothesis that is corroborated in the conclusions of the systematic literature review made by Radević *et al.* (2017). Anyway, the authors indicate the technical feasibility of this type of mixture on roads with low traffic volume (MOTTER; MIRANDA; BERNUCCI, 2015).

In addition to the environmental appeal, the concept of sustainability is also subject to satisfactory technical performance, a fact that cannot be overlooked in the study of recycled mixtures. A pavement is designed to meet a specific project period (service life) and the design methods for this have been increasingly improved in order to better portray the conditions of application to which this pavement will be subjected. In this evolution there is a tendency to apply mechanistic design methods, which incorporate the knowledge of elastic parameters of the materials that make up the layers of the pavements, such as resilient modulus (RM) and fatigue life.

As for the RM of recycled asphalt mixtures, Zhao *et al.* (2013) concluded that the content of RAP incorporation did not significantly interfere in the results. However, in the studies by Xiao *et al.* (2009), the results indicate a significant increase in the value of RM with the addition of RAP. For Shu *et al.* (2012), who also obtained higher RM results in samples with RAP incorporation, this increase can be attributed to the greater stiffness coming from the aged asphalt present in the RAP.

Regarding the incorporation of RCA, Pasandín and Perez (2015) indicate that the studies are not unanimous when it comes to the RM of the mixtures tested. According to Radević *et al.* (2017), in asphalt mixtures produced with partial or total replacement of natural aggregates by RCA, the maximum size of RCA has a great influence on the rigidity of the mixtures. For the authors, the results of mixtures produced with 100 % RCA in its fine fraction are greater with regard to stiffness, and vice versa, when compared to control mixtures. Contrary to the results presented by Radević *et al.* (2017), Zulkati, Wong and Sun (2013) concluded that the mixtures produced with RCA, both in the coarse and in the fine fraction, presented less stiffness than the reference mixtures, probably due to the increase in the optimum binder content that these mixtures require due to the aggregate's high porosity.

Regarding the fatigue of recycled mixtures, Zhao *et al.* (2013) concluded that the addition of RAP in the mixture increases resistance to cracking and fatigue in the warm mixture, and decreases in the hot mixture, limited to the content of 30 % of incorporation. Genesseeux (2015) evaluated warm mixtures produced with a high percentage of RAP (50 %) and the conclusions pointed to this impairment of the fatigue life indicated by Zhao *et al.* (2013), reducing the strength of warm mixes. In any case, the author points out that, although they are more sensitive to

fatigue than hot machined mixtures, all the warm asphalt mixtures evaluated presented deformation values equal to or higher than those required by the standard.

According to the studies by Wu, Muhunthan and Wen (2017), the increase in RCA incorporation negatively affects the fatigue strength of asphalt mixtures, especially when it comes to cyclic tests. In the studies by Pasandín and Pérez (2017), the authors concluded that the higher the percentage of incorporated RCA (up to 42 %), the longer the fatigue life of the asphalt mixture. Thus, according to them, the incorporation of RCA not only does not impair the fatigue performance, but also benefits the mixture as to this property, a fact that can be explained by the higher binder content.

Still with regard to performance, based on the literature review, it is possible to state that the size and quantity of incorporated waste (coarse or fine fraction) have a direct impact on the performance of the mixture (CHEN; LIN; WU, 2011; MOTTER; MIRANDA; BERNUCCI, 2015; RADEVIĆ *et al.*, 2017). In the case of RAP, for example, this incorporation into fractions can be even more valuable, since it is known that the asphalt binder contained in a mixture is distributed among the grains according to their specific surface, this being the relationship between the total surface area of the grains and their density (GENNESSAUX, 2015). In this case, the thin part of a mixture is richer in binder than the heavier part, due to the greater specific surface of the fines and, therefore, the use of fine RAP can contribute to further reducing the need for incorporation of neat binder in the recycled mixtures.

It is a known fact that there are still very few studies dealing with the joint application of the two wastes proposed in asphalt mixtures, and the conclusions of the literature are not unanimous regarding the performance of recycled mixtures (FREIRE *et al.*, 2014; PASANDÍN; PEREZ, 2015; RADEVIĆ *et al.*, 2017; ZULKATI; WONG; SUN, 2013) corroborating the technological importance to verify the potential use of this type of study. In addition, the assessment of the resilient modulus or fatigue life in isolation may not be decisive in proving the quality of the material. According to Fritzen *et al.* (2019) mixtures that have higher resilient modulus, work with lower tensile strain, which could suggest better fatigue strength. However, there may be mixtures that, even with lower resilient moduli, and working at higher levels of tensile strain, may behave better in fatigue. Therefore, the evaluation of these two parameters together is fundamental for designers and builders to use recycled

mixtures in the field, through the empirical-mechanistic design.

In view of the above, this research had as main objective to evaluate the performance in terms of fatigue and resilient modulus of asphalt layers produced with two types of residues (RAP and RCA) and using the technique of warm mixtures, specifically regarding the thickness of the layer necessary to support the traffic actions, a parameter that is directly linked to the durability of the pavement (VIDOTTO; FONTENELE, 2013).

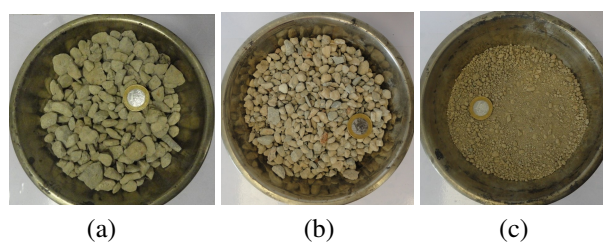
Materials and Methods

The research evaluated the performance of asphalt mixtures with respect to resilient modulus and the fatigue curve, made with the use of two wastes, RAP and RCA, using the warm mix technique. These two tests were defined in order to enable the dimensioning of the necessary layer thickness of each of the studied mixtures in a hypothetical pavement structure. The type of Petroleum Asphalt Cement (PAC), the granulometric range chosen, the additive for the production of warm mixtures and the other variables of the respective tests for performance evaluation were kept constant. The control variable of the study was the fraction in which each waste was incorporated (coarse, fine or both).

Materials

The binder used to produce the mixtures was CAP 50/70. The natural aggregates are of granitic origin and were collected in the fractions: crushed stone 1, pebble and stone powder. The aggregates of concrete waste came from the recycling plant Soliforte Reciclagem Ltda., They were collected in the fractions crushed stone 1, and recycled pebble and sand, as shown in Figure 1.

Figure 1 – RCA fractions: (a) crushed stone; (b) pebble; (c) stone powder.



Source: The authors.

The RAP made available for the present study came from a reclaimed asphalt pavement deposit, resulting from the milling of a section of Highway PR-407. However, there is no information on the characteristic of the mixture or binder used, confirming the need to characterize both the aggregate and the binder extracted from the studied RAP. The additive used for making the warm mixtures was of the surfactant type, which, according to the manufacturer, does not alter the viscosity of the asphalt binder, as it is made of molecules from natural plant oils.

Methods

Characterization of non-recycled materials

The aggregates were characterized in terms of granulometry tests as per NBR NM 248 (ABNT, 2003b), water absorption as per NBR NM 30 (ABNT, 2001a), apparent and bulk specific gravity as per NBR NM 53 (ABNT, 2009b) and NM 52 (ABNT, 2009a), loose and rodded unit weight as per AASHTO T19, fine content as per NBR NM 46 (ABNT, 2003c), Los Angeles abrasion as per NBR NM 51 (ABNT, 2001b) and shape index as per NBR 7809 (ABNT, 2006). The neat asphalt binder was tested for dynamic viscosity using the Brookfield viscometer according to NBR 15184 (ABNT, 2004), specific and relative density according to NBR 6296 (ABNT, 2012). As for the binder recovered from RAP after distillation, it was characterized in terms of penetration, softening point and Brookfield viscosity according to the standards NBR 6576 (ABNT, 2007), NBR 6560 (ABNT, 2016), and NBR 14950 (ABNT, 2003a), respectively.

RCA Characterization

The results of RCA characterization are shown in Table 1.

Despite the porous characteristic and the low resistance of the mortar adhered to the RCA, commonly reported in the literature, the coarse fractions met the requirements of DNIT 031 (DNIT, 2006), used as a Brazilian reference, regarding the wear measured in the Los Angeles abrasion test. As for the shape index, the fractions showed indices higher than the limit of 2.0, established by the standard NBR 12948 (ABNT, 1993), which indicates a more lamellar configuration.

Table 1 – Results of RCA characterization.

Parameter	RCA		
	Crushed stone	Pebble	Stone powder
Bulk specific gravity (g/cm^3)	2.330	2.180	2.080
Apparent specific gravity (g/cm^3)	2.610	2.550	2.610
Water absorption (%)	4.65	6.52	10.88
Fine content (%)	1.48	1.77	8.91
Loose unit weight (g/cm^3)	1.275	1.230	1.409
Rodded unit weight (g/cm^3)	1.459	1.369	1.625
Shape index	2.1	2.2	-
Los Angeles Abrasion (%)	32.7	34.6	-

Source: The authors.

Also, it is important to highlight the high values of water absorption, mainly of the recycled fine aggregate, a fact that is reported in the vast majority of the studies presented in the bibliographic review. According to the literature, this water absorption is directly linked to the consumption of binder in the asphalt mixture.

RAP Characterization

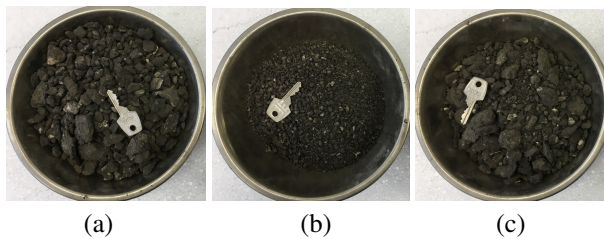
The method used for extracting the asphalt binder from RAP was solvent extraction, according to the recommendations of the DNIT ME 158 standard (DNIT, 2011). It is known that the asphalt binder contained in a mixture is distributed among the grains according to their specific surface, which is the relationship between the total surface area of the grains and their density.

Thus, the thin part of a mixture is richer in binder than the thick part, due to the greater specific surface of the fines. Given these considerations, the RAP was separated into two fractions, through the # 4 sieve. The material retained in the # 4 sieve was called the coarse fraction and the material passing through the # 4 sieve was called fine fraction. In order to determine the binder content, two samples of each of the fractions were tested: coarse, fine and total RAP (without separation of the # 4 sieve).

Figure 2 shows the fractions used in this study, coarse (a) and fine (b), as well as the total fraction (c).

After the extraction of the asphalt binder from the RAP, the “washed” aggregate was characterized according to the same properties tested for the natural aggregate and the RCA. Binder recovery was performed using a rotoevaporator, where it was possible to separate the asphalt binder contained in the RAP from the solvent used in the extraction.

Figure 2 – Fractions of RAP: (a) coarse; (b) fine; (c) total.



Source: The authors.

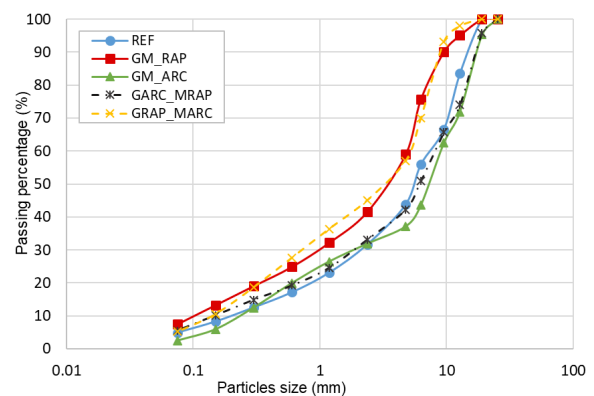
As expected, the small fraction is the richest in asphalt binder with 6.06 %, followed by the total fraction that presented 5.00 % and lastly, the large fraction with the lowest binder content, 4.44 %. This fact, explained by the greater specific surface area of the fines, is interesting from a practical point of view, in the sense of making it possible to separate the RAP into heaps with different granular fractions (coarse and fine, for example). By storing RAP in heaps of different particle sizes it is possible to minimize the variability of the recycled mixtures produced. In addition, it will be possible to allocate different applications for each fraction, optimizing each one, such as the use of the small fraction (which has higher binder content) in coating layers and the large fraction (with lower binder content) in base layers, for example.

Mix Design

The experiment was planned based on the making of five mixtures produced with the incorporation of RAP and RCA, in different granulometric fractions (coarse and/or fine). A mixture was produced with incorporation of RCA in the coarse fraction and RAP in the fine fraction, called GARC_MRAP, and another mixture with incorporation of RAP in the coarse fraction and RCA in the fine fraction, called GRAP_MARC. Besides these, a mixture was produced with 100 % RCA, called GM_ARC, and a mixture with 100 % RAP, called GM_RAP. Finally, in order to validate the results, a reference mixture was made with 100 % natural aggregates, called REF.

The granulometric range of the mixtures was chosen using the Bailey methodology, as it is a more analytical aggregate selection method, and the curves were adjusted to fit the average value of the proportion of coarse aggregate established by the method. Figure 3 shows the granulometric curves of the five mixtures, as well as the data presented in Table 2. It is possible to perceive the proximity of all curves, except for the granulometric curves of the GM_RAP and GRAP_MARC mixtures that are distant from the others due to the aforementioned characteristics of the milled material. It is important to note that, aligned with the objective of the present research to evaluate the incorporation of wastes in controlled fractions, no granulometric adjustment was made with neat aggregates, which could de-characterize and incorporate additional variables in the results.

Figure 3 – Granulometric curves of the study mixtures.



Source: The authors.

The mixtures were machined in a mechanical mixer at 120 °C, kept in an oven for two hours at the compaction temperature (110 °C) and later molded in the Superpave Gyratory Compactor (CGS). The choice of optimum binder content was based on the 4 % void criterion, subject to compliance with the limits established for the bitumen/void ratio, according to the DNIT ES 031 (DNIT, 2006) standard for the asphalt layer. Following this criterion, the optimum binder content was determined for each of the mixtures, the largest of which was in the mixture with 100 % RCA due to the porosity of the aggregate, corroborating the indications in the literature.

For the preparation of warm mixtures, a surfactant additive was used. The additive was incorporated in the proportion of 0.4 % on the weight of the binder, according to the manufacturer’s guidelines.

Table 2 – Composition and Vv of the study mixtures.

Composition			REF	GM_ARC	GARC_MRAP	GRAP_MARC	GM_RAP
Agreg.	NAT	Coarse	53.5				
		Fine	41.7				
	RCA	Coarse		56.8	54.6		
		Fine		33.6		53.1	
	RAP	Coarse				39.9	38.4
		Fine					55.4
Asphalt Binder	CAP 50/70		4.8	9.6	3.1	5.3	
	CAP remob. RAP				2.4	1.7	4.4
	RCA						1.8
	Total binder		4.8	9.6	5.5	7.0	6.2
	Void volume		3.7	4.1	4.1	4.1	3.8

Source: The authors.

The working temperatures were established in relation to the machining and compaction temperatures of a hot mixture (which would be 150 °C and 140 °C, respectively) considering the reduction of 30 °C in both, a reduction that is common among in the relevant literature (GENNESSAUX, 2015; MOTTA, 2011; PROWELL; HURLEY, 2007).

For the formulation of asphalt mixtures that contained RAP (GM_RAP, GRAP_MARC and GARC_MRAP) the granulometry of the material after extraction was used, that is, without binder, considering that 100 % of the asphalt binder contained in the RAP is being remobilized for the mixture. Only in the GM_RAP mixture, which has 100 % milled material, a rejuvenating agent (RA) was used in order to recover the properties of the aged binder. In the case of the GRAP_MARC and GARC_MRAP mixtures, taking into account that the percentage of milled material incorporated in the mixture did not exceed 50 % of the total aggregates, RA was not used, as well as in other studies with similar conditions (GENNESSAUX, 2015; OLIVEIRA, 2013).

Resilient modulus and fatigue performance

The resilient modulus tests were performed by repeated load diametral compression, according to the recommendations of DNIT ME 135 standard (DNIT, 2018).

The tests were performed in a universal triaxial tester (Figure 4), in the same way as for the fatigue life test, by means of indirect cyclic loading, with a constant temperature of 25 °C, applying load at a frequency of 1Hz and obtaining the displacement readings through an LVDT (Linear Variable Differential Transducers).

In order to determine the RM of each mixture, 12 specimens of 10 cm diameter were molded and compacted with the CGS. The average of these was the test result for each sample. The fatigue life tests were performed by diametrical compression at controlled stress, according to the DNIT 183 ME standard (DNIT, 2018), in 15 cylindrical specimens molded in the same way as the RM test. It is important to note that the specimens were produced in order to meet the specific geometry and volumetry required in each test.

In view of the inherent heterogeneity in the production of asphalt mixtures with wastes, specimens that did not meet the aforementioned specifications were discarded and this reported quantity corresponds to the specimens actually tested. Subsequently, the statistical treatment of the data was applied through the analysis of variance, which allows, in the case of experiments where there is repeatability, to verify if there is a statistical difference between the samples, using the Tukey test for 95 % confidence.

With the RM results and the fatigue curves of the mixtures produced, a hypothetical flexible pavement structure with a granular base was pre-dimensioned, initially considering 10 cm of coating and 20 cm of graded crushed stone base, in order to verify the number of load requests each would withstand. Subsequently, the structures were inserted into the software for effective design of this coating layer.

Thus, at the end, five structures were evaluated, the only difference between them being the asphalt coating characteristic (the base and subgrade characteristics were maintained for all analyses). The design was performed using the MeDiNa software, which corresponds to the new Method of Empirical Mechanist Design of Brazilian

Figure 4 – Fatigue life test: (a) tester; (b) loading.



Source: The authors.

Asphalt Pavements, currently in the dissemination phase. MeDiNa performs the design and mechanistic-empirical verification, through the EAML routine “Elastic Analysis of Multiple Layers”, calculating stresses and deformations in pavement structures under loading of standard road axis type wheels and applying fatigue and permanent deformation models to adjust the thickness of the layers (FRANCO, 2018).

The structure of the flexible pavement analyzed, as well as the thicknesses and the applied characteristics are shown in Table 3. For traffic composition, the Average Daily Volume (VMD) of 2500 vehicles in the year of traffic opening was indicated in the software, selecting the type via Primary Arterial System considering the road axis and 100 % vehicles in the project range, in addition to the zero growth rate and 10-year design period. The software uses the Brazilian standard road axis of 8.2 tons and, based on the information entered, a total N number of 9.13×10^6 was determined.

Table 3 – Parameters of the adopted pavement structure.

Type of Material	RM (MPa)	Poisson	Thickness (cm)
Asphalt mixture	variable	0.30	Variable
Graded Crushed stone Gnaisse C5	381	0.35	20
Silty Soil NS'	189	0.45	-

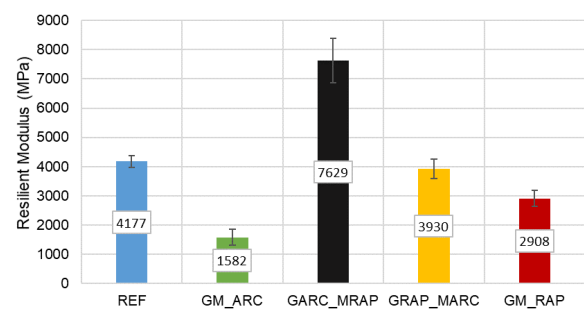
Source: The authors.

Results and Discussion

Resilient Modulus

Figure 5 shows the average values obtained from the resilient modulus of the 12 test specimens assessed, as well as the standard deviation of the samples.

Figure 5 – Result of the RM mixtures tests studied.



Source: The authors.

As described in the literature (ZAUMANIS *et al.*, 2014), RAP influences the stiffness of mixtures, with the harder (less elastic) aged binder of RAP, typically increasing the stiffness of asphalt mixtures when incorporated. Therefore, the analysis of Figure 5 must be done in accordance with the data of asphalt binder content (CAP 50/70, remobilized from RAP and total) indicated in Table 2. Regarding the incorporation of RAP in the large fraction (GRAP_MARC mixture), there was no significant difference between the RM values of the REF mixture, 3930 and 2908 MPa, respectively, confirmed by statistical analysis. In this sense, despite the difference between the total binder content of the GRAP_MARC mixture (7 %) and that of the REF mixture (4.8 %), it is necessary to analyze the content of new incorporated binder, which in the case of the first mixture is 5.3 %. These similar contents can explain the similarity between the results of RM and, in this case, the incorporation of new binder in a higher content (5.3 % for GRAP_MARC and 4.8 % for REF). It can act as a “rejuvenating agent” of the mixture, reducing the stiffness that would be increased by the stiffness of the aged binder when the RAP is incorporated. The GM_RAP mixture had its resilient modulus influenced by the action of the

rejuvenating agent, which “softened” the aged binder and, consequently, decreased the mixture’s stiffness. Furthermore, there was also an influence of the higher binder content of the mixture, which resulted in greater resilient deformation and smaller modulus. In this sense, it was possible to infer that the RA design methodology used, based on the viscosity and penetration parameters, may not be the most suitable for mixtures with high levels of RAP.

As for the incorporation of RCA, it is possible to perceive the influence of the porosity of the aggregate on the content of incorporated binder and, consequently, on the RM of the studied mixtures. The mixture with incorporation of RCA in the GARC_MRAP coarse fraction (less water absorption according to Table 1) required only 3.1 % of new incorporated binder, whereas incorporation in the fine fraction GRAP_MARC (greater water absorption according to Table 1) required 5.3 % of new binder, resulting in lower RM. Still in this context, in the case of the GM_ARC mixture it is possible to conclude that the addition of 100 % of RCA in the asphalt mixtures has a significant influence on the resilient modulus, decreasing its value, directly related to the fact of the higher total binder consumption (9.6 %). This fact, in addition to an unsatisfactory technical performance, compromises the economic viability of the mixture, since the binder is the most expensive item in an asphalt mixture.

The coefficient of variation presented by the analyzed data was 10.35 %, indicating the low dispersion of the values obtained in the RM test of the studied mixtures.

In general, the RM values were inversely proportional to the CAP 50/70 content incorporated in the mixture, with the GARC_MRAP mixture having the highest RM with the lowest content (3.1 %), and the GM_ARC mixture presenting the lowest RM with the highest content (9.6 %).

Fatigue life

Figures 6 and 7 present the comparison of the mixtures regarding fatigue, the first considering the stress difference (MPa) and the second, the specific resilient deformation (ϵ_r), both correlated with the number of stresses required for the end of the test.

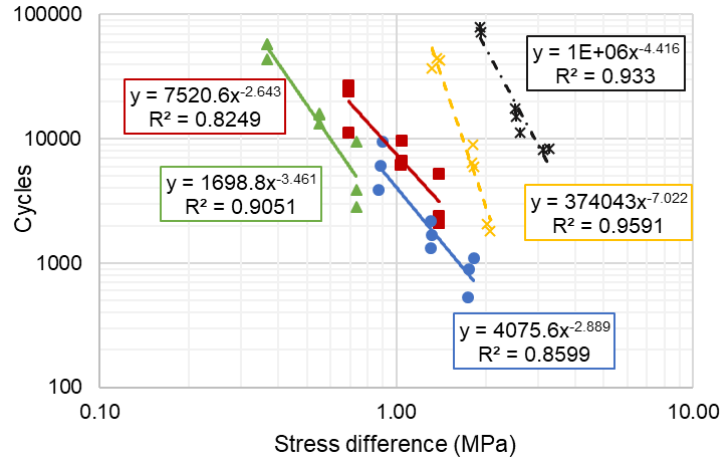
In view of the data presented, it was possible to compare the different results of the two mixtures that presented statistically equal RM, REF and GRAP_MARC.

Thus, the incorporation of RAP in the coarse fraction showed better performance in terms of fatigue life, in relation to the REF mixture. In this case, for a similar stress (30 % of RT), 331.3 kPa for the REF mixture and 355.1 kPa for the GRAP_MARC mixture, for example, the former resisted a number of load requests almost 24 times less than the latter. This performance is directly related to the binder content of the REF mixture (4.8 %), being the lowest content among the studied mixtures. In addition, the fact may be linked to the adhesion between aggregates and binder, which in the GRAP_MARC mixture was favored by the porosity of the RCA, generating a mechanical anchorage, and also by the RAP having been covered with binder for a long time, generating strong adhesion. In any case, the values found for the REF mixture are of the same magnitude as the results of Johnston *et al.* (2015), who evaluated the fatigue by diametrical compression of warm mixtures with surfactant additive, also using the criterion of failure to reduce the initial RM by 50 %.

As for the RCA, it was possible to notice that for the same specific resilient deformation, all mixtures with incorporation of this waste (in the fine, coarse or total fraction) presented a higher number of cycles than the REF and GM_RAP mix. The most likely hypothesis for this result would be related to the higher binder content of these mixtures (due to the RCA porosity). However, in the case of the GARC_MRAP mixture, this is not the finding. The GARC_MRAP mixture was the mixture that contained the least amount of new binder incorporated in the mixture (according to Table 2) and, even so, obtained better results than the REF mixture, for example. As for the coarse RCA aggregate, the mechanical anchoring already mentioned was even more pronounced and may have contributed to the increase in the number of cycles until reaching the rupture criterion.

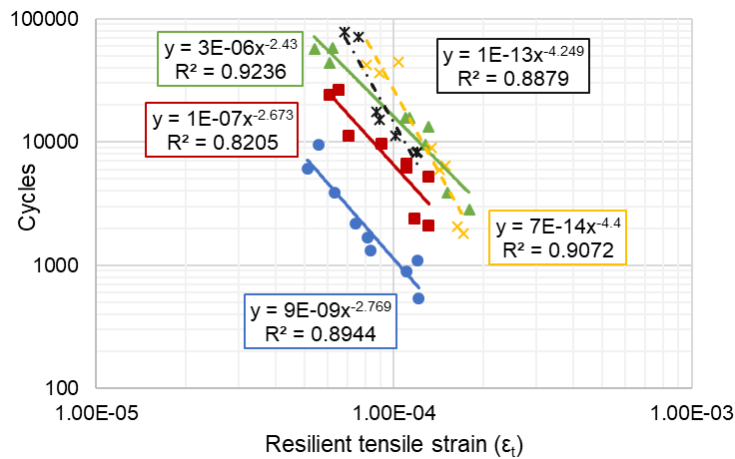
Regarding the specific resilient deformation, for a deformation of $1E-04$, the fatigue life of the GRAP_MARC mixture was about 12 times greater than that of the REF mixture. Authors Pasandín and Pérez (2017), who researched asphalt mixtures with different levels of RCA, corroborate this fact, concluding that the higher the percentage of incorporation of RCA in the mixture, the longer the fatigue life of the mixture, a fact directly related to the binder content of the mixtures. In any case, the durability assessment of the mixtures can only be carried out taking into account a mechanistic analysis, which can translate the effects of these fatigue curves in terms of pavement service life, for each of the studied mixtures, as presented in the topic below.

Figure 6 – Fatigue life versus stress difference.



Source: The authors.

Figure 7 – Fatigue life versus resilient tensile strain.



Source: The authors.

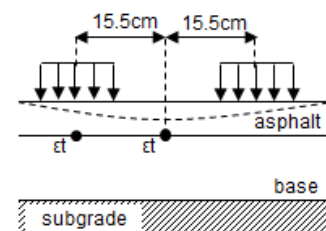
Design

From the results in the EAML routine, it was possible to obtain the results of specific tensile strain (ϵ_t) in the lower fiber of the pavement for each of the mixtures, considering the RM characteristics and fatigue life of each one, initially maintaining the thickness of 10cm for all analyses. The two deformation analysis points considered are illustrated in Figure 8, the highest value being used between them. From this result, it was possible to apply this parameter in the fatigue life model used by the MeDiNa software, according to equation (1)

$$N = K_1(\epsilon_t)_{2}^k, \quad (1)$$

where N is the number of load repetitions necessary to meet the rupture criterion, ϵ_t is the specific tensile strain, k_1 and k_2 are the laboratory test parameters (fatigue life).

Figure 8 – Load applied and points of analysis.



Source: The authors.

Table 4 – Estimated service life (N) for each of the mixtures.

Parameters	REF	GM_ARC	GARC_MRAP	GRAP_MARC	GM_RAP
Specific tensile strain (ϵ_t)	0.000255	0.000444	0.000175	0.000264	0.000315
Estimated service life (N)	8.39E+05	4.27E+06	1.32E+07	3.67E+06	3.02E+06

Source: The authors.

Table 5 – Summary of mechanical properties and performance of mixtures.

Parameters	REF	GM_ARC	GARC_MRAP	GRAP_MARC	GM_RAP
Specific gravity (g/cm^3)	2.402	2.116	2.293	2.232	2.355
Void volume (%)	3.7	4.1	4.1	4.1	3.8
Binder content (%)	4.8	9.6	5.5	7.0	6.2
Tensile strength (MPa)	1.104	0.458	1.629	1.184	0.871
Resilient modulus (MPa)	4177	1582	7629	3930	2908
Regression coefficient k_1	9.40E-09	3.04E-06	1.44E-13	6.62E-14	1.32E-07
Regression coefficient k_2	2.769	2.430	4.249	4.400	2.673

Source: The authors.

Table 6 – Summary of the design of each mixture.

Parameters	REF	GM_ARC	GARC_MRAP	GRAP_MARC	GM_RAP
Cracked area at the end of the period (%)	29.5	*	24.2	28.9	28.7
Pavement layer thickness (cm)	13.8	*	5.0	7.2	6.3

* Fatigue class= 0, according to MeDiNa software.

Source: The authors.

Table 4 presents the results of estimated service life for each of the mixtures. It was possible to verify that the GARC_MRAP mixture has the longest estimated service life, resisting a number of requests approximately 300 % greater than the second most resistant mixture (GM_ARC) in this regard. In addition, all mixtures with wastes had a longer service life than the reference mixture.

Subsequently, the studied mixtures were properly dimensioned, defining the thicknesses necessary to meet traffic requests, using the MeDiNa software. For each of the mixtures, the information on the resilient modulus, specific gravity, tensile strength, asphalt content, void volume and regression coefficients (k_1 and k_2) obtained in the fatigue life test were inserted in the software, as shown in Table 5.

Designing was performed by adopting the primary arterial system as a type of road, which the software considers in accordance with the hierarchy of functional systems published by DNIT. For this type of road, the level of reliability of the analysis is 85 %, with the percentage of cracked area being a maximum of 30 % and the limit of

permanent deformation of 13mm. Table 6 presents the results of the design in terms of cracked area, sinking of the wheel track and thickness of the coating layer, for each of the studied mixtures.

The MeDiNa software uses the concept of fatigue classes, which confronts the resilient modulus with the Design Fatigue Factor (DFF). From the insertion of the material properties, the program automatically calculates the DFF and the mix class. In the case of GM_ARC, the software indicated fatigue class 0, which shows that this mixture would not be suitable for field application, as it cracked very quickly. Therefore, the results of this mixture's design were not considered for comparison between the samples.

The pavement that presented the lowest thickness among all the studied mixtures was GARC_MRAP, that is, the mixture withstands a greater number of stresses with the same deformation. It is important to note that this is the mixture that has the lowest content of new binder incorporated (3.1 %) and the highest resilient modulus among all mixtures. Although the total binder content of

GARC_MRAP (5.5 %) is higher than the binder content of the REF mixture (4.8 %), when it comes to mixtures with RAP incorporation, this factor needs to be assessed in a dissociated way with relation to new binder and recovered binder. In addition, this greater resistance to the number of requests may be related not only to the binder content of the mixtures, but also to the adherence between binder and aggregate, as already considered in the analysis of RM results. The adhesion between binder and aggregate in the REF mixture is recent, whereas in the GRAP_MARC mixture the aggregate has been adhered to the binder for much longer, this added to the mechanical anchoring of the binder that enters the pores of the RCA.

It is also interesting to note that the REF and GRAP_MARC mixes, which have statistically equal RM, had very different coating thicknesses, resulting in a coating thickness 92 % greater in the REF mix than in the GRAP_MARC. This difference may be related to the binder content, which is 4.8 % for the REF mixture and 7.0 % for the GRAP_MARC mixture (5.3 % of new binder). Anyway, this fact corroborates the importance of mechanistic analysis of the pavement, proving that evaluating only one of the parameters, such as the resilient modulus, for example, is not enough to determine the quality of the material. It is necessary to consider the set of RM and fatigue life of the mixtures, so that it is possible to evaluate the performance of the pavement more assertively.

In view of the above, the mixture with the best performance in terms of service life, that is, which withstands a greater number of load repetitions, was the GARC_MARC mixture, even though this was not the mixture with the highest binder content (5.5 %), a fact that reinforces the previous hypothesis regarding the adhesion between binder and aggregate.

Conclusions

In view of the study carried out, it was possible to verify that, from the designing point of view, there is potential for the use of mixtures produced with the incorporation of the two wastes, especially considering their application in the primary arterial system. In general terms, the main results found are listed below.

Asphalt binder content is the component that has the greatest influence on the resilient modulus of the studied mixtures. The high binder content of mixtures with RCA, resulting from the porosity of the aggregates, reduced their resilient modulus, being compensated, in the cases of combination of RCA and RAP, by the stiffness of the aged asphalt binder, making the resilient modulus increase. In this sense, in mixtures with RAP incorporation, it is important to take into account the content of neat binder incorporated, which ends up acting as a rejuvenating agent. This fact can be observed in the similarity of the RM results of the GRAP_MARC mixture (total binder content 7 %) and the REF mixture (total binder content 4.8 %). In the case of mixtures with RAP, it is necessary to analyze the content of new incorporated binder, which in the case of the first mixture is 5.3 %, similar to the 4.8 % of the REF mixture.

Fatigue life of the mixtures was directly influenced by the binder content, being considerably lower for the REF mixture, which has the lowest content among the studied mixtures. In any case, the mechanical anchoring caused by the asphalt binder in the pores of the RCA (mainly in the coarse aggregate) may have contributed to the good fatigue performance of the GARC_MRAP mixture, which was the mixture that resisted the greatest number of cycles during the test.

The mixture that had the longest service life in the mechanistic analysis and, consequently, the lowest coating thickness needed to meet traffic demands, was GARC_MRAP. From the point of view of input, the economic viability is promising, since it is a mixture produced with 100 % of wastes and with the need to incorporate a new conventional binder of only 3.1 % (2.4 % comes from RAP). Also, all mixtures with RAP resulted in lower pavement thicknesses compared to the REF mix, for the same load request.

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