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Laboratory study of hot recycled asphalt mixtures with different contents of RAP

Estudo laboratorial de misturas asfálticas recicladas à quente com diferentes teores de asfalto fresado

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ABSTRACT
Reclaimed asphalt pavement (RAP) has potential use in the composition of new granular layers and even as a surface course. In countries like Europe, the USA and Japan, the asphalt mixtures use RAP percentages of around 10 to 30%, encouraging the establishment of such methodology also in Brazil. Nationally, some highways have implemented this, but in the state of Goiás there are no incentives for RAP recycling. Therefore, the objective of this paper is to study the mechanical behavior of Goiás regional asphalt mixtures with high incorporation of RAP, and compare them to recycled and conventional mixtures. To this end, mixtures composed of 33%, 45% and 100% of RAP, new aggregates and binders, and also a rejuvenating agent were produced on a laboratory scale. The mixtures were designed by Bailey's particle size selection and SuperPave dosage, and submitted to mechanical tests to verify their performance. When comparing the RAP mixtures to conventional asphalt mixtures, similar or superior mechanical behavior was obtained. By proposing the use of Bailey method, it was possible to verify the influence on the stiffness, considering the increasing relationship between the coarse aggregate and resilient modulus data. On the other hand, the flow number results decreased with the increasing asphalt content. Generally, the results support the technical viability of using RAP, as well as the efficiency of better aggregate selection methods and particle size evaluation. The importance of further studies is also emphasized, aiming at standardization, in order to obtain more sustainable and durable pavement structures.

RESUMO
O *Reclaimed asphalt pavement* (RAP) tem se revelado de uso potencial na composição de novas camadas granulares e até mesmo de revestimento de pavimentos. Em países como os europeus, EUA, Japão, as misturas asfálticas utilizam porcentagens da ordem de 10 a 30%, incentivando a instauração de tal metodologia também no Brasil. Nacionalmente, existem obras com tal implementação, mas no estado Goiás não há incentivos para o uso do RAP. Portanto, o objetivo deste artigo é estudar o comportamento mecânico de misturas asfálticas com elevada incorporação de RAP e compara-las a misturas recicladas e convencionais. Para tanto, misturas compostas por 33%, 45% e 100% de RAP, agregados e ligantes novos e, ainda, agente rejuvenescedor foram produzidas em laboratório. As misturas foram projetadas por meio de seleção granulométrica Bailey e dosagem *SuperPave*, e submetidas a ensaios mecânicos para verificação de desempenho. Quando as misturas compostas por RAP foram comparadas às misturas convencionais, verificou-se comportamento mecânico similar ou superior. Ao propor o uso do método Bailey, pôde-se verificar a influência frente à rigidez, por meio da relação entre o agregado graúdo e os valores de módulo de resiliência. Já os valores de flow number diminuíram com o aumento do teor de ligante. Em geral, os resultados obtidos embasam a viabilidade técnica do uso de RAP, bem como a maior eficiência dos métodos de seleção e avaliação granulométrica. A importância da continuidade desses estudos também é enfatizada, objetivando a padronização, para a obtenção de estruturas asfálticas mais sustentáveis e duráveis.

1. INTRODUCTION

According to DNIT (2017), pavement reconstruction or resurfacing comprises the crushing and screening of one or more layers of pavement, aiming at the execution of a new surface course. The removed material is therefore composed of aggregates and an aged binder, and known as reclaimed asphalt pavement (RAP).

Bonfim (2007) reports that RAP began to be studied and used in 1970 in Europe and North America, but it was only in the second half of the 20th century that a specific equipment was designed for this purpose. In Brazil, it was first used in 1980, during the maintenance of the Via Anchieta highway. Balbo (2004) cites the use of RAP in an asphalt plant on Rodovia Anhanguera, SP-330, and *in situ* on Rodovia Presidente Dutra, BR-116/SP.

The RAP methodology has been designed in numerous countries, such as Europe, the USA and Japan, where conventional asphalt mixtures include the use of 10 to 30% of RAP. EAPA (2017) also emphasizes the majority use of this material in the production of hot-mix recycled asphalt mixture (HRAM), citing the use of 96 and 84% of the RAP available annually in the USA and Germany, respectively. However, this occurs in response to strict environmental legislation, which prevents the disposal of materials that are not final products in landfills (Brosseaud, 2011; Unger, 2019).

Brazil does not have a database on RAP, and, in general, these data are held by private highway concessionaire and city halls, making it difficult to predict their generation and reuse. In the state of Goiás, there are no records on the proper reuse of RAP, resulting in the generation of a large amount of material that is disposed of in unsuitable areas or reused in landfills without adequate technological control. Thus, it appears that there is a need to implement policies for the reuse of this material and encourage its use in the public and private sectors.

If new materials are of interest for pavement purposes, another aspect of great importance is the process of the dosages of asphalt mixtures capable of meeting current requirements in terms of traffic and vehicle configurations. Therefore, more efficient structures are needed, especially in terms of permanent deformation and fatigue (ANTT, 2014). It is in this sense that the Strategic Highway Research Program (SHRP) created the design method for dense asphalt mixes, SUperior PERformance asphalt PAVEments (SuperPave). Through this methodology, the gyratory compaction process was developed, in order to replicate in the laboratory mixtures with behavior similar to that observed in the field; thus, with mechanical data of greater reliability (ANTT, 2014).

Regarding the study of the granulometric selection of aggregates for asphalt mixtures, the Bailey method stands out with the intention of forming an interlocked, stabilized solid skeleton, with continuous and balanced graduation (Mendes and Marques, 2012). The method consists of analyzing the proportions of aggregates, according to the ranges proposed by Vavrik *et al.* (2002) as a function of the nominal maximum aggregate size (NMAZ) obtained by the mixture. Figure 1a illustrates the parameters that are evaluated in the method, including coarse aggregate (CA), the coarse fraction of fine aggregate (FAc) and the fine fraction of fine aggregate (FAf). The efficiency of the Bailey methodology was verified against the ranges proposed by uperPave, and Ghuzlan, Al-Mistarehi and Al-Momani (2020), who obtained fine and coarse grade mixtures with less variable behavior and resistance to deformation, in addition to lower asphalt content values and amounts of compaction gyres.

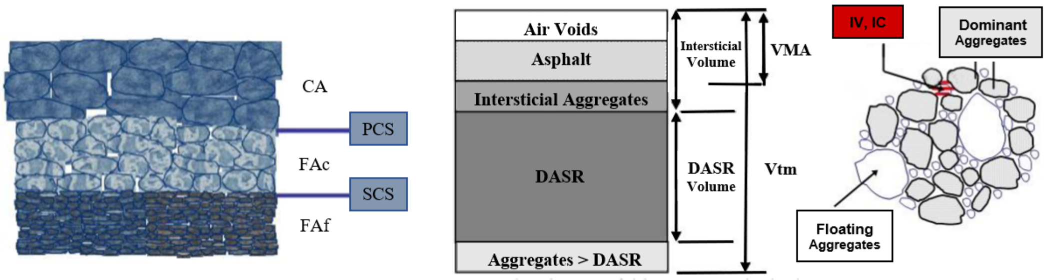


Figure 1. Parameters used in the Bailey and DASR methodologies: a) Divisions of a continuous gradient (Vavrik *et al.*, 2002). b) Asphalt mixture components according to DASR (Ferreira, Bastos and Soares, 2015; Kim, 2006)

The aggregate grain size distribution can also be analyzed by the dominant aggregate fraction (DARS) methodology, which verifies the particles responsible for the formation of the skeleton (dominant aggregates), the filling of voids (interstitials) and the particles without structural function (floating), as shown in Figure 1b. Kim (2006) observed that the proportion of material retained between two consecutive sieves in the intervals of 0.43 to 2.33 provides a more effective contact between the grains. However, there is also the DARS porosity value, defined as the ratio between the volume of voids and the total volume, which would provide a prediction of the mixture's permanent deformation behavior, and which should be below 48% for greater resistance (Kim, 2007; Ferreira *et al.*, 2020). Chun *et al.* (2017) also point out this parameter as a good indicator regarding the susceptibility to segregation of asphalt concrete.

Thus, the present study aims to carry out the mechanical characterization, mainly in terms of stiffness and permanent deformation, of hot recycled asphalt mixtures composed of different percentages of RAP. Such mixtures have their aggregate grain size distribution selected by the Bailey methodology, verified by DARS and dosed by SuperPave.

2. MATERIALS AND METHODS
2.1. Materials

The materials used in this study were: RAP, rejuvenating agent (RA), virgin aggregate and petroleum asphalt cement (CAP).

2.1.1. Aggregates

For the composition of the asphalt concretes, the virgin aggregate used was mica-schist, characteristic of the Midwest region, in the scales of gravel 1, gravel 0 and sand, according to the standards established by DNIT (2006). The Los Angeles shape and abrasion indices of this aggregate indicate good cubicity and low wear, enabling its use in the production of asphalt mixtures. However, generally, as for the adhesiveness obtained with the use of conventional binders (DNER, 1994), adequate results are not obtained, which requires the use of a chemical adhesion improver (dope) in the amount of 0.5% of the mass of binder.

2.1.2. RAP

The RAP was available from the Municipal Department of Infrastructure and Public Services (SEINFRA) of Goiânia-GO, obtained from an existing road surface in an urban section of the city (Figure 2). Through the characterization of its aggregates, the density values were similar to those of the virgin aggregates observed in the region, which indicates that it is from mica-schist rock.

Figure 2. Location of RAP collection (Rua 90, Setor Sul, Goiânia-GO)

2.1.3. Asphalt binder and rejuvenating agent (RA)

The asphalt binder used was CAP 50/70, commonly used in the concrete asphalt produced in the studied region. It was supplied by a private distributor, located in Aparecida de Goiânia-GO. Table 1 presents the characterization results, the respective tests standards and their limit values. Comparing the virgin binder with that extracted from RAP, it is possible to observe the variation in density, softening point and penetration values, evidencing the rigidity triggered by the aging process of the milled material. Similar results were observed by Silva and Farias (2018) for the same type of aged binder (CAP 50/70). Other important data obtained during the characterization was the relation between viscosity and temperature, which pointed to the maximum mixing and compaction temperatures values: 155°C and 140°C, respectively.

Table 1 – RAP aged asphalt binder characterization results for asphalt (CAP 50/70), rejuvenating agent (RA) and standard criteria

Tests	Standard	CAP 50/70	Standard Criteria	RAP	RA	Standard Criteria
Density Relative at 25°C (g/cm³)	NBR 6296 (ABNT, 2012)	1.007	-	1.095	1.003	-
Softening point (°C)	NBR 6560 (ABNT, 2016)	47	> 46	53.8	-	-
Penetration index (mm)	NBR 6576 (ABNT, 2007)	66.5	50 a 70	37.4	-	-
Brookfield Viscosity 60°C (cP)	NBR 15184 (ABNT, 2004)	-	-	-	410	176 a 900
Brookfield Viscosity 135°C (cP)		355	> 274	342	42	-
Brookfield Viscosity 150°C (cP)		163	> 112	171	20	-
Brookfield Viscosity 177°C (cP)		61	57 a 285	58	11	-
Flash point (°C)	NBR 11341 (ABNT, 2014)	310	> 235	-	290	> 218
RTFOT - Retained Penetration (%) (1)	ASTM D2872 (ASTM, 2019)	60	> 55	-	-	-
RTFOT- Increase Softening Point (°C) (1)		5	< 8	-	-	-
RTFOT- Ductility at 25 °C (cm) (1)		> 150	> 20	28	-	-
RTFOT- Mass Loss (%) (1)		-0.14	-0.50 a 0.50	-	-	-
Temperature Susceptibility (2)		-	-	- 0.93	-	-
Elastic Recovery (%) (2)		-	-	2.3	-	-

Note: CAP = petroleum asphalt cement; RAP = Reclaimed asphalt pavement; RA = rejuvenating agent; (1) Data from the test certificate, provided by the supplier; (2) Data from the supplier.

The shale oil-based rejuvenating agent is the same as that used by Silva and Farias (2018), Oliveira (2020) and Cabral (2021), and was supplied by a national company that distributes oil derivatives. This was then incorporated into the RAP, in order to guarantee the chemical rebalancing of the aged binder, making it an appropriate binder for pavement use.

The characterization of the AR was based on the Brazilian specification, regulated by APN (2022), and the results obtained are shown in Table 1, where it is possible to identify it as an AR-5. Thus, it was decided to use 20% of RA on the oxidized binder content, since Silva and Farias (2018) pointed this out as the most appropriate in the chemical recompositing of the RAP used by them, which, as already discussed, presents characteristics similar to the RAP used in the present study.

Due to the incorporation of RAP, it was necessary to adjust the proportion of mixtures with virgin aggregates. This granulometric correction was performed after mathematical calculations, applying the criteria of the Bailey methodology, the SuperPave limits and verification by DARS porosity.

2.2. METHODS

The methods used for the development of the study are detailed next.

2.2.1. Granulometric aggregate composition and mixture dosages

The aggregate grain size distribution was defined using an Excel spreadsheet, following the steps proposed by Cunha (2004) to obtain the parameters that met the ranges recommended by the Bailey method, as well as the limits of the SuperPave methodology. It is noteworthy that the percentages of RAP used in this study were chosen in order to investigate dosages with higher levels of RAP, above 25%. For this amount of RAP, the AASHTO M 323-17 standard indicates the effective use of RA, and the choices must be combined with environmental and economic advantages (Gennesseaux, 2015). Thus, the levels of 30%, 50% and 100% of RAP were defined as targets, which were approached due to the calculations of the granulometric composition for each mixture. In addition to these limits, dosages with different NMAZ in the intermediate mixtures (19.0 and 12.5 mm, respectively) were considered, obtaining the following proportions:

- ***Mixture 1 (M33):*** 32.56% RAP; 18.75% Gravel 1; 16.37% Gravel 0, and 32.32% Sand;
- ***Mixture 2 (M45):*** 44.99% RAP; 8.88% Gravel 1; 1.69% Gravel 0, and 44.44% Sand;
- ***Mixture 3 (M100):*** 100% RAP.

In the RAP mixtures' dosage processes, it is not so easy to understand their behavior, and whether the aged binder will be fully remobilized or not, acting as a black stone. Wellner *et al.* (2015) suggest that the RAP granulometry in the mixtures has to be between 60% and 100% of asphalt binder activation (Bowers *et al*., 2014; Ding, Huang, Shu, 2016; Gaspar, 2019). Thus, in this paper a preliminary study was carried out first, and it indicated that the adoption of the RAP grain size distribution curve without considering the asphalt binder presented the best homogeneity.

For the SuperPave compaction phase a number of 100 gyres was used, corresponding to an "N" design for heavy traffic. From there, according to the PRO178 standard (DNIT, 2018), the optimal binder contents predicted for each mixture were determined, and compacted samples (CSs) were molded with binder contents of ±0.5% and +1.0%. In this process, the sum of the added virgin binder and remobilized RAP was considered. Thus, four percentages of binder were used for each mixture, respecting the repeatability of three CSs for each one.

After the gyratory compaction, the CSs were submitted to the tests prescribed by the ME427 (DNIT, 2020b) and ME428 (DNIT, 2020c) standards, from which the specific masses and volumetric parameters of the mixtures were calculated to determine the optimal binder content necessary to obtain an air void (Va) of 4.0%.

Leandro *et al.* (2017), when studying the interference of the compaction method in the dosage process of a 12.5 mm NMAZ mixture, showed that the amount of 100 gyres applied to the 150 mm diameter mold generates over-compaction, which implies levels of reduced binders and can compromise fatigue behavior. In this case, it is highlighted that better behaviors are obtained when using the 100 mm diameter cylinder. For this reason, although PRO178 (DNIT, 2018) indicates the use of the larger mold, in this research the 100 mm mold was used. This procedure was also adopted in the regional studies used in the comparative analysis of the results presented in this paper.

2.2.2. Mechanical tests

The mechanical laboratory tests carried out are listed in Table 2, and for each mixture, three compacted samples were molded at the optimal levels, in order to verify the repeatability of the results, to obtain the coefficient of variation (CV) and the standard deviation (SD). It is important to emphasize that fatigue tests were not performed in this study, as the conventional mixtures by Barroso (2018) and Guabiroba *et al.* (2023) used for comparative analysis performed well. However, the flow number (FN) results obtained by the authors were unsatisfactory, generating greater study interest in this paper.

Table 2 – Mechanical characterization tests

Tests	Standard
Tensile Strength (TS)	ME 136 (DNIT, 2018c)
Cantabro Loss	ME 383 (DNER, 1999)
Moisture-induced damage (MID)	ME 180 (DNIT, 2018d)
Resilient Modulus (RM)	ME 135 (DNIT, 2018b)
Flow Number (FN)	ME 184 (DNIT, 2018e)
Compaction Densification Index (CDI) and Traffic Densification Index (TDI)	IE 426 (DNIT, 2020d)
Dynamic Modulus (DM)	ME 416 (DNIT, 2019d)

The CSs produced for the FN and dynamic modulus (DM) tests met the standard prescription, with the degree of compaction equal to 97.0 ± 0.5% and 98.5 ± 0.5% of the bulk specific gravity of the compacted paving mixture sample (Gmb), respectively, which generate air void values different from the 4.0% defined in the dosage: 7.0% for FN and 5.5% for DM.

During determination of the compaction (CDI) and traffic (TDI) densification indexes, it was difficult to reach 98% of the degree of compaction, as established by the IE426 standard (DNIT, 2020d). Thus, the data obtained were interpolated, generating a logarithmic trend curve up to the point of interest, with an R^2 greater than 0.98. The graphs and calculations of the areas needed to determine the parameters were obtained using the Origin (2018) software. To calculate the CDI, data from the compaction curves of the CSs produced for other mechanical tests were also considered.

It is noteworthy that the studies selected for comparison of the results consist of studies from the Midwest, dosed by the SuperPave methodology and using the same raw materials: mica-schist-type aggregate and CAP50/70 binder. Such questions were defined in order to allow the evaluation of the influence of the granulometric selection methodology, as well as the use of RAP in the behavior of the mixtures. Thus, the conventional mixtures studied by Barroso (2018) were considered, selected granulometrically with the DNIT C range limits, and by Guabiroba *et al*. (2023), using the Bailey method. As for mixtures with RAP, the works by Oliveira (2020) and Cabral (2021) were considered, who used RAP taken from the same pavement, but using different amounts of the rejuvenating agent (AR-5): 20% in the study by Oliveira (2020) and 30% in the study by Cabral (2021).

3. RESULTS

This section presents the results obtained for the grain size distribution, dosages and mechanical parameters of the mixtures studied. In addition to the data obtained in this study, Table 3 also contains information on asphalt mixtures already studied in the region, both with the incorporation of RAP (Oliveira, 2020; Cabral, 2021) and conventional ones without RAP (Barroso, 2018; Guabiroba *et al*., 2023), aiming to carry out comparative analyses to help better understand the study and the technical-scientific impacts generated by the reuse of the RAP.

The granulometric curves considered in the study are shown in Figure 3, where a similarity can be observed between the curves of the M33 and M45 mixtures and with other RAP mixtures studied by Cabral (2021). Considering the conventional mixtures evaluated by Barroso (2018) and Guabiroba *et al*. (2023), higher levels of fines are observed in mixtures composed of RAP. The curve of the M100 mixture (without CAP) differs from the curve with 100% RAP (with CAP) obtained by Cabral (2021), showing its higher content of fines, a fact corroborated by the high FAf value shown in Table 3. The Bailey parameters of the other mixtures complied with the methodology, and the mixtures M33 and M45 presented FAf and CA close to the upper limits, respectively.

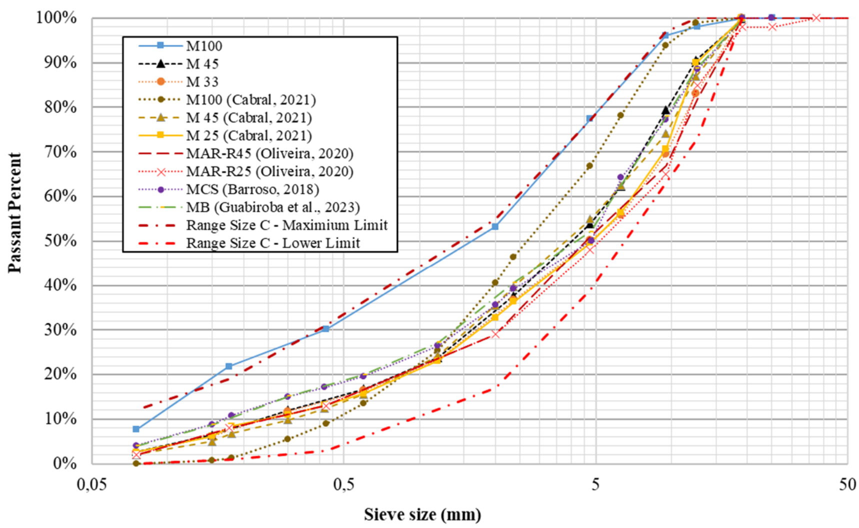


Figure 3. Aggregates grain size distribution curves.

For the DARS parameters, the mixtures M33 and M45 presented an extensive range, showing an efficient graduation, with proportionality of the grains. For the DARS porosity, with the exception of the M33 mixture, all the others presented values between 38% and 48%, which configures a good aggregate skeleton and can contribute to greater resistance to permanent deformation. When comparing with data from the literature, it appears that both the mixtures with 100% RAP evaluated by Oliveira (2020) and Cabral (2021) and the conventional ones studied by Barroso (2018) and Guabiroba *et al.* (2023) do not meet this criterion and, therefore, may present limited behaviors. These results demonstrate that it is possible to apply the Bailey and DARS methods in asphalt mixtures with RAP, defining granulometric curves that meet their criteria and contributing to dosages that generate mixtures with better mechanical behavior.

Regarding the volumetric parameters, the values of voids in the mineral aggregate (VMA) met those established by the AASHTO M323/2017 standard, with values above 13% (NMAS 19) and 14% (NMAS 12.5). However, the value of the voids filled with asphalt (VFA) must be in the range of 65 and 75%, and, in this study, the M100 mixture showed a higher value due to the characteristics of the material (fineness and binder content). The values of the dust proportion of mixtures M33 and M45 did not reach the range of 0.8 to 1.6, which indicates that the dosage of these mixtures can still be improved. The highest binder contents were obtained for the mixtures with the highest amount of RAP and lowest NMAS, which generated a greater specific surface and, consequently, the need for a greater amount of bituminous material for the adequate covering of the aggregates.

Table 3 – Summary of dosage and mechanical characterization results obtained for the studied mixtures and from others similar studies conducted in the region

Parameters	This study			RAP Mixtures (Cabral, 2021)			RAP Mixtures (Oliveira, 2020)			Conventional mixtures	
	M33	**M45**	**M100**	**M25**	**M45**	**M100**	**M25**	**M45**	**M100**	**Barroso (2018)**	**Guabiroba *et al.* (2023)**
Materials											
Aggregate rock type		Mica-schist			Mica-schist			Mica-schist		Mica-schist	Mica-schist
RAP type		Urban road			Highway			Highway		-	-
Particle Size Selection and Evaluation											
NMAS	19.0	12.5	12.5	19.0	19.0	9.5	19.0	19.0	9.5	19.0	19.0
Bailey CA	0.677	0.654	0.542	0.723	0.772	0.513	0.457	0.574	0.513	1.160	0.640
Bailey FA_c	0.438	0.445	0.394	0.465	0.466	0.539	0.475	0.453	0.539	0.570	0.470
Bailey FA_f	0.508	0.383	0.646	0.476	0.467	0.498	0.444	0.409	0.498	0.150	0.500
DASR particles	12.5-1.18	12.5-1.18	9.5-4.75	12.5-1.18	12.5-1.18	4.75-1.18	12.5-1.18	12.5-1.18	4.75-1.18	4.75-1.18	12.5-1.18
DASR porosity (%)	30.1	36.9	34.9	34.6	35.6	51.1	36.0	35.4	51.1	64.9	23.5
Metodology		Bailey			Bailey			Range Size C		Range Size C	Bailey
Dosage											
AC (%)	4.90	6.10	6.03	4.43	4.38	4.00	4.90	4.60	4.00	5.60	5.90
V_a (%)	20	20	20	20	30	30	30	20	20	-	-
Gmm (g/cm³)	2.56	2.52	2.52	-	-	-	2.47	2.46	2.45	2.53	2.53
Gmb (g/cm³)	2.44	2.42	2.46	-	-	-	2.36	2.36	2.33	-	-
VMA (%)	15.31	17.04	15.52	15.35	15.58	16.06	16.71	17.31	16.25	16.00	15.50
VFA (%)	70.17	74.54	81.03	73.94	74.32	75.09	76.06	76.81	75.38	75.30	72.80
Dust Proportion (%)	0.41	0.45	1.27	-	-	-	-	-	-	0.71	0.41
Mechanical Tests											
TS (MPa)	1.28	1.16	1.17	1.59	1.97	2.17	1.14	1.58	2.31	1.40	0,94
Cantabro Loss (%)	13.10	6.10	9.40	-	-	-	7.44	8.58	9,11	6.00	-
MID (%)	69.60	79.50	83.70	-	-	-	89.50	85.30	92.70	35.00	87.80
RM (MPa) at 25°C	6,345	5,454	4,475	8,959	9,016	10,577	4,224	5,360	11,441	7,658	5,805
RM/TS	4,957	4,682	3,825	5,635	4,577	4,874	3,692	3,397	4,946	5,470	6,176
FN (cycles) at 60°C	138	99	507	323	695	3,170	-	-	-	118	88
CDI	70	12	22	-	-	-	-	-	-	34	-
TDI	4,817	1,910	974	-	-	-	-	-	-	198	-

Note.: NMAS= Nominal Maximum Aggregate Size. CA= Coarse aggregate; FAc= Coarse aggregate in fine aggregate; FAf = Fine aggregate in fine aggregate; DASR = Dominant Aggregate Size Range; AC = asphalt content; Va = percentage of air voids in compacted mixture; Gmm = maximum specific gravity of paving mixture sample; Gmb = bulk specific gravity of compacted paving mixture sample; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; TS = Tensile Strength; MID = Moisture-induced damage; RM = Resilient Modulus; FN = Flow Number; CDI = construction densification index; TDIm = modified traffic densification index.

As concerns the densification indexes, according to IE426 (DNIT, 2020d), the CDI indicates the workability of the mass in the construction process, while the TDI would be linked to over-compaction due to the action of traffic during its useful life. For this purpose, Bahia and Faheem (2007) indicated CDI values lower than 200 and TDI values greater than 800 as good criteria for average traffic. Nascimento (2008) presented the following minimum values: 50 for CDI and 250 for TDI. Therefore, in terms of CDI, all mixtures met the maximum limit, but only the M33 mixture met the minimum, which may point to some difficulty during the compaction process, both for mixtures with higher RAP contents and for the conventional one studied by Barroso (2018). As for the TDI, all the mixtures in this study obtained good indexes, highlighting the achievement of higher values for the mixtures with RAP in relation to the conventional one. As discussed by Onofre *et al.* (2011) and Huang and Sun (2020), mixtures with low CDI values are expected to have better workability and mixtures with high TDI values are more resistant to permanent deformation.

The final part of Table 3 summarizes the results obtained in terms of mechanical parameters. It is noteworthy that all CSs produced for the mechanical tests showed similar Va values and according to the standard of each test. The maximum coefficient of variation between the repeatability of each test was equal to 4.12%, indicating homogeneity of the samples' volumetric characteristics.

In terms of tensile strength (TS), all mixtures met the minimum of 0.65 MPa specified by the ES031 standard (DNIT, 2006). Note that for the M33 mixture, slightly higher TS and RM values were obtained compared to the other mixtures, but it presented the worst behavior in terms of moisture-induced damage (MID) and Cantabrian loss. These results may be related to both granulometric and dosage characteristics, emphasizing that the M33 mixture presented, for example, limited results in terms of DARS porosity, VFA and dust proportion. In Table 3, similar values can be seen in terms of support capacity, but in the results obtained it was verified that the energy required for breaking the M100 mixture was less than half of the other mixtures.

When analyzing the RM values, it is observed that, for the three mixtures studied, there is a slight reduction in its value with increase of the RAP content. This behavior can be explained by the differences in granulometry and binder contents obtained. These results were lower than those observed in the studies by Oliveira (2020) and Cabral (2021), a fact that may be related both to the aggregates grain size distribution and to the behavior of the existing binder in each mixture. When comparing the mixtures M25 and M45 from Cabral (2021) with those from Oliveira (2020), higher RM values can be seen when the Bailey methodology was used in selecting the granulometric curves, to the detriment of the Range Size C.

To clarify the question of the influence of the asphalt binder, the information presented in Table 4 for the aged binders can be observed. This table shows the highest aging of the binder used in Oliveira's research (2020) and, in turn, the lowest in Silva and Farias's (2018). Thus, the percentage of RA used may not have been sufficient to restore the original characteristics of the CAP 50/70, which impacts and corroborates the values of the evaluated stiffness parameters.

In the case of the comparison of RM values between mixtures with and without RAP, it is observed that, in addition to the variation in the binder content and the rate of RA used, the fact that an asphalt mixture is dosed without meeting the Bailey and DARS criteria can generate higher or lower RM values. In general, the values obtained for the mixtures in this study would be close to conventional mixtures, meeting the range indicated by Bernucci *et al.* (2022) as a standard for national mixtures, between 2,000 and 8,000 MPa. This behavior could indicate that the 20% RA content would have achieved its objective of restoring the characteristics of the asphalt binder. However, Table 4 shows evidence that the binder used in this study would be more aged than that used by Silva and Farias (2018) and that for the complete remobilization of the binder to occur, the RA rate should be increased.

Table 4 – Comparison of aged binders' characterization

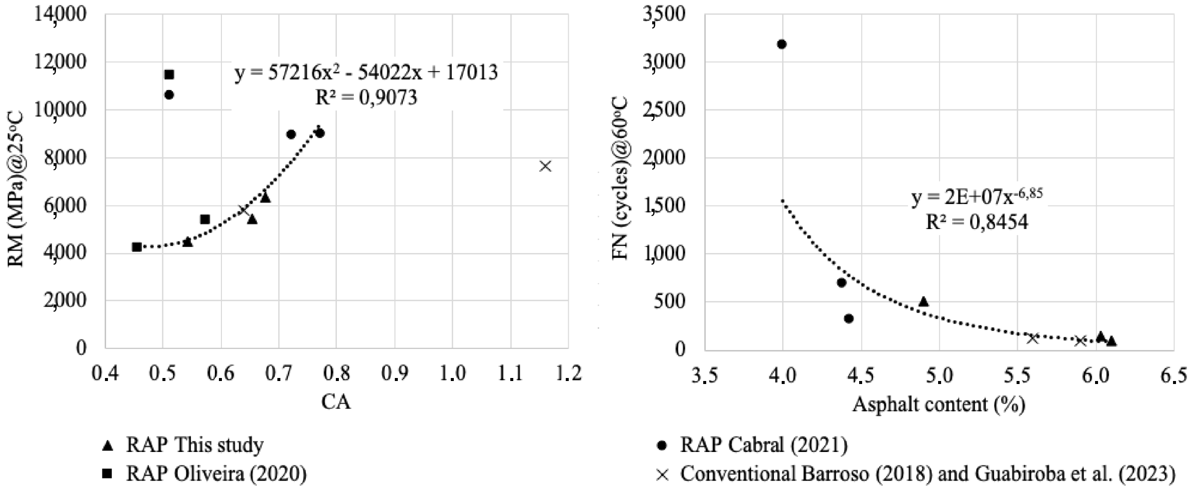
Test	Standards	Criteria for CAP 50/70	Silva and Farias (2018)	Oliveira (2020)	This study
Density Relative at 25ºC (g/cm³)	NBR 6296 (ABNT, 2012)	-	1.06	1.14	1.10
Softening point (°C)	NBR 6560 (ABNT, 2016)	> 46	51.0	64.1	53.8
Penetration index (mm)	NBR 6576 (ABNT, 2007)	50 to 70	40.0	29.4	37.4
Brookfield Viscosity 135°C (cP)	NBR 15184 (ABNT, 2004)	> 274	545	600	342
Brookfield Viscosity 150°C (cP)		> 112	256	528	171
Brookfield Viscosity 177°C (cP)		57 to 285	99	417	58

In the case of the comparison of RM values between mixtures with and without RAP, it is observed that, in addition to the variation in the binder content and the rate of RA used, the fact that an asphalt mixture is dosed without meeting the Bailey and DARS criteria can generate higher or lower RM values. In general, the values obtained for the mixtures in this study would be close to conventional mixtures, meeting the range indicated by Bernucci *et al.* (2022) as a standard for national mixtures, between 2,000 and 8,000 MPa. This behavior could indicate that the 20% RA content would have achieved its objective of restoring the characteristics of the asphalt binder. However, Table 4 shows evidence that the binder used in this study would be more aged than that used by Silva and Farias (2018) and that for the complete remobilization of the binder to occur, the RA rate should be increased.

When evaluating the behavior of the mixtures with the TS and RM parameters, through the relationship between both, it is observed that all mixtures composed of RAP presented RM/TS values between 3,300 and 5,700. These values are lower than those observed for conventional asphalt concrete, which, according to Santos (2006), may indicate, in a preliminary way, better mechanical behavior in terms of fatigue for mixes with RAP.

As for the behavior in terms of FN, according to the criteria defined by Bastos, Soares and Nascimento (2017) and which were considered in the National Pavement Design Method (MeDiNa), the M100 would support heavy traffic (FN between 300 and 750 cycles) and the M33 would be indicated for medium traffic (FN between 100 and 300 cycles). On the other hand, the M45 mixture would be close to the limit of being used only for light traffic (minimum FN of 100 cycles). The better FN result obtained for the M33 mixture in relation to the M45 may be linked to the aggregate grain size distribution and lower binder content, generating better interlocking of the aggregate skeleton. In turn, the better result of M100 may be related to the aged binder being not completely remobilized, as also observed in the study by Cabral (2021). Regarding the conventional mixtures studied by Barroso (2018) and Guabiroba *et al.* (2023), there is a limitation in their use due to these criteria, and mixtures with RAP appear as an alternative to improve this behavior.

Finally, with the data presented in Table 3, it is possible to verify the existence of a correlation between the CA values with RM obtained at 25ºC (Figure 4a) and the binder content with FN obtained at 60ºC (Figure 4b). Thus, it appears that, by excluding the extreme values of these parameters, the increase in CA generates an increase in RM, which points to the significant influence of coarse aggregates or the aggregates' skeleton on the stiffness of asphalt mixtures both with and without RAP. The increase in the binder content generates a reduction of FN in all mixtures, which indicates that the issue of permanent deformation is related more to the behavior of the mastic or the rejuvenated binder than to the coarse aggregates. Regarding the DARS porosity and the CDI and TDI indexes, it was not possible to verify the existence of a correlation with the FN for the evaluated mixtures.



(a) (b)

Figure 4. Parameters' correlations: a) CA *versus* RM. b) Asphalt content *versus* FN

Figure 5a shows the master curves obtained from the dynamic modulus tests. It is possible to observe similar behavior between the mixtures M45 and M100, since both have similar NMAS and binder content. The curve obtained for the M33 mixture is above the others, showing higher modulus values at low and intermediate frequencies. However, at high frequencies there is a similarity between all the curves. Another relevant aspect is that mixtures with RAP have higher dynamic modulus values when compared to conventional mixtures, possibly due to the characteristics of the binder, as previously discussed.

Through the data plotted in Black Space (Figure 5b), the coincidence of the maximum value of the phase angle (φ) for mixtures M33 and M100 is observed, although with M33 proving to be more concave, indicating the smallest variation of values of Log|E*| throughout the test. However, the curve obtained for the M45 mixture stands out among the others because it is more open and has higher values of . Thus, this finding evidences its higher viscosity and thermal susceptibility, which can be explained by the higher binder content.

In the analysis of the Cole-Cole plane (Figure 5c), the real (elastic) and imaginary (viscous) parts of the DM results are plotted, which represents the storage behavior, E1=|E*|·cos(φ), and energy dissipation, E2=|E*|·sin(φ), of the mixtures. In this sense, the curves are similar, with the M33 mixture curve positioned slightly above the others, indicating a more elastic behavior. It is also observed that the M100 mixture has a smaller elastic portion, configured by the smaller curvature concavity, which points to a material with less energy storage, that is, more rigid. Thus, it appears that in the mixture with 100% RAP there will be less activation of the aggregates in the face of demands imposed by the traffic, since the internal friction of the grains implies a consequent storage of energy (Mensch, 2017; LAPAV, 2017).

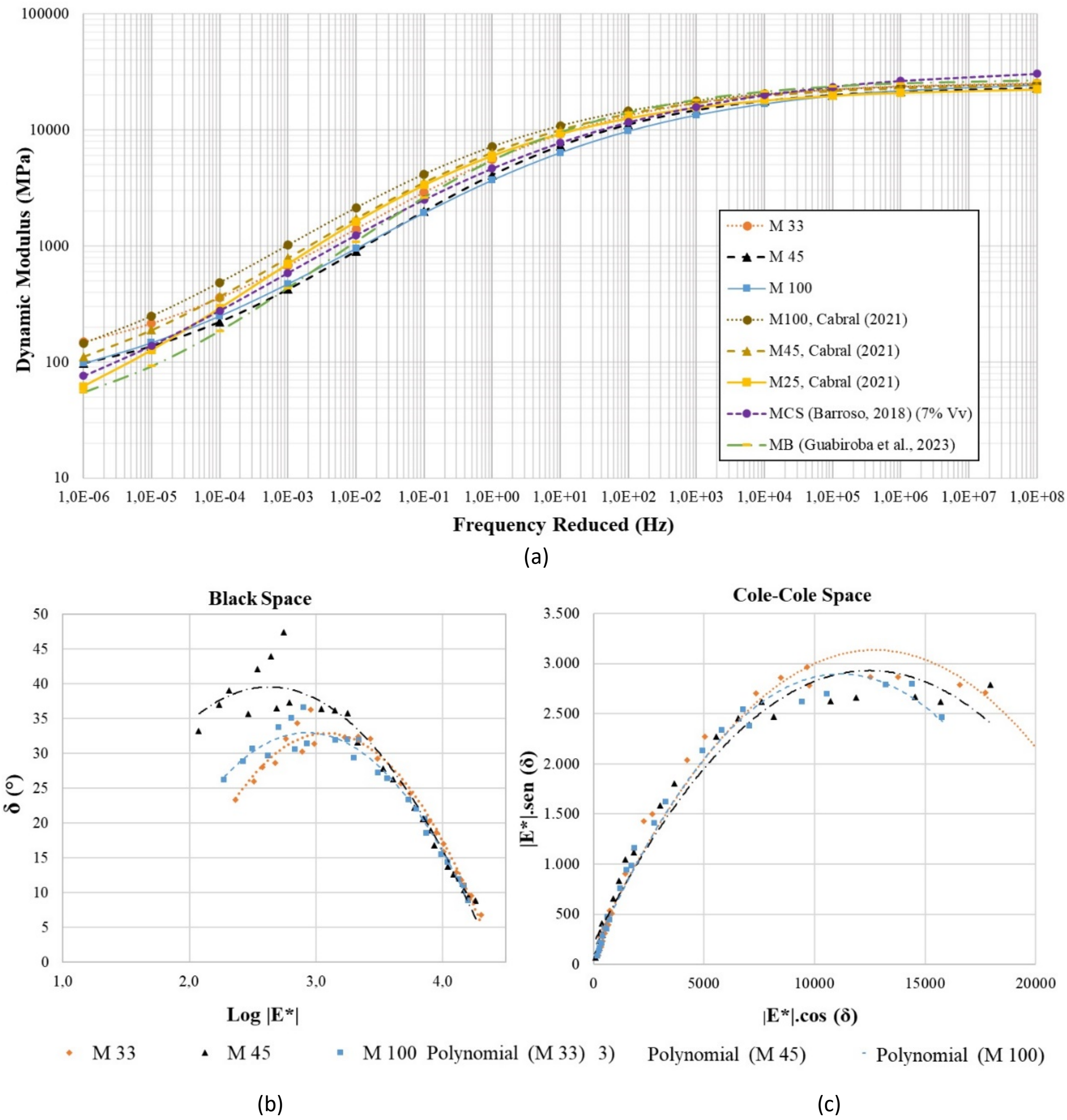


Figure 5. Dynamic modulus results. a) Comparative master curves. b) Black Space. c) Cole-Cole

4. CONCLUSIONS

With the results presented in this paper, it is concluded that the recycled mixtures composed with higher RAP contents meet the parameters required by current regulations, obtaining mechanical performance similar to or superior to that of conventional mixtures studied in the region. It is important to highlight that the variability of RAP, considering its composition (aggregate, binder and granulometric curve), aging, demands and/or milling (milling machine characteristics and depth), will naturally imply different materials. Therefore, the alteration of this material will result in asphalt mixtures with different characteristics, lacking proper characterization, as well as requiring investigation of the resulting mechanical behavior, which may achieve different data from those obtained in this study.

The use of the Bailey method for choosing the granulometric curve of aggregates with RAP in detriment to the classification in Range C of the DNIT makes it possible to obtain a more closed aggregate skeleton and reduce the ideal binder content in the SuperPave dosage. However, at this stage it is necessary to verify that all dosage criteria are actually being met.

In this study, it was possible to observe the direct relationship of the CA parameter of the Bailey method with the RM values obtained at 25oC, which demonstrates the influence of the aggregate skeleton of the mixtures with and without RAP on their stiffness. Through the DARS porosity, it was verified that it is possible to evaluate the question of the proportionality of the grains in the mixtures composed by RAP and to prioritize those that present more efficient grading. However, contrary to what was expected, in this study it was not possible to observe the existence of a direct relationship between the DARS porosity and permanent deformation results. This indicates that this issue needs to be better studied in future research.

It was also found that the FN values obtained at 60oC were more influenced by the binder content and that the rate of rejuvenating agent used may not have been sufficient to recover all the binder. This aspect also deserves further investigation, so that better mechanical results can be obtained with mixtures composed of higher RAP contents.

In terms of mechanical parameters (TS, RM, DM and FN), it appears that the mixtures with RAP presented better results than the conventional ones used in the region. Certainly, with the search for the best aggregates' granulometric selection, the choice of the most adequate rejuvenating agent rate and compliance with the SuperPave dosage parameters, the use of asphalt mixtures composed of RAP can resolve the issue of limiting the behavior of traditional asphalt mixtures, mainly in terms of permanent deformation in a more sustainable and less costly way.

Finally, it is concluded that recycled asphalt mixtures, despite being researched and having their efficiency reported in technical-scientific communications, need to have their dosage process standardized so that their use can be disseminated in national executive practices. In this sense, the results of this paper contribute part of this process and can help in the discussion of more efficient solutions.

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