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Hot recycled asphalt mixtures with the incorporation of milled material: analysis of the mechanical performance and economic presumption in the applicability of the technique

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ABSTRACT

The paving technique ensures the guarantee of functional traffic conditions, optimizing the performance of the structure in providing travel with comfort and safety. Considering that due to time and the action of traffic, when the pavement reaches the end of its useful life, interventions are necessary, aiming at a gain in serviceability, comprised of the thinning of the coating, generating waste, for later execution of a new layer, which can be recycled. This recurrent technique for road pavements has been widely applied to the use of RAP (reclaimed asphalt pavement), to compose new layers of pavement, given its mechanical performance, especially in terms of permanent deformation, and given the sustainable and economical premise. The paper sought to evaluate, using a laboratory study, the mechanical performance of hot recycled asphalt mixtures with the incorporation of 25%, 45%, and 100% of RAP, and to perform an economic analysis of the applicability of the technique. The dosage methodology occurred according to the Superpave specification whose results listed a significant gain in stiffness, and good mechanical performance with proportionality in the values obtained according to the incorporation rate of RAP. As for the economic analysis, it was observed that the costs of applicability of the technique are related to the percentage of incorporation in mass and the logistical costs of processing, which may be lower than or higher than that of a conventional mixture. Above all, the results were satisfactory to prove the feasibility of the technique in paving works.

Keywords: Recycled mixtures; Mechanical performance; Pavements.

1. INTRODUCTION

The search for transport infrastructures that are increasingly durable and economically sustainable has been a necessity. In this regard, research organizations as well as the industry have increasingly sought the insertion of recycled and inert materials as components and/or as the main raw material in the design of these infrastructures.

The importance of the use of alternative materials in the construction industry is due to the concern for the environment, due to the incessant exploitation of natural resources, since they can reach scarcity [1], and also due to the final destination of much of the waste that is produced daily in different service fronts [2]. The transportation infrastructure industry is one of the producers of waste, because of the large number of interventions that are realities in existing structures. These pavement structures, considered the preponderant modal has been the road, responsible for more than 60% of cargo transport and more than 90% of passenger transport [3].

This preponderance of road transport over the others can be explained by the need for interconnection of geographic spaces, which is possible mostly only by land, and also because the country has dimensions equivalent to that of a continent [4].

The road network in Brazil is measured at around 1.73 million km, of which only 12.4% are paved, and of these, 99% are of the flexible type. Data from CNT [3] show that on this type of pavement, wear continued to be the main quantified deficiency, with the percentage of segments with wear increasing by over 300% in the last 16 years, with rates jumping from 13% in 2004 to 50.9% in 2021, which consequently caused the decrease in the rate of pavement in perfect condition.

Such reason for the increase of pavements in poor condition can be explained by the growth of the fleet operating in Brazil in the last 10 years, plus the non-proportionality of the size of the structure for the respective

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use [5]. With the deactivation of the scales, even with the increase in up to 12.5% of the PBT as a legal load [6], the number of requests increased due to the high productivity in the country and concomitantly for the purpose of transport economy, carriers exceed the load limits established, causing greater stress on the pavement and consequently greater deterioration.

Thus, the process of wear and the appearance of pathologies tended to occur in a more intensified manner, causing the appearance of interconnected cracks, deformations, rutting, undulations, and potholes, which compromise the functionality of roads, evolving to situations where the pavement is totally destroyed and with inadequate serviceability [3].

NUNES [7], states that the main cause of damage is associated with repeated loading that leads to fatigue cracking and permanent deformation, reflected in the excessive sinking of the overlay and granular layer, and in the disintegration of material of the overlay, which allows water to infiltrate the granular layers, causing the pumping of fines, evolving in the future to the appearance of potholes and/or pans.

And he complements that added to the excess of exceptional loads, the absence of maintenance, the lack of technological control of the materials, the deficiency of the inspection process, the inexistence of an efficient drainage system, and infrastructure management, compose the causal factors of the damages.

Damages that compromise the functionality of the infrastructure, and generate losses to operations, whose amount of losses of inputs on the highways represents on average 8% of what is produced in a harvest [8–10]. Coupled with the losses, there is an increase in the cost of transportation, whether fixed or variable, resulting from higher fuel consumption, maintenance of rolling stock, and travel time, all due to the functional and structural conditions of the pavement [2, 5, 10, 11].

The functionality of the road transport infrastructure is mainly due to the quality of the pavement network. When the pavement is in unfavorable conditions that put operations at risk, it becomes necessary to adopt maintenance and rehabilitation (M&R) actions to restore functionality and ensure the performance and serviceability of the structure during its service life [12].

M&R actions, understood as pavement interventions and also as restoration techniques, are part of the pavement management system, which starts at the production and technological control of materials stage and ends at the final destination of the waste of a condemned pavement that has reached the end of its service life. These actions include every intervention performed on the structure, whether it is for the recomposition of the traffic lane and/or for signaling, and adaptations of the domain lane, so that both aim at returning the pavement to its functionality, to operate in comfort and safety [2, 4, 12].

The interventions performed on the traffic lane and the roadway platform are the most recurrent, giving rise to the RAP (reclaimed asphalt pavement) waste resulting from the process of thinning the asphalt concrete coating layer of the old pavement [13], and of asphalt mixtures machined outside the service specification [14], which are destined for disposal in dumps, and or even are left along the highways domain lanes, causing environmental concern [2].

Thus, due to the generation of waste, pavement recycling arises, which enables the reuse of this material in new pavement structures [15], combined with virgin materials, since the reduction of the number of virgin materials required, and given the principle of sustainability in reducing the impacts caused either for the design of a new road engineering project or to increase the capacity of an existing one with the rehabilitation of the pavement structure [16–18].

RAP is understood as the main residue resulting from the restoration services, and it is highlighted in the paving industry, the addition of this milled material as a component of new asphalt mixtures and granular layers as a granulometric stabilizer [2, 14, 19–21]. Since each RAP sample consists of stone units (aggregate), covered by a mastic (filler and aged binder) forming lumps of the milled material [22], requiring in the dosage process that granulometric corrections are performed, and additions of rejuvenating agents and binders KEARNEY *et al*. [23–25].

However, through all the benefits in the applicability of the recycling technique, with advantages in the reduction of transportation costs, conservation of remnant materials, preservation of the geometry of the existing pavement, maintenance of drainage conditions, less impact on the environment, energy conservation Among the percentages mentioned in the literature and the ones used in the industry, they vary a lot, from mixtures with 20% to 100% of incorporation [2, 14, 26–28].

Thus, the percentage of RAP to be added to asphalt mixtures depends on the properties of the recycled and virgin material, requiring RAP management to obtain homogeneous mixtures with quality equal to or superior to that of a conventional asphalt mixture [14].

Since mixtures resulting from the incorporation of milled material tend to be very stiff and, consequently, less workable, they can lead to failures in the field, such as reduced strength, cracking under traffic actions, and fatigue damage, with greater predominance in hot recycled asphalt mixtures [14, 20, 29–32].

Therefore, since the material itself has high stiffness, due to the presence of aged binder, researchers have used rejuvenating agents to give back to the material (binder) its viscoelastic properties, and thus have a control of the stiffness and consistency of the mixture.

It is a fact that asphalt concrete as it ages undergoes a relative increase in asphalt content, and a decrease in the content of resins and aromatic oils [15]. For recycled mixtures with considerable contents of RAP, it is necessary to add rejuvenating agents capable of restoring the viscoelastic properties of the binder, reversing the aging process through which the binder has passed, allowing the complete recycling of the aged mixture [33].

In the paving industry, RA has been a widely used material both for cold-recycled mixtures and for hot-recycled mixtures, with shale oil and tar-based agents having the highest market share. Choosing the type of rejuvenator to be used, is related to the type of mixture machining and according to the aging characteristics of the remaining binder present in the RAP, a fact that the consistency of the AR to be used is inversely proportional to the aging rate of the remaining binder [34], where the consistency scale of the shale oil-based AR is discretized as AR-1 the lowest consistency, and AR-5 the highest consistency [23, 25, 35].

The interest in this research arose from the observation of the number of interventions that have been routinely performed on asphalt pavements, and the amount of RAP generated with these interventions. Given the constant need to have pavements that are increasingly durable and economically sustainable, the research sought to incorporate RAP as a building material composed of new asphalt mixtures, to analyze the mechanical behavior of mixtures obtained with this material, through scanning and performance tests.

2. MATERIALS AND METHODS

The materials used in the research were those commonly used to make asphalt mixtures, such as virgin aggregates of the micaxist type with grades of gravel 2, gravel 1, gravel 0, stone powder, and filler, asphalt binder of the CAP 50-70 type (petroleum asphalt cement), aggregates and binder remaining in the RAP and rejuvenating agent.

The milled material was provided by the National Department of Infrastructure and Transportation (DNIT), and its origin corresponds to the milling of the asphalt pavement coating on highway GO 060 at km 118, a highway under private administration with a high number of operations, N>10^7.

The binder CAP 50-70 (petroleum asphalt cement) was provided by an asphalt distributor in the Midwest region, the rejuvenator by a company in the binder business, and the virgin aggregate was supplied by a quarry in the northern region of the state of Goiás, whose aggregate was obtained by crushing micaxist rock. The choice of the virgin aggregate type was due to the origin of the aggregate present in the RAP being from the same rock typology, i.e., also micaxist.

The research methodology was carried out through an experimental study, consisting of material characterization, a dosage study, sample preparation, and evaluation of the mechanical behavior of recycled asphalt mixtures, as shown in Figure 1.

This method consisted of the dosage of hot recycled asphalt mixtures with 25, 45, and 100% incorporation of RAP (HMA-R25, HMA-R45, and HMA-R100) through the Superpave methodology, which establishes control points concerning the TMN (maximum nominal size) and the restriction zone, avoiding the use of an

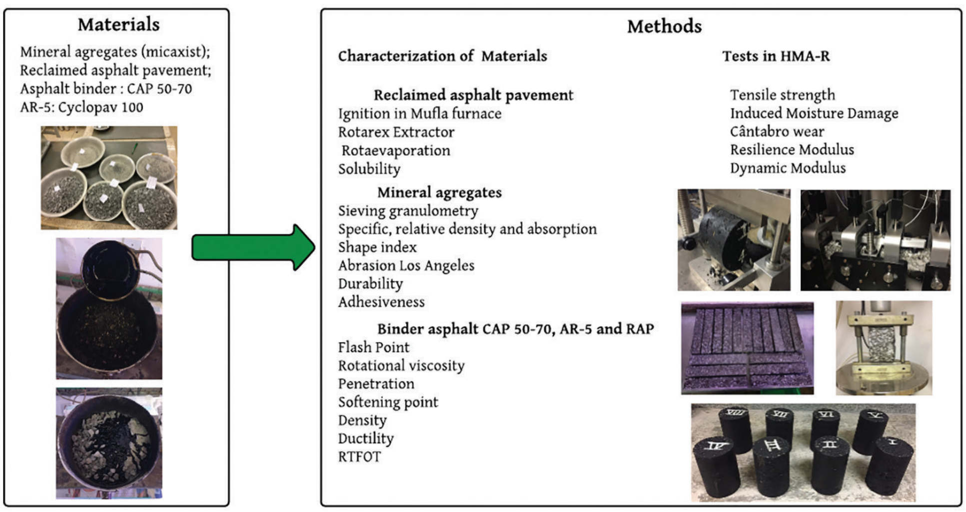

Figure 1: Flowchart of the materials and methods.

excessive amount of fine material in the mixture, and determines the optimum binder content in the mixture given an initial Vv in 4%. The mixtures with a percentage of RAP of 25 and 45% underwent particle size correction according to the Bailey methodology, and dominant aggregate range (FAD), so that the aggregates remained within the DNIT Band C prescribed by ES 031 [36].

Parameters regarding machining and compaction temperature were obtained as a function of the viscosity of the CAP50-70 and the AR-5 rejuvenator commercially known as CICLOPAV 100, rotational viscosity test 0.17±0.02 Pa TU and 0.28±0.03 Pas TC. Test conditions such as temperatures, aging time, loading, and confinement level were followed as recommended in the literature and recommended by manuals.

3. EXPERIMENTAL ANALYSIS

The RAP after benefiting and homogenized, went through the process of physical characterization, as to its natural state and also as to the materials components of the waste separately. The characterization of the black aggregates was performed, and later the gray aggregate was obtained by the extraction process of the remaining oxidized binder, through the burning method by ignition in a muffle furnace [37].

With the need to perform the characterization of the binder, the extraction of oxidized CAPpresent in the RAP, followed by the extraction method through rotarex prescribed by NBR 16208 [38], with subsequent application of the rota-evaporation method [39] as a mechanism for recovery of this binder. Thus, the characterization of the binders and aggregates, virgin and remaining, followed the procedures and specifications for the characterization of materials used for making asphalt mixtures.

3.1. Material characterization

Data such as maximum measured specific mass (Gmm) [40], remaining oxidized binder content and particle size (with and without PAC) were obtained in the RAP after processing. Table 1 shows values for the density of the material in its natural and loose condition, and also shows density data determined by hydrostatic weight analysis in the loose condition.

To know the percentage of binder remaining in the material, a parameter analyzed when designing the calculations of the number of materials needed for the dosage of a recycled asphalt mix, analysis was performed by the method of extraction by centrifugation through rotarex [38], and burning by ignition in a muffle furnace [37].

According to the results presented in Table 1, there is a difference of 4.15% under the highest content attested between the contents extracted by the two methods, this situation occurs because the rotarex allows the

Table 1: Aggregates characterization

RAP CHARACTERIZATION		**CHARACTERIZATION OF THE REMAINING AGGREGATE**			
Parameters	**RAP**	**Parameters**	**Big**	**Kid**	**Fíller**
Actual specific mass (g/cm^3)	2,57	True density (g/cm^3)	2,751	2,764	2,692
Apparent specific mass (g/cm^3)	2,28	Apparent specific mass (g/cm^3)	2,725	2,631	–
Absorption (%)	1,43	Absorption (%)	0,52	0,605	–
Gmm (g/cm^3)	1,35				
Rotarex (%)	6,03	Impact wear Marshall (%) 16,04			
Muffle furnace (%)	5,78	Form index 0,645			
CHARACTERIZATION OF VIRGIN AGGREGATE – MICAXYST					
Parameters	**Method**		**Gravel 1**	**Gravel 0**	**Stone powder**
True density (g/cm^3)	DNIT ME 413/19 DNIT ME 411/19		2,78	2,79	2,81
Apparent specific mass (g/cm^3)	DNIT ME 413/19 DNIT ME 411/19		2,74	2,73	2,78
Absorption (%)	DNIT ME 413/19 DNIT ME 411/219		0,62	0,74	2,08
Adhesiveness	DNER ME 078/94		satisfactory		–
Shape index	NBR 7809/19		0,81	0,71	–
Abrasion Los Angeles	DNER ME 035/98		31,44%		–
Durability	DNER ME 089/94		satisfactory		–

outflow of fines in the extraction process, so for dosage was adopted the value of the binder content obtained in the burning by ignition in a muffle furnace, because it presents more reliable results [41], so to perform the recovery of the remaining binder, the extraction was performed by rotarex and then the solvent-asphalt solution went through the rotary evaporation method [39], to perform the separation of CAPfrom the solvent trichloroethylene.

Having obtained the recovered binder, it underwent a characterization process as well as the virgin binder, this process is based on the methodology of tests for asphalt binders established in Brazil, which seeks to obtain parameters such as viscosity, thermal susceptibility, softening point, ductility, and density, which are presented in Table 2.

It is possible to observe through the characterization results that the virgin binder presented satisfactory levels, within the limits set by the Brazilian standards, adopted as a reference in the study. The recovered binder, by being oxidized, lost part of its original properties, explained by the superiority of the density parameters, and difficulty of penetration of the sampler in the test specimen, whose value obtained was less than 45.25% of the attested in CAP 50/70 (petroleum asphalt cement) virgin, and if compared with the penetration retained, performed in the binder that underwent the process of short-term aging in oven RTFOT, this still showed a penetration lower by 8.7%.

It should be noted that the retained penetration, obtained in the binder that underwent short-term aging, corresponded to an index less than 40.3% of that obtained in the CAP50-70, so the values obtained in the recovered binder and aged in oven RTFOT are very close.

Also concerning the parameters obtained in the characterization, it is possible to note, from the date of the softening point test, that the material presents a more viscous behavior, confirmed by the measurement

Table 2: Binder characterization.

BINDER CAP 50/70 CHARACTERIZATION.				
Test	**Method**		**Limits DNIT**	**CAP 50-70**
Penetration (mm)	DNER ME 003/09		50–70	53,7 mm
Softening point (°C)	DNIT ME 131/10		min. 46 °C	48,3 °C
Flash Point (°C)	DNER ME 148/94		min. 235 °C	302,4 °C
Rotational viscosity	ASTM	135°C	min. 274 cP	342 cP
		150°C	min. 112 cP	171 cP
		177°C	min. 57 cP	58 cP
Susceptibility Index	–		(–1,5) a 0,7	–1,47
Density (g/cm^3)	DNER ME 193/96		–	1,0117 g/cm^3
Ductility (cm)	DNER ME 163/98		min. 60 cm	> 100 cm
Elastic recovery (%)	DNER ME 130/10		–	10%
RTFOT	ASTM D113	Var. em mass (%)	max. 0,5%	0,29%
	ASTM D5	Pen. retained (%)	min. 55%	59,96% (32,2 mm)
	ASTM D36	P. softening (°C)	max. 8 °C	2,6 °C (50,9 °C)
CHARACTERIZATION OF THE REMAINING BINDER				
Test	**Method**		**Binder remaining**	
Penetration (mm)	DNER ME 003/09		29,4 mm	
Softening point (°C)	DNIT ME 131/10		64,1 °C	
Flash Point (°C)	DNER ME 148/94		194,6 °C	
Rotational viscosity Brookfield (cP)	ASTM D 4402/15	135°C	600 cP	
		150°C	528 cP	
		177°C	417 cP	
Density (g/cm^3)	DNER ME 193/96		1,14 g/cm^3	
Ductility (cm)	DNER ME 163/98		18,6 cm	
Elastic recovery (%)	DNER ME 130/10		0,193	

of the viscosity in 75% higher than that obtained in the virgin binder. Only the ductility, elastic recovery, and flash point have lower values than the virgin CAP50-70, due to contamination of the material by chemical agents and CO2, because the binder is oxidized and aged, characterizing as a material whose behavior is more rigid.

The use of a rejuvenating agent was justified, to improve the viscoelastic properties of the remaining binder, whose AR-5 characterization (Ciclopav 100) followed the methodology recommended by the manufacturer, where the parameters of rotational viscosity at 60°C (409.78 cP), density at 20°C (1.18 g/cm^3) and flash point (318.6°C) were analyzed. The results of which met the requirements of the Brazilian specification DNC No. 04 [42], and fit within the limits established according to the test standards, with flash point and density higher than the virgin binder and oxidized, and low viscosity, even for analysis at lower temperatures than the test on conventional binders, showing a considerable viscosity at 60 ° C.

Because it is a recycled mix, and because it works with three different levels of incorporation of RAP, virgin aggregates were used as a component of the mixtures HMA-R25 and HMA-R45. The aggregate used was of the same mineral origin as the black aggregate, i.e., from the micaxist rock, given the need to obtain mixtures with a mineralogical skeleton equal or similar to that found in the field.

Three fractions of mineral aggregate were used: gravel 1, gravel 0, and stone powder, similar to the fraction adopted in the study by BARROSO *et al*. [43], who worked with the same material, and concluded that it presents a good application in dosing studies and production of asphalt mixtures.

The decision to use the stone powder in the natural washed river sand, occurred because the RAP has undergone a micro-milling [15], and has in its composition a lot of fine material, so because the stone powder is an inert material, it would be closer to the behavior of the fine material present in the RAP, since it has no organic material in its composition, as found in washed river sand.

The characterization of the virgin aggregate, as listed in Table 1, allowed the observation that the coarse fraction presented satisfactory indexes regarding the durability and adhesiveness of the material, besides the parameters of abrasiveness and shape of the aggregates fitting within the limits recommended by norms and literature for use in asphalt mixtures. As for the apparent specific mass (excluding the Vv) and the real density of the grains, both for the coarse and fine fractions, the values found were also satisfactory, in such a way that the absorption is greater as the specific surfaces are larger, i.e., a greater amount of fine material.

3.2. Dosing study

Because it deals with recycled asphalt mixtures, the ideal percentage of material incorporated in mass to be used in the design of these mixtures has still been an unknown factor, through several studies already conducted and those that are in progress, it is possible to note the variability of the percentages of RAP that are added to asphalt mixtures, to succeed in solutions that are economically sustainable for the paving industry [44].

Aiming at the mechanical performance of the material, in the state of the art, the incorporations that provided the most favorable data from the point of view of performance and economy were those whose incorporated percentages were less than 60% by mass [45]. In the studies [14, 26], the amounts of RAP used for incorporation in asphalt mixtures were in the order of 25, 45, and 100%, and the behavior of the material was analyzed in the study for a recycled mixture with conventional binder and with a polymer-modified binder, under hot and warm machining conditions.

Proving the nobility of RAP by itself, there are also performance analyses regarding the mechanical behavior of recycled asphalt mixtures, with modification of the binder, aiming even more economy and sustainable practice in the manufacture of asphalt mixtures, replacing conventional binders, modified binders, and rejuvenating agents, with waste vegetable oils and bioligands [28].

According to studies [46], the residual oil in the modification of asphalt binder, is an economically sustainable solution, since it allows for reducing the viscosity rates of binders, enabling better adhesion in the mixture with aggregates, consequently better adhesion and cohesion, reducing costs in plants. They can be characterized as a material of good oxidative stability, for being rich in unsaturated fatty acids, which leads the material to have a resistance to high machining temperatures, which allows the use for recovery of aged asphalt binders, and this may be a more sustainable technology applied to the modification of aged binders compared to rejuvenating agents on the market [47, 48].

Considering that the RAP is characterized as an inert material with the presence of aged and oxidized binder, it is necessary for the dosage study of recycled asphalt mixtures, that this remaining binder has viscoelastic plastic properties and presents a virgin binder, For this reason, it is necessary to modify the remaining binder through rejuvenating agents and/or vegetable oils, residues, and bioligants.

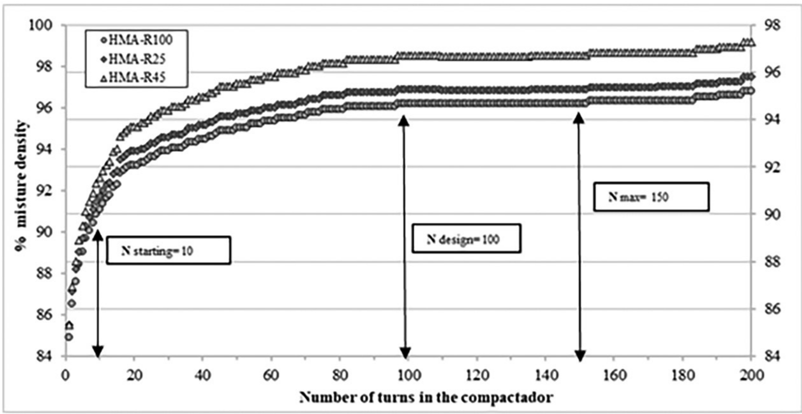

Figure 2: Compaction and densification of the recycled mixtures.

In this study, the rejuvenating agent type AR-5 (Ciclopav 100) was used in the mixtures, whose incorporation percentage was established at 20% of the weight due to the content of oxidized binder present in the RAP sample, based on studies [22], and to obtain an economy in the amount of virgin binder to be incorporated.

The amount or percentage of rejuvenating agent that is added to the mixture has as its main objective to modify the stiffness of the material, and to prevent this material from continuing to age at an accelerated rate [49]. However, several studies analyze the percentage of incorporation of the rejuvenating agent aiming to return the viscoelasticity to the aged binder as well as reduce the consumption of virgin binder in the mixture, however, since it is not the focus of this study, to deduce what percentage is the most effective, it was established in the quantitative 20% of the weight due to the content of oxidized binder present in the RAP sample, which showed favorable results that have been listed in the literature.

The studies [50, 51] show that at the end of the service life of a pavement, as the structure is being used, the pavement layer may present a voids volume of 2.5% to 2%, and when this road is newly built and opened to traffic as a result of field execution factors, they normally present a Vv of 7%.

Thus, a Vv of 4% represents a pavement working throughout its service life. In the mix design study, the amount of material needed to obtain samples with a 4% voids volume was determined, seeking first to obtain the maximum measured density (Gmm) of the mixture, to control the degree of compaction of the sample as a function of the number of turns of the Superpave rotary compactor, so that the mixture would present a gain in stiffness, and better attenuate traffic loads on the structure, as shown in Figure 2.

From Figure 2 it is possible to notice that the mixture with the highest amount of RAP presents easier compaction than the others, due to the granulometry of the mixture being completely composed of black aggregate, i.e., each aggregate itself is surrounded by a thin film of oxidized binder, which when heated promotes greater ease of agglomeration and consequently greater densification of the mixture.

Cylindrical specimens were also molded in the same dimensions 100mm × 63.5 mm with Vv at 7%, representing the beginning of the pavement life, to obtain the parameters of adhesion and cohesion of the mixture, through retained tensile strength data. And with the need for mechanical characterization of the mixtures, specimens were also molded in prismatic beams [52], with dimensions of 50 mm high, 63 mm wide, and 380 mm long, as shown in Figure 1.

3.3. Dosing superpave and making the samples

The methodology followed for dosing the hot recycled asphalt mixtures was the Superpave, according to ASTM D6925-09 [53]. It should be noted that the granulometric curves for the three levels of incorporation for the mixtures were within the DNIT Range C [36] and that the limitations imposed by the dosage method were respected, such as not passing through the restriction zone and fitting within the control points, as shown in Figure 3, which shows the particle size distribution curves adopted in the mix design study, where it can be seen that the RAP was classified as a conventional aggregate in the recycled mixture, even for the mixture of 100% RAP that did not undergo particle size correction.

The HMA-R100 mixture already contained a certain proportion of binder, the optimum content corresponding to the residual content present in the milled material.

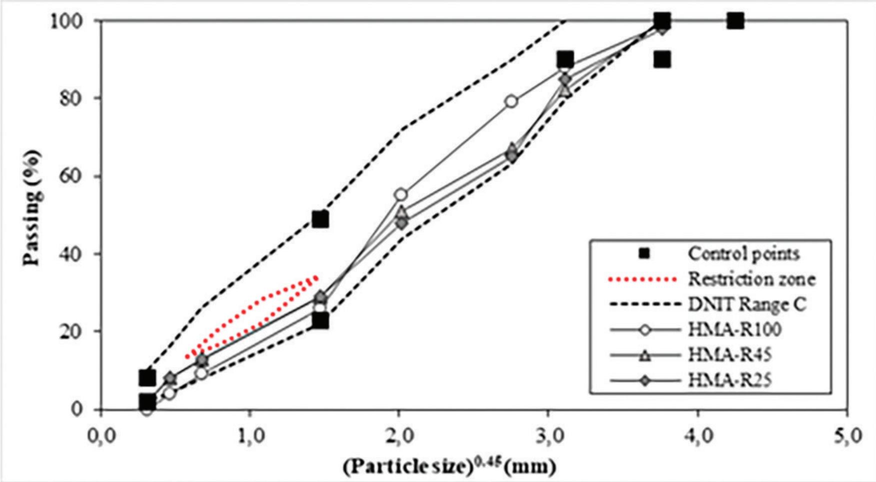

Figure 3: Particle size distribution curves of the recycled mixtures.

Table 3: Volumetric data of mixtures.

MIXTURE	VIRGIN BINDER CONTENT (%)	AR CONTENT (%)	Gmb (g/cm³)	Gmm (g/cm³)	Vv (%)	VMA (%)	RBV (%)
HMA-R100*	0	20	2,332	2,454	4,2	16,25	75,38
HMA-R45*	4,6	20	2,361	2,461	4,05	17,31	76,81
HMA-R25*	4,9	20	2,36	2,469	4,1	16,71	76,06
HMA-R100**	0	20	2,33	2,457	4,45	16,15	75,23
HMA-R45**	4,6	20	2,317	2,46	4,38	17,34	76,93
HMA-R25**	4,9	20	2,359	2,472	4,36	17,30	76,87

RBV: empty binder ratio.
*samples compacted with rotating compactor - cylindrical test specimen.
**samples compacted with plate compactor roller - prismatic test specimen.

For other mixtures, through the dosage study, a binder content of 4.6% was defined for HMA-R45 mixtures and 4.9% for HMA-R25 mixtures. The other levels tested varied according to the Superpave recommendation, which recommends variations in T% ±0.5 and T% + 1.0, due to a percentage of 4% initial voids, respectively.

Table 3 presents, in summary, the volumetric parameters found after compaction of the specimens and realization of the Rice Test ASTM D 2041 [54], fact that was performed compaction by the rotating compactor to obtain the cylindrical specimen, and compaction employing the roll plate to obtain the prismatic specimen, and for the prismatic specimen has performed an adaptation of the mold to obtain the volumetric parameters and obtaining the Gmm and Gmb. Whose procedure was done using hydrostatic balance and pachimetric measurement ME 428 [55], besides having the densification data from the number of spins in the rotating compactor and number of closures of the plate compactor roller.

Note that the densities found, whether real or measured, in the compaction through the rotating compactor and with the plate roller were quite similar, which validates the applicability of the method, given that the compaction with the plate roller took place outside the laboratory where the temperature and degree of compaction were critical aspects of difficult control.

This becomes noticeable because the voids volume of the mixtures compacted with the flat roller was higher than the mixtures compacted in the laboratory, where the densification criterion of the mixture occurred through the number of closures (roller passes) from the correlation of dimension, load, and tension applied by the drum of the flat roller.

As for the bitumen void ratio, it fits within the limit range intended for asphalt mixtures according to the Superpave methodology, a fact that the mixtures with higher contents of RAP, tended to have lower densities, with the greater number of voids, and volume of mineral aggregate greater than 11%. The tendency of a higher number of voids, the higher the percentage of incorporation of RAP, is linked to the correlation of aging of the binder in the aging of asphalt mixtures [56], where it was confirmed that the aging of the mixture presents the same mechanism that occurs in the binder, i.e., the oxidation of the binder compounds causes an increase of carbon chains in the material, so that its flexibility decreases, also decreasing the workability, viscosity data of the remaining binder Table 2 [57].

3.4. Evaluation of the mechanical behavior of mixtures

The tests performed to evaluate the mechanical behavior and characterization of the recycled asphalt mixtures followed the prescriptions imposed by standards for both the preparation and conditioning of the samples, whose quantitative samples for each test ranged from 3 to 15 specimens, whether cylindrical or prismatic, adopted in the determination of the dynamic modulus (DM) EN 12967-26 [58] for each mixture.

Wear analysis was performed, through the cantabrator wear test, in addition to verification of the tensile strength, and the retained tensile strength using the induced moisture damage test, considering the conditioning for low and high severity.

Table 4 shows the values of tensile strength and wear of the mixtures studied, and Figure 4 illustrates the values of tensile strength retained in the samples for both high and low conditioning.

The ES 031 [36] states that the RT values for conventional asphalt mixtures must be greater than 0.65 MPa, then of the mixtures studied, it can be observed that the lowest RT found, still remains higher than 75% of the minimum RT established in the standard for asphalt mixtures.

Thus during the test, it was observed and found that the asphalt mixtures whose content of RAP incorporation was higher, tended to break suddenly, disintegrate completely, and present a peak strength in obtaining the values of RT without presenting post-peak strength, while the samples with lower levels of incorporation, tended to lower values of RT, given that they showed smoothness in the dissipation curve of the load.

The significant gain in RT value is proportional to the increase of RAP content in the mixture [14, 20], a fact that recycled asphalt mixtures tend to present higher tensile strength if compared to a conventional mixture, which presents average recurring values between 0.5 and 2.0 MPa [59].

These values correlate to the gain in stiffness due to the basic property of the incorporated material, where despite being considered an inert material, the RAP itself has different properties from other aggregates because

Table 4: Mixtures characterization.

MIXTURE	Vv (%)	Gmm (g/cm³)	Gmb (G/cm³)	RTm (MPa)	WEAR (%)
HMA-R100	4,2	2,435	2,328	2,3134	9,11
HMA-R45	4,05	2,461	2,358	1,5782	8,58
HMA-R25	4,1	2,469	2,366	1,1442	7,44

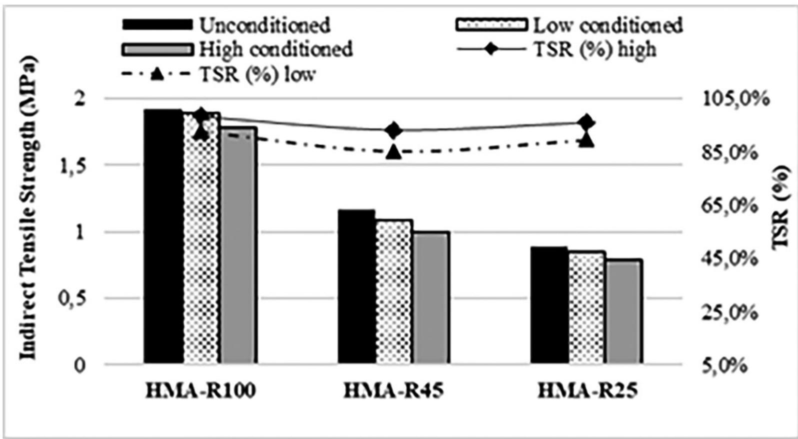

Figure 4: Indirect tensile strength and retained tensile strength of recycled mixtures.

it has already undergone a machining process. Such rigidity was verified by the wear measured in the mixtures studied, where the proportionality of wear was directly related to the content of RAP present in the mixture.

From the wear values presented in Table 3, it can be seen that the mixtures with a higher percentage of RAP showed wear higher by almost 2% compared to the mixture with a lower percentage of milled incorporation. This scenario shows that mixtures with higher contents and therefore more rigid, tend to present difficulties in tire-pavement adhesion, and the literature shows that these mixtures are subject to early degradation, proven by data that the wear increases in proportion to the content of oxidized binder present in the mixture, so mixtures with higher amounts of RAP have higher percentages of remaining binder present in the material [20].

Analyzing the RRT results of the mixtures studied, illustrated in Figure 4, both for high and low severity conditioning, it can be affirmed a similarity of the behavior of the evaluated mixtures, is within the limits adopted by the Superpave methodology and literature data.

Among the three mixtures, HMA-R100 showed the highest tensile strength, with a percentage of deleterious damage due to the water of only 1.5% with RRT of 98.5% for high severity, which can be justified by not containing in its composition virgin aggregates and binders, only rejuvenating agent, with all minerals already wrapped by the binder film. Thus, the damage ratio varied between 1.5% and 7.3% for HMA-R100 in high and low severity conditioning, 6.7% and 14.75 for HMA-R45, 3.8% and 10.5% for HMA-R25.

Therefore, the adhesiveness was proven to be satisfactory both by the adhesion test performed according to ME 079/94 through an empirical validation, and proven according to RRT values close to 1 [14, 26, 27, 60].

Considering that for recycled mixtures with RAP incorporation it is recommended that asphalt mixtures have RRT higher than 30%, to cause a maximum loss of adhesion by adhesion or cohesion of up to 0.7 BOHN *et al*. [26]. Considering that when dealing with conventional mixtures the Superpave methodology adopts RRT values above 80%, and North American transportation departments adopt limits higher than 70%, HICKS [61], thus the analyzed mixtures meet the recommendations for both recycled and conventional mixtures because the lowest RRT attested for the most critical situation of conditioning and simulation of the deleterious effect of water was equivalent to 85.3%.

Evaluating the deleterious effect of water on an asphalt mixture is extremely important to understand the performance of flexible pavements, because it is possible to highlight deficiencies in the adhesion of aggregate with binder [59]. These deficiencies arise from loss of adhesion due to water percolation between the binder and the aggregate, which causes the detachment of the binder film, and loss of cohesion due to the reduction of the binder stiffness and the loss of bonds between asphalt binder and SPECHT aggregate [62].

From the value obtained in the tensile strength test, a loading stress level equivalent to 25% of that used to determine the modulus of resilience was adopted, according to ME 135 [63], to work in the most critical loading situation. According to Figure 5, to obtain the resilient modulus, 25% of 2.314 MPa for HMA-R100, 25% of 1.578 MPa for HMA-R45, and 25% of 1.144 MPa for HMA-R25 were adopted as input tension.

The literature shows that mixtures with higher stiffness tend to have high modulus values, since they have very low deformability, and one of the ways to increase the stiffness of asphalt mixtures so that they have a higher modulus than a conventional mixture is to incorporate inert materials in the mixture matrix [64].

Based on the modulus results obtained in this study, it was observed that the mixtures with a higher concentration of RAP tended to have high modulus, with the HMA-R100 mixture having a modulus of 12,000 MPa

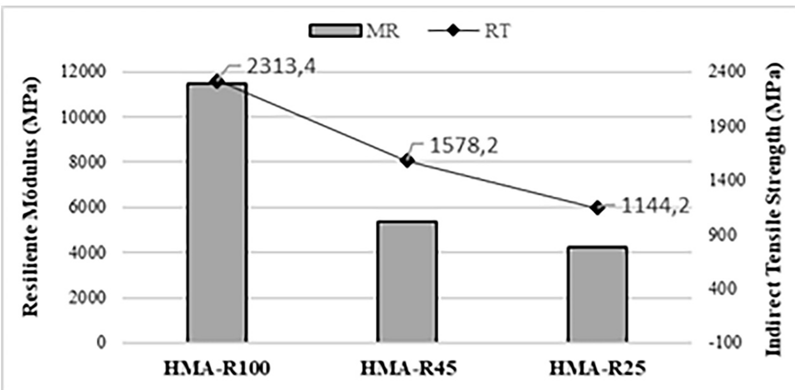

Figure 5: Resilient modulus and indirect tensile strength of recycled mixtures.

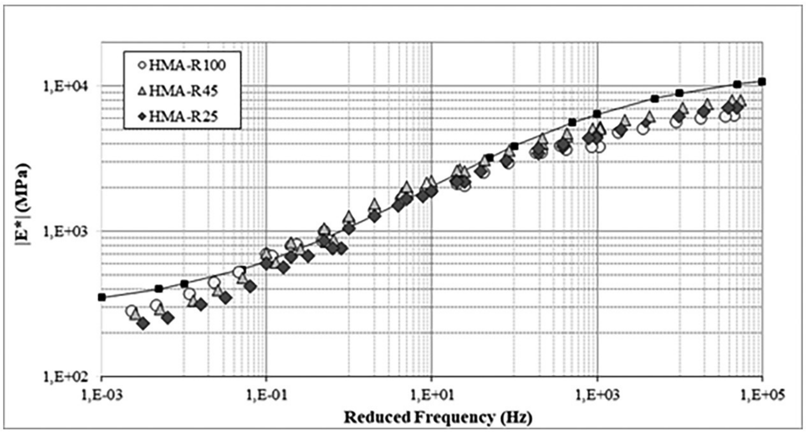

Figure 6: Master curve of the dynamic modulus of recycled mixtures.

and the HMA-R25 mixture having a modulus value of 4,200 MPa. It is possible to consider that the rejuvenating agent acts to increase the stiffness of the mixture, which makes it less susceptible to permanent deformation [14, 20, 27], and that the porosity of the mixture also has a direct relationship with the resilient modulus, i.e., the decrease in stiffness of the mixtures occurs with increasing porosity, and the most rigid mixtures are those with granulometry close to the line of maximum density.

Therefore, based on the results of the tensile strength of the mixtures studied, it was noticed that they would also present high modulus values, considering that the resilient modulus is obtained by the relationship between the tensile stress and the tensile strain, and involves the estimation of stresses and strains in the evaluated layer [65].

Consequently, considering that the ratio between resilience modulus and tensile strength (MR/RT) is an indicator of the fatigue life of the mixture, it is better the lower the value of this ratio, i.e., the higher the tensile strength and the lower the stiffness, so that the material does not absorb too much stress [59].

The test methodology used to obtain the dynamic modulus (MD) was that described by EN 12967-26 [58], which establishes the guidelines for the relationship between stress and deformation in materials whose behavior is linear viscoelastic. The sample adopted for this determination was through prismatic beams due to equipment needs, and the software UTS015 from IPC Global was adopted for analysis and determination of the modulus.

The frequencies adopted in the test to obtain the dynamic modulus ($|E^*|$) and determine the phase angle (φ) were respectively 0.1; 0.2; 0.5; 1; 2; 5; 10; 15; 20; 25 Hz at temperatures of 5, 15, 25 and 35°C, with the application of 50$\mu\varepsilon$ of deformation in the samples in a cycle of 200 repetitions per loading. The results of which are described in the master curve illustrated in Figure 6.

Among the mixtures studied, it is noted that for higher frequencies the result is the higher modulus, however, analyzing the HMA-R100 for the same test frequency, it is noticeable that it presents a decrease in modulus as the test temperature increases. And it is also noticeable the increase in phase angle values at higher temperatures, so that the phase angle varies with the reduction in frequency. These findings explain the behavior of asphalt mixtures when they are subjected to high temperatures in the field, because they tend to lose some of their elastic properties, behaving closer to a viscous material.

The HMA-R45 and HMA-R25 mixtures had the same behavior as the HMA-R100 mixture, with the phase angle being inversely proportional to the elasticity modulus of the mixture, as there is an increase in temperature and reduction in test frequency.

The stiffness of a recycled asphalt mixture may be related to the increased viscosity of the oxidized binder remaining in the material, associated with the non-activation of this binder, and also in the way, the RAP was conditioned before the dosing and compaction process [14].

It is also observed that for the HMA-R45 mixture, the remaining binder was completely activated, where even though the mixture had a considerable percentage of RAP incorporation, due to the machining and compaction temperature, together with the percentage of rejuvenating agent and the portion of virgin binder, contributed to the complete activation of oxidized binder, resulting in higher modulus for the HMA-R45 mixture compared to the others.

Therefore, the activation condition of the binder, the void volume, and the percentage of RAP present in the mixture is directly linked to its performance, a fact that mixtures with high Vv tend to have their share of stiffness affected by not complete compaction, which can be explained by the way the asphalt concrete slabs that gave rise to the prismatic beams were compacted, i.e., due to the difficulty in controlling the temperature and the degree of compaction.

However, in research already conducted with the incorporation of milled material in the asphalt mixture, it was observed that mixtures whose contents are less than 30% tend to have a similar modulus to a conventional asphalt concrete mixture, while those with a content higher than 50%, in addition to having high modulus, tend to have smaller void volumes, and consequently have a greater portion of stiffness [14, 26, 27].

The fatigue life analyses for the present mixture still lack validation, since the fatigue life of the studied mixtures is already known by the method of determination by controlled tension ME 183 [66].

For the determinations performed by the Brazilian test, 3 specimen tests for each stress level and of each mixture were tested, to determine the ratio of fatigue life by stress difference ($N \times \Delta\sigma$) and fatigue life by resilient strain ($N \times \varepsilon r$) besides the average initial stiffness, and the elastic coefficients K0 and K1.

The results so far showed that the mixture with a lower content of RAP showed more favorable results for fatigue cracking compared to the others, because it has a lower portion of stiffness. Consequently, the HMA-R100 mixture should be the mixture whose fatigue life was the most critical, however, the mixture with 45% RAP presented a lower fatigue life than the mixture with 100% RAP, due to the sharp drop in the curve between the number of pulses of stress applied to the sample, both by the resistant specific deformation, and by the stress difference. This suggests that this mixture would have a low fatigue life, presenting an early cracking of the coating layer [57].

Such failure in the field, arising from fatigue cracking can be explained by the lack of remobilization of the remaining binder, for this it will be confirmed by determining the fatigue beam by controlled deformation, to attest, by the two methods, the proportionality of fatigue cracking with the excess stiffness of the mixture [27], and if the RA improves the fatigue life of the recycled mixture [14].

4. SUSTAINABLE AND ECONOMIC ANALYSIS

Comparing the production technique of conventional asphalt mixtures with recycled mixtures, it is clear the difference in manufacturing methods because the conventional one uses only virgin materials without additions of alternative materials, whereas the recycled one substitutes part of the aggregates and binder with the use of RAP, resulting in material savings, and is characterized as an economically sustainable technique [44, 67].

Paving with recycled asphalt mixtures has currently been widespread in the road environment, proven by the similar and even superior benefits to the performance of a conventional asphalt mixture.

The technique is attractive because it contributes to minimizing the costs of purchasing, transporting, and processing stone materials, as well as saving money by reducing the amount of virgin binder in the mix. This scenario is very attractive nowadays due to the shortage of binders and rejuvenators in the paving industry, resulting from the excessive increase in oil and its derivatives.

However, it is necessary to analyze the existing scenarios so that the adoption of the technique of producing recycled asphalt mixtures does not result in higher costs than those of a paving front end obtained with conventional asphalt mixtures.

The fact that the amount of RAP incorporated into the mix, and the location where this milled material is stored, can generate higher cost compositions when compared to paving the road platform with a conventional asphalt mix, making the cost-benefit ratio ineffective. Figure 7, using the golden ratio, illustrates the cost-benefit ratio of the recycled mixtures according to the content of RAP to be incorporated, and the average transportation distance from the processing site to the plant, considering that in many sections this material is found on the edges of highways and in the domain strips.

According to GONÇALVES NUNES [68] one of the cost maximizing indexes in paving is due to the average transportation distances, which is explained by the movement and use of non-stationary asphalt plants in service fronts whose road to be paved is extensive.

This analysis is even more relevant in the current scenario, where the high oil prices have become one of the items responsible for the number of requests for economic-financial rebalancing in opening contracts, capacity increase, and/or maintenance of road works [69].

Therefore, for more reliable comparative cost analyses between the applicability of hot recycled asphalt mixtures and conventional asphalt mixtures, methods expressed by PB (payback period), such as NPV (net present value) and IRR (internal rate of return) can be very useful, considering only financial principles. The fact is that in the corporate environment, projects are analyzed under the economic aspect of value generation, and classified where there are fewer resources available, i.e., decisions are made in view of budgetary constraints [70].

In detriment of the scarcity of resources, the classification of projects under the perspective of value generation is of vital importance to the company, as it involves its budget in the search for solutions that bring

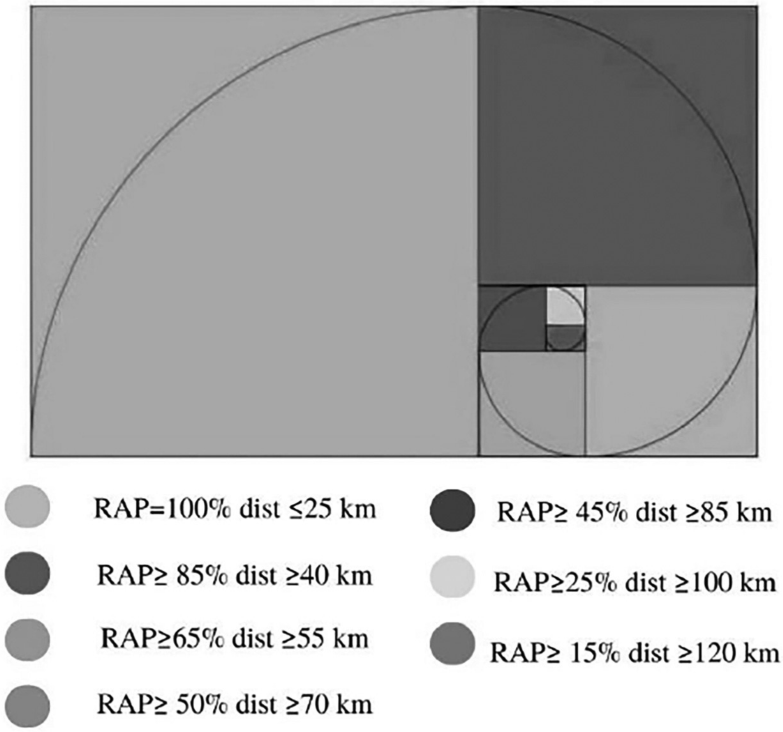

Figure 7: Area portion of the cost of applicability of the technique of recycled mixtures.

profitability and perpetuity, aspects that are necessary within an investment analysis, and strategic to find the best method of project investment analysis, usual in decision making [71].

Starting from the consideration that the investment is related to ceasing to consume today in order to consume in the future with obtaining a greater flow of benefits [72], and that the cost of capital employed in the investment considers the financial and economic risk involved in each project. Analyses must be performed using indicators that demonstrate the viability or otherwise of the investment [73]. Once the basic requirement of an investment is the generation of economic return, and that this compensates the cost of capital and the risks involved.

Payback can be an important indicator in the analysis, because from it you can know the period of time needed to recover the capital invested, and it complements the internal rate of return [74]. Which can be compared with the minimum rate of attractiveness desired for decision making. Where, if the internal rate of return is greater than the cost of capital and higher than the minimum rate of attractiveness, the project is accepted, because the investment is economically viable.

The net present value method, on the other hand, compares the initial investment capital and the total value of future cash flows, which in the present analysis of asphalt mixtures application can be represented by the number of maintenance operations that would be performed on this sidewalk structure. According to this definition, the choice between recycled and conventional mixtures will be made by taking into consideration the present value of future cash flows that is greater than the initial investment, represented by fewer maintenance and rehabilitation actions, which would imply lower resource expenditure for the structure's conservation.

Thus, having already proven the efficiency of recycled asphalt mixtures from the point of view of mechanical performance, it becomes necessary to know the economic implications of the investment described above, in addition to the sustainable inferences involving its dissemination and practicability.

For this, it should provide more favorable scenarios from the economic and sustainable point of view and mechanical performance compared to the conventional production technique, so that the adoption of the technique in paving contracts can be better justified and required, either by infrastructure agencies, concessionaires, and contractors.

5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORKS

As a result of the analysis and results obtained in this paper, it can be concluded that:

- The mixtures obtained in the study fell within the limits recommended by asphalt concrete mixtures standards, where characterization parameters were satisfactory, being even higher than those of studies on recycled mixtures in the literature;

- As for the mechanical performance, it was observed that the mixture stiffness is directly linked to the amount of RAP incorporated in this mixture, and the HMA-R100 mixture had higher values of cohesion, tensile strength, resilient and dynamic modulus, consequently, this same configuration caused higher wear rates, justified by the volume of voids in the mixture that favored cracking and loss of sample mass, representing the detachment of granular material in the field due to premature cracking of the coating when requested, confirmed by the premature fatigue analysis performed;
- It was observed that the cohesion and stiffness of the mixture are correlated, by observing a greater bond between binder and aggregate when there is the activation of oxidized binder, due to the aggregate from RAP having a film of remaining binder, which when heated and activated, tends to present a more viscous behavior, favorable to tensile stresses, causing increased cohesion in the mixture, so that there is a lower loss of adhesion when subjected to the deleterious effect of water. It is resolved that adhesiveness analyses for fine material and/or pulverized RAP will be performed to evaluate the cohesion and adhesion in the fine aggregates portion of the mixture;
- It is concluded that the stiffness portion of a recycled mixture is related to the increase in viscosity of the oxidized binder, with the activation or not of this binder, and with the way, the RAP was conditioned, because all these factors contribute to the gain in modulus. Therefore, the more rigid mixtures are favorable to permanent deformation at higher temperatures, and mixtures of less rigidity at milder and lower temperatures, confirm a better performance regarding fatigue life.
- It was concluded that the mixtures perform well for permanent deformation as a function of the modulus values obtained (a tendency of larger phase angles with increasing test temperature) and stiffness. However, mixtures with higher amounts of RAP are more susceptible to cracking, presenting a low fatigue life, confirmed by the analysis of the mixtures with higher RAP content at low temperatures, which presented cracking sections and defined rupture plane, thus mixtures whose stiffness and voids volume are high, tend to fail in the field early;
- As for the economic analysis, it was concluded that even being considered as an economically sustainable technique, which has for its configuration generates savings for the service fronts with economic gains, with lower binder consumption, lower cost in the acquisition of inputs, and to generate less degradation to the environment by giving destination to waste that would be destined to the environment, and minimize the exploitation of natural deposits. The applicability of the technique is connected with the level of incorporation, with the processing of the material, and with the logistics of transport. In situations where the percentage of incorporation is low and the logistics of the construction site are intercepted by large displacements in the collection and acquisition of material, the technique may not be attractive, resulting in a cost-benefit equal to that of conventional mixtures.

However, new analyses should be carried out, since limitations were found in the study, which is linked to the difficulty of performing other analyses due to the pandemic situation faced with COVID-19. Thus, it is intended in future and subsequent studies to perform more reliable analyses of:

- Extraction and recovery of the remaining binder without changing the chemical composition of the material, because it is believed that the activation of the remaining binder was not achieved due to the contamination of the binder recovered through solvents, for this it is intended to evaluate in the future the chemical composition of the oxidized binder through SARA fractionation, and perform thermal analysis on the material;
- Evaluation of the adhesiveness of the fine RAP material, to verify the cohesion and adhesion of the mixture, because it is believed that a large part of the consumption of binder and the rejuvenating agent is being performed by the pulverized RAP material, also evaluating the adhesiveness of the RAP aggregate with the RA; Dosing a mixture with 100% virgin materials with the same characteristics as the mixture that originated the RAP, for comparison purposes;
- To evaluate from the mechanical performance point of view, the permanent deformation through traffic simulator (DWT, and fatigue life through uniaxial fatigue test, 4-point bending fatigue, and diametral compression fatigue, and to compare the performance of the recycled mixtures with a conventional mixture.

However, the study brings contributions to the literature and the paving industry by evaluating the performance of recycled mixtures at different rates of incorporation into the mix, highlighting the limitation of the amounts of RAP to be inserted into the mixture, and the variability of the decision in the applicability of the technique for different conditions and applications. As there is maximization in some mechanical performance evaluation indicators, there is minimization in others, and the same occurs when evaluating economic and environmental indicators.

Thus, given the need to design increasingly durable pavements, and to adopt sustainable methodologies that are more economical, the results obtained in this research show that the technique of designing hot recycled asphalt mixtures with the incorporation of RAP is not only a favorable alternative based on the principle of sustainability, but also an alternative of economic cost reduction based on competitiveness for the design of flexible pavement overlays.

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