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SMA Mix with Sintered Aggregate of Calcinated Clay (SACC) and Curauá Fiber

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Abstract

The mechanical behavior of asphalt mixtures of the Stone Mastic Asphalt (SMA) type was analyzed regarding the resilient modulus (RM), indirect tensile strength (TS) and dynamic modulus (MD). In addition to the traditional materials (sand, Portland cement and Petroleum Asphalt cement (PAC)), the Sintered Aggregate of Calcined Clay (SACC), as a coarse aggregate, as well as the Curauá fiber, Ananas erectifolius also participated in the analysis. Such

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components were physically characterized, and the dosage followed the guidelines described by the National Asphalt Pavement Association (NAPA). The results indicated a decrease in the values of all the analyzed parameters (tensile strength, modulus of elasticity and dynamic modulus) with the increase of temperature. Regarding the Resilient Modulus, although different loading levels were analyzed, the mechanical behavior remained basically constant. The results of the RM/TS ratio were lower than the maximum value recommended by the Brazilian and Australian standards. The Dynamic Modulus produced increasing values with the increase in frequency and reduction in temperature, in addition to increased stiffness.

Key words: sintered aggregate of calcined clay, Curauá fiber, resilient modulus, tensile strength and dynamic modulus.

1. INTRODUCTION

Natural inputs, due to their finite availability and because they are limited in certain regions - especially stone materials - evoke the study of alternative materials, turning this into an essential research field for Civil Construction.

Regarding Pavement Engineering, asphalt mixtures of the Stone Mastic Asphalt (SMA) type contain in its composition a high participation of coarse aggregates, usually represented by stone materials. For the replacement of these natural materials, the literature mentions studies such as the use of construction and demolition waste (Pérez, Pasandín, and Medina 2012; Zou et al. 2020; Pasandín and Pérez 2013), and the use of ceramic building materials coming from bricks (Choudhary, Kumar, and Gupta 2020; Senisna and Bentebba 2017; Arabani, Tahami, and Taghipoor 2017). In the aforementioned scenario is located the Sintered Aggregate of Calcined Clay - from clay soil, studies mention that hot asphalt composites containing this alternative material have improved the mechanical properties of hardness, susceptibility to permanent deformation (Silva, Frota, and Frota 2015) and bending stiffness (Spínola et al. 2019). It should also be noted that studies have shown the satisfactory mechanical performance of formulations with these calcined aggregates regarding the tensile strength and resilient modulus, compared to mixtures containing conventional aggregates (Frota et al. 2007). With regard to the viscoelastoplastic performance, high rigidity at high temperatures and low frequencies of compositions with sintered clay aggregates are also found in the literature, thus being a promising alternative for areas with warm climates, as it is the case of the Amazon Region (Silva, Silva, and Frota 2014).

On the other hand, fibers that aim to provide stability and, also, to prevent petroleum asphalt cement (PAC) drainage (Woodward et al. 2016) are also present in asphalt mixtures of the Stone Mastic Asphalt (SMA) type. An alternative to synthetic fibers, conventionally used, is those of vegetable origin, a biodegradable material of relatively lower cost and with recycling potential (John and Thomas 2008). It should also be emphasized that adding fibers to hot asphalt formulations increases the dynamic modulus, strengthens the mastic and reduces thermal susceptibility, in addition to increasing fatigue strength and ductility (Fitzgerald 2000). Originating in the Amazon region, the natural fiber from Curauá, Ananas erectifolius, provides tensile strength and bending stiffness superior to those derived from coconut, sisal or jute, reaching physical properties close to fiberglass and flax (Zah et al. 2007).

In this context, the mechanical behavior of asphalt compositions of the Stone Matrix Asphalt (SMA) type with the addition of two alternative materials, the Sintered Aggregate of Calcined Clay (SACC), in the condition of coarse aggregate, and the vegetable fiber from Curauá, Ananas erectifolius, are studied in the present paper according to the Tensile Strength (TS), the Resilient Module (RM) and the Dynamic Module (DM).

2. MATERIALS AND METHODS

2.1. Materials

The coarse aggregate that is part of the asphalt compositions - Sintered Aggregate of Calcined Clay (SACC) - was obtained from the raw material of a typical clay soil in the North of Brazil. For its production, the process consisted of crushing solid bricks of geometry 60 mm × 10 mm × 200 mm, with two central holes of ϕ16 mm. In order to physically characterize them, the following aspects were evaluated:

granulometry (ASTM C 136), the parameters Gas, Gsb, absorption (ASTM C 128), and the Los Angeles (ASTM C 131) abrasion impact.

The additional components of the SMA mixture, such as the fine aggregate - sand - were analyzed for the parameters Gsa, Gsb and absorption, following the same guidelines used for the coarse aggregate. The Portland CP-IV Cement, specifically in the filler condition, was characterized according to granulometry (ASTM C 136) and real specific mass (ASTM C 188). Finally, regarding the bituminous binder, Petroleum Asphalt cement was applied, which the analysis was carried out by the Isaac Sabbá refinery (UN - Reman) in Manaus.

2.2. Methods

The granulometric range of the mineral composition was located within the limits established by the NAPA methodology (National Asphalt Pavement Association 2002), in which the nominal maximum size (NMS) of the adopted aggregate is 19mm **(Figure 1)**.

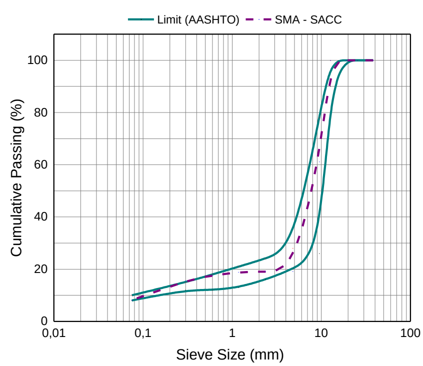

Figure 1. Granulometric curve of the composition with SACC, according to the maximum nominal size

To determine the project content, the stages of compaction of the specimens with the Superpave Rotary Compactor (CGS) were followed, considering the Los Angeles abrasion of the material and according to the NAPA standards (National Asphalt Pavement Association 2002), having used the number of turns Nproject equal to 100; and a simulation of short-term ageing (machining, transport and compaction in the field) by inserting the samples into an oven at a temperature of 150 ° C for 2 (two) hours. Bulk Specific Gravity (Gmb), according to the standards ASTM D 1188 and ASTM D 2726; a Maximum Specific Gravity (Gmm), according to ASTM D 2041, and the volumetric parameters Air Voids (AV), Voids in the Mineral Aggregate (VMA), Voids in Coarse Aggregate (VCA) and VCA of the Coarse Aggregate Fraction (VCA_{DRC}) were also obtained. It should also be observed that the percentage of fiber to prevent mastic leaking (TSR) was calculated according to the AASHTO T 305/97 standard. **Figure 2** shows part of the process for obtaining the SMA-SACC asphalt composition.

Figure 2. SMA-SACC mix

Regarding the mechanical behavior, SMA-SACC composites were evaluated according to the tests of the Tensile Strength (TS), Resilient Modulus (RM), and Dynamic Modulus performed on the Universal Testing Machine (UTM) of IPC Global.

As for the tensile strength testing by diametral compression, the assessment followed the methodology described in ASTM D6931. The test was performed at the temperatures of 25°C, 40°C and 60°C. Regarding the Resilient Modulus test, it was based on the regulations of AASHTO TP-31-96 (2000) and ASTM D7369, at the temperature levels of 25°C and 40°C; frequency of 1hz with loading period of 0.1s (load) and 0.9s (rest); and an applied load of 5%, 15% and 30% of TS. Finally, the Dynamic Modulus test followed the standards ASTM 3497-05 and AASHTO TP 62-03, in specimens with cylindrical geometry, at the temperature levels of 5°C, 25°C, 40°C and frequencies of 0.1, 0.5, 1, 5, 10 and 25 Hz.

3. RESULTS

3.1. Analysis of Aggregates and Asphalt Binder

Table 1 presents the results of the physical characterization of the coarse and fine aggregates. It is noted that SACC and residual sand presented density values within the usual ranges. In addition, the values of the Los Angeles abrasion test for SACC resulted in a value of 37.8%, within the acceptable, that is, lower than 30% (ASTM C 131). In the case of Portland cement, 100% of the sample passed through the 0.075mm sieve, classifying it as filler **(Table 2)**. In relation to its specific mass, the value was of 3.136 g/cm³.

Table 1. Physical Characterization of Aggregates

Material	Properties	Result
SACC	Bulk specify gravity (g/cm³)	2,780
	Apparent specific gravity (g/cm³)	2,760
	Absorption (%)	0,32
Fine aggregate	Bulk specify gravity (g/cm³)	2,730
	Apparent specific gravity (g/cm³)	2,615

Table 2. Granulometry (Portland Cement)

Sieve size (mm)	Limits (DNER-EM 367)	Result
0,42	100	100
0,18	95 – 100	100
0,075	65 - 100	100

Regarding the characteristics of the bituminous binder, it can be seen in **Table 3** that all results presented values within the recommendations. It is noteworthy that Penetration, Solubility in trichlorethylene and Increase in Softening Point indicated values close to the upper limits. It was also found that the sample was classified as a 50/70 PAC.

Table 3. Asphalt Binder Properties

Parameter measured	Test Method	Limits	Result
Penetration (0.1mm)	ASTM D5	50-70	69
Softening Point (°C)	ASTM D36	46	49,7
Flash Point (°C)	ASTM D92	235	318
Solubility in Trichloroethylene	ASTM D2042	99,5	99,9
Ductility	ASTM D113	60	> 100
Saybolt Furol Viscosity at 135°C (s)	ASTM E102	141	283
Brookfield Viscosity at 135°C (cp)	ASTMD 4402	274	539
Saybolt Furol Viscosity at 150°C (s)	ASTM E102	50	140,7
Brookfield Viscosity at 150°C (cp)	ASTMD 4402	112	279,8
Saybolt Furol Viscosity at 177°C (s)	ASTM E102	30-150	50,8
Brookfield Viscosity at 177°C (cp)	ASTMD 4402	57-285	96,8

3.2. Dosage

The dosage resulted in 81% for the SACC contribution in the condition of coarse aggregate, 10% for residual sand as a fine aggregate, 9% of the Portland cement as a filler, and 12.5% of PAC, considering an average to elevated traffic. The inclusion of the Curauá fiber residue corresponded to 0.3%, a percentage necessary for placing the mixture within the leaking limit established by NAPA (National Asphalt Pavement Association 2002). The volumetric parameters of this formulation, shown in **Table 4**, presented values according to those required by NAPA.

Table 4. Volumetric Parameters, SMA-SACC

Property	Requirement (NAPA)	Result
Asphalt Cement, %	6, minimum	12,5
Air voids, %	4	4
VMA, %	17, minimum	30,7
VCA (%)	Less than VCA_{DRC}	29,7
VCA_{DRC}	-	39,17

3.3. Mechanical Characterization

3.3.1. Tensile Strength (TS)

The TS values obtained for the temperature levels of 25°C, 40°C and 60°C resulted, respectively, in 690kPa, 500kPa and 130kPa. During temperature transitions, the following decreases in TS were observed: 27.53% in the transition from 25°C to 40°C, 74% from 40°C to 60°C, and an expressive result of 81.15% from 25°C to 60°C. It is noteworthy that at a temperature of 60°C, the asphalt binder presented a highly viscous behavior, resulting in a lower TS value.

Referring to the literature, there is an overall absence of studies on obtaining TS values in asphalt mixtures with SACC. However, considering the results found in the study under discussion, at a temperature of 25°C higher values are observed for compositions with coarse aggregates derived from basalt and limestone (Cao, Liu, and Feng 2013), with a percentage difference, at a temperature of 20°C, respectively, of 26.09% and 18.96%. In formulations with the presence of steel slag, the mixture with SACC presented an analogous result, that is, 690kPa, regarding the value of 700kPa (Behnood and Ameri 2012; Ahmedzade and Sengoz 2009). This result is promising, considering that steel is notorious for its beneficial properties regarding abrasion and rolling resistance, and stiffness.

3.3.2. Resilient Modulus (RM)

The SMA composition with the sintered aggregate and Curauá fiber presents, according to **Figure 3**, RM values approximately constant for different percentages of TS. Such results varied between 2700 MPa (25°C) and 1200 MPa (40°C), which provided a percentage difference equal to 55%, demonstrating the predictable decrease with the increase in temperature.

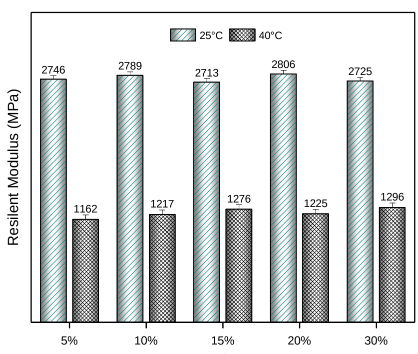

Figure 3. Resilient Modulus

For comparison purposes, although among studies using different temperatures, the values obtained in the present research were compared to analyses performed with different types of fibers, including rock wool, polyester (Lavasani, Latifi Namin, and Fartash 2015) and cellulose (Sadeghian, Latifi Namin, and Goli 2019) (**Table 5**). It can be observed that the resilient modulus of the asphalt mixtures containing SACC presented higher values, respectively, for the temperatures of 25 and 40°C, referring to the formulations with rock wool (49.23%; 94.01%), polyester (63.66%; 101.87%) and cellulose (11.68%).

Table 5. Resilient modulus with different fibers

Temperature (°C)	Curauá (30% of TS)	Rock Wool	Polyester	Cellulose
25	2725	1826	1665	2440[b]
40	1296	668[a]	642[a]	-

[a] temperature 35°C; [b] temperature de 20°C.

The RM/TS ratio was also verified, which can evaluate the behavior of asphalt mixtures regarding cracking (Santos et al. 2015). Ideally, this ratio should be the lowest possible, as it unites two fundamental concepts from a mechanical point of view: flexibility and adequate tensile strength. Based on this, the results of this correlation for the SACC for temperatures of 25 and 40°C were, respectively: 2913.043 and 2500 - below the maximum value (5,000) recommended by the Brazilian (Departamento Nacional de Estradas de Estradas de Rodagem 1994) and Australian (Main Road Western Australia 2012) norms.

3.4.3 Dynamic Modulus (DM)

In **Figures 4 and 5**, respectively, the punctual values of the Dynamic Modulus |E*|, and the Phase Angles (φ), are exposed as a function of the frequencies and temperatures. It is observed that the Dynamic Modulus grows with the increase of the load application frequency and decreases with the temperature. Confronting the most extreme points, |E *| = 1654 MPa, temperature of 5°C (25 Hz) and |E*| = 386.4 MPa, temperature of 40°C (0.5 Hz), a variation of over 4 times (4.2) in the material stiffness can be seen.

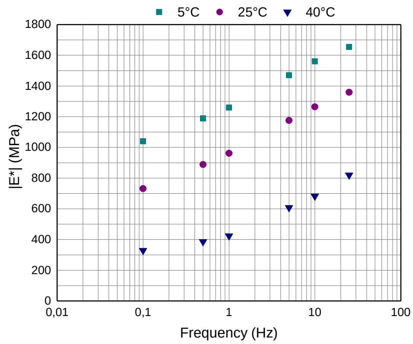

Figure 4. Dynamic modulus x frequency, SMA-SACC

Evaluating the phase angles (φ) of the SMA-SACC compositions, it appears that the highest and lowest values were, respectively, 21.03° (40°C), and 7.87° (5°C). It was also observed that the decrease in this parameter was due to an increase in frequency, especially at low temperatures. However, it is emphasized that at 40°C this parameter increased with higher frequencies. According to (Xie, Hongbin & Watson, Donald & Brown 2005), at high temperatures the effect of the aggregate stone matrix predominates.

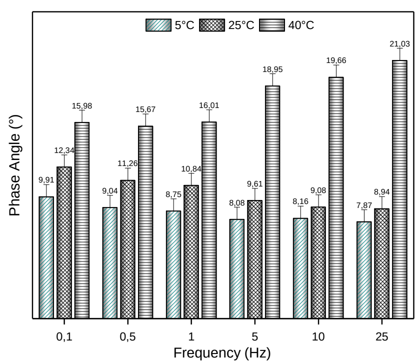

Figure 5. Phase Angle x frequency, SMA-SACC

Figure 6 shows the master curve for the SMA-SACC mixture. It was built for a reference temperature and the time-temperature superposition principle was employed, in which the DM values are displaced in relation to the loading frequency until they merge into a single curve. When observing the figure, the possibility of obtaining values of |E*| for very low and very high frequencies can be perceived, which would hardly be experimentally determined due to the limitations of the equipment typically found in laboratories. Likewise, it is possible to define relevant temperature ranges different from those tested, with the use of the referred curve.

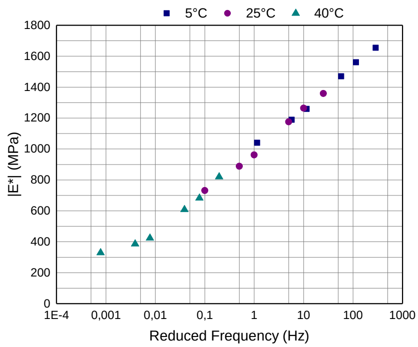

Figure 6. Master Curve, SMA-SACC

CONCLUSIONS

After analyzing the mechanical behavior of the SMA asphalt mixture, with the addition of the alternative material SACC and the fiber of Curauá, the following can be concluded:

1. The influence of temperature on mechanical behavior, that is, with its increase it is possible to visualize a decrease in tensile strength (TS) and in the resilient modulus (RM).

2. Constant behavior of the resilient modulus (RM), when the percentage of tensile strength (TS) was varied.

3. The behavior of the dynamic modulus (DM) showed to be similar to the other parameters, that is, with the increase of temperature, DM decreased.

4. Regarding the phase angles (φ), it was perceived, in general, its increase as the frequency decreased, regardless of the temperature variation.

5. Compared to further literature, regarding the studied parameters (TS, RM and DM) there were significant percentage increases in the SMA-SACC mixture.

6. By what was exposed above, the importance of the addition of natural and industrial residues into asphalt compositions is emphasized, which provides for the preservation of finite inputs,

besides to an environmentally correct destination for these by-products.

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