International
OPEN ACCESS Journal
Of Modern Engineering Research (IJMER)

Dosage of Dry Mixed Rubberized Sma by Bailey Method

José Carlos Dias Curvelo Júnior[1], Nilton de Souza Campelo[2]
Adalena Kennedy Vieira[3], José Leomar Fernandes Júnior[4]
Elias Santos Souza[5]

[1]Associate Professor, M.Sc., Department of Civil Engineering, Rondônia Faculty (FARO), Porto Velho, RO, Brazil;
[2]Full Professor, D.Sc., M.Sc. Program in Civil Engineering, Federal University of Amazonas, Manaus, AM, Brazil;
[3]Visiting Professor, D.Sc., M.Sc. Program in Civil Engineering, Federal University of Amazonas, Manaus, AM, Brazil;
[4]Full Professor, D.Sc., Department of Transport Engineering, University of São Paulo, São Carlos, SP, Brazil;
[5]Civil Engineer, M.Sc., Federal University of Amazonas, Manaus, AM, Brazil;

ABSTRACT:*This study addresses the use of Rubberized Stone Matrix Asphalt using dry process to mix the crumb rubber and mineral aggregates through the Bailey method of aggregates dosage. It used two rubber particle sizes, commercially known as G1 and G3, ranging in dimensions from 4.75 to 2.40 mm and from 2.40 to 0.60 mm, respectively, at the same 2% (in mass) content in the mixtures. The mixes with and without crumb rubber (control one) were submitted to laboratorial tests in order to determine Marshall parameters, resilient modulus, fatigue life and moisture susceptibility. The results indicated that the control mixtures presented higher values of Marshall stability, resilient modulus, indirect tensile strength and fatigue life, while rubberized mixtures showed higher values of air voids volume, flow value and tensile strength ratio. Among the rubberized mixtures, the ones with the finer rubber particle size showed higher values of resilient modulus, indirect tensile strength and fatigue life and tensile strength ratio in relation to those coarser rubber size. For the control mixture, there were higher values of resilient modulus and indirect tensile strength when compared to rubberized mixture values, with differences in the resilient modulus and indirect tensile strength values close to 50% and 37% and to 47% and 32% for coarser and finer rubber particle sizes, respectively. The absence of a curing time in the dry process, higher air void volume values (between 13% and 50%), the setting of a constant crumb rubber value of 2% in the blend, and even the grading through the Bailey method are attempts to justify those abnormal behaviours of rubberized mixtures in relation to control mixtures. Nevertheless, the rubberized blend had better performance than the control mixture in the case of moisture susceptibility.*
KEY WARDS:*Crumb rubber; Stone Matrix Asphalt (SMA); rubberized SMA; fatigue life; moisture susceptibility; resilient modulus; Marshall stability; dry process, Bailey method.*

Date of Submission: 14-01-2020 Date of acceptance: 31-01-2020

I. INTRODUCTION

The increasing number of vehicles around the world generates millions of used tyres every year. Current regulations prohibit the stockpiling of used tyres because they can be a fire hazard source and pose a potential threat to human health and potentially increase environmental risks. Because of this, the placement of discarded tyres in landfills and similar waste dumps has been prohibited [1-4]. Waste tyre rubber has been used as an additive for constructing asphalt pavement for decades because of its elastic properties, which had the potential to improve the skid resistance and durability of asphalt mixtures [5]. Crumb Rubber (CR) Modifier is the common name used to identify the recycled tyre rubber (RTR) particles used to modify bitumen [1, 5-7].

CR has been used to modify asphalt mixtures usually by employing two different processing methods. The first is the ‘wet process’, whereby fine rubber is blended with hot bitumen to produce a ‘rubberized bitumen’ binder. The second means of rubber modification is through the ‘dry process’, which substitutes a proportion of the mix aggregate with coarse rubber, thereby causing the rubber to function essentially as an elastic aggregate within the mixture [8-9]. The majority of research pertaining to the dry process generally assumes that the reaction between the rubber and bitumen in the mixture is insignificant or that does not completely react with bitumen [3, 5, 10]. Compared to the wet process, the reaction time in the dry process is considerably less (maximum six hours) and slower due to the larger rubber particle sizes (RPS) and that the fundamental difference between the wet process and dry process is that in the wet process, the finer RPS (0.075 mm to 1.2 mm) are charged into the bitumen at high temperature prior to mixing with the aggregate to allow reaction between them to produce modified bitumen, and in the dry process, coarser RPS (0.4 to 10 mm) are added directly to the mixtures with an assumption that the CR is solely part of the aggregate and that the reaction between bitumen and crumb rubber is negligible [11].

After 1981, 20% of the originally used coarse rubber grading was replaced with fine crumb rubber passing 0.85 mm sieve size [5]. Typically, larger RPSs between 6.4 and 0.85 mm are used to substitute for fine aggregates at a 1%-3% replacement rate [11]. Mixtures with fine rubber gradation (1.18 to 0.15 mm) performed better with respect to permanent deformation in comparison to conventional asphalt mixtures due to the binder modification [12]. The addition of CR or other modifiers in conventional dense-graded mixes have either shown poor performance or completely failed due to improper mix designs. The reason for this unsuccessful blend of dense gradation and addition of CR can be attributed to insufficient voids in the mineral aggregates that is required to accommodate CR inclusions in the dense-mix matrix. However, the literature notes that CR could be successfully engineered with an unconventional aggregate skeleton by using gap and/or open-graded gradation since these gradations provide enough room for CR particles to coalesce within the mix matrix [6,11]. In mixtures modified with 1%, 2% and 3% of CR to produce Rubberised Stone Mastic Asphalt (RSMA) and concluded that in a gap graded mixture, if the spaces are inadequate, the rubber will resist compaction, and the resultant pavement will have excessively high AVV content and lack durability. Therefore, by opening up the aggregate gradation, the problem can be reduced [8].

In dry process CR mixes, there is an absorption of asphalt by the CR, which increases the asphalt content requirements for the mix to attain the required volumetric properties, mainly AVV targets [3, 13]. Hence, in rubberized SMA mixes, the optimum asphalt content is larger than that of SMA control mixes, without CR [14]. The optimum asphalt content (OAC) required to reach a certain minimum void level for rubber-modified mixes depends on rubber and aggregate gradation and rubber content [15]. As the CR content is increased, more bitumen is absorbed, which in turn increases the OAC of the mix [16]. In general, the laboratory air voids volume (AVV) for CR mixtures are recommended to range from 0 to 4% maximum depending on the traffic level of the facility being designed (low traffic: 2 to 3%; medium: 3% maximum, and high: 4% maximum) [15]. When the RPS decreases, the AVV also decreases [17-18]. Gap-graded asphalt rubber mixtures (GGAR) can have larger AVV than typical values for a conventional SMA [14]. RSMA have lower average AVV than the control SMA [19]. Bulk specific gravity (GMB), Marshall stability (STA), flow value (FLV) and OAC of asphalt mixtures are affected by the addition of CR and because the GMB of rubber is far less than that of aggregate, the GMB of CR asphalt mixtures decrease with the increase in rubber content [3, 17, 20]. Voids in the mineral aggregate (VMA) increases and voids filled with asphalt (VFA) decreases with increasing rubber percentages in CR asphalt mixes [13] and RPS [17]. For each 1% of increase in the AVV value, FL will be reduced by 40% [21].

The density of the dry-process CR mix is slightly lower than that of conventional mixes due to the resiliency of the rubber, which causes decompaction and reduced mix density [20, 22]. However, in the words of the last author, the compaction effort does not appear to have any more significance on the CR mixtures than it had on the control asphalt mixtures. Analysing the performance of CR incorporation between dry and wet methods. In relation to the dry process, those authors claimed that the mixes did not effectively react with the asphalt binder, had poorer compaction (i.e., higher AVV content), poor distribution of the CR through the mix, and poorer cohesion between the binder and the aggregate, leading to increased moisture sensitivity. In addition, the differences in performance between the dry and wet processes decreased in significance with decreasing rubber content and decreasing RPS [23]. Compaction of dry process mixes may still require a hold time while the specimens cool to prevent expansion after the load is released. Adding CR and increasing its content to the mixture, the unit weight and specific gravity decreased [17]. A CR asphalt mixture is more susceptible than conventional mixtures to problems in preparation and compaction because of the need to add and control a third ingredient that has a major effect on overall mix properties and performance [15].

Adding CR and increasing its percentage in the dry process mixtures, the STA results are better than those of the conventional mix [24-26]. Nevertheless, there are some studies that found the opposite; i.e., as rubber was added and its percentage in the mixture increased, the STA of the samples diminished [2-3, 9, 13, 15, 17-18] or there was no difference [14]. That fact can be explained by considering the structure of the specimen [18]. An asphalt specimen is composed of an assembly of aggregates and bitumen, where intergranular forces are transmitted through points of contact. When rubber is added, the resulting mixture is not always homogeneous at all contact points due to the size and shape of the rubber. Due to lower compressive strength and higher elasticity of rubber [3], the FLV decreases with the increase in rubber contents [29] or there was no difference [14]. In the opposite sense, [17] claimed that the addition of CR into asphaltic concrete using the dry process method generally increased the FLV regardless of the RPS used, as confirmed by [15]. Rubberized SMA has slightly lower FLV than control SMA [19].

Several test procedures and theories for determining the moduli of asphalt mixtures are available in the literature. Among these moduli are Young's modulus, resilient modulus, complex modulus, dynamic modulus, etc. [39]. The dynamic stiffness (stiffness modulus or resilient modulus - MR) is a measure of the load-spreading ability of the bituminous layers; it controls the levels of the traffic-induced tensile strains at the underside of the lowest bituminous bound layer, which are responsible for fatigue cracking, as well as the stresses and strains induced in the subgrade that can lead to plastic deformations. Asphalt concrete should have high stiffness to be able to resist permanent deformation. On the other hand, the mixtures should have enough tensile stress at the bottom of the asphalt layer to resist fatigue cracking after many load applications. The dynamic stiffness can be computed by indirect tensile modulus test, which is a quick and nondestructive method [27]. The addition of CR reduces the MR and increasing the RPS reduces the MR of the porous asphalt mixtures substantially [28]. The dry process mixes show a decrease in the MR when CR is added and increased in the mixes [13]. Modified bitumen improves the MR of asphalt mixtures compared to the control mixtures due to higher viscosity and thick bitumen films leading to better resilience properties [29]. In addition, the MR of reinforced SMA samples containing various contents of CR is significantly high in comparison with that of nonreinforced samples [10, 16]. Nevertheless, MR is significantly higher for the control mixture than for modified CR mixes [30]. Additionally, MR generally decreases with increasing AVV, while [15] said that mixtures with finer rubber gradations has higher MR than do mixtures with coarser rubber gradations. In general, increasing the RPS decreases the indirect tensile strength (ITS) of the mixtures, and ITS values were less than the control ones [13, 20, 24, 28, 30]. According to [20], the reduction in ITS values is due to cohesion and, in turn, may be due to adhesion problems between the CR and the binder.

The addition of CR by the dry process, mainly in rubberized SMA mixes, enhances the mechanical performance of these mixes and their resistance to fatigue and deformation, which are the main causes of cracking, and exhibit significantly higher fatigue life (FL) compared to the mixtures without CR [8, 10, 14-16, 26-27, 31]. According to [16], the resistance of CR mixes to the generated horizontal tensile stresses decreases the formation of vertical cracks and prevents these cracks from propagating along the diameters of asphalt samples. This in turn improves the FL of reinforced samples. Analysis of the fatigue test data indicated that despite significant reductions in stiffness, CR mixtures maintain better FL compared to conventional asphalt mixtures [22]. Moisture susceptibility (MS) of asphalt mixtures, generally called stripping, is one of the major concerns in bituminous pavements and can be considered as a degradation of the mechanical properties of the asphalt due to the action of moisture or water, causing serious distresses in asphalt pavement. That distress is often associated with high concentrations of fine aggregate particles since these can have a detrimental action on asphalt mixtures because of their impact on mixture stiffness and air void content. In addition, MS is normally associated with the loss of adhesion [28] between asphalt binder and aggregate and/or loss of cohesion within the binder mainly due to the presence of water [32-34]. The results of their study showed that the SMA mixtures are not prone to moisture damage [33]. Nevertheless, [22] and [30] concluded that CR mixtures were found more susceptible to moisture induced damage compared to unmodified mixtures. Additionally, Tensile Strength Ratio (TSR) values for CR mixes were significantly reduced compared to the control specimens. In addition, Modified Lottman Test (MLT) results indicated that the addition of CR did not improve the MS performance. Highly compacted CR asphalt mixtures (4% target air voids) are more susceptible to moisture than conventional mixtures irrespective of rubber content and compaction effort, with the degree of susceptibility primarily depending on the amount of rubber in the mixture rather than the difference in compaction; this behaviour is different than conventional mixtures where, as expected, poorly compacted mixtures were found to be more susceptible to moisture than well compacted mixtures [11, 22].

Based on the results of the works described in the previous paragraphs, this present study addresses the use of Rubberized Stone Matrix Asphalt (RSMA) utilizing two rubber particle sizes in the mixtures by dry process. In order to mix the CR and mineral aggregates it was used the Bailey method of aggregates dosage. The mixes with (RSMA) and without CR (control one) were submitted to laboratorial tests in order to determine Marshall parameters, resilient modulus (MR), fatigue life (FL) and moisture susceptibility (MS). The results of the laboratory tests will be discussed in the next sections.

II. MATERIAL AND METHODS

2.1 Origin of Materials.

The coarse and fine aggregates (crushed basalt) came from a quarry named "Pedreira 29", located in the city of São Carlos, State of São Paulo, Brazil, on the Luiz Augusto de Oliveira highway, km 148.90. The crumb rubber (CR) was supplied by a company specializing in crushing and recycling tire waste (UtepBrasil), located in the city of Guarulhos, State of São Paulo. Two different types of rubber particle sizes, commercially known as G1 and G3, most ranging in dimensions from 4.75 to 2.40 mm and from 2.40 to 0.60 mm, respectively, were used as shown in Figure 1. The asphalt cement (AC - 30/45 penetrating grading) came from the Paulínia Refinery (REPLAN), which is located in the city of Paulínia, State of São Paulo. The materials used in this research and their respective origins are listed in Table 1.

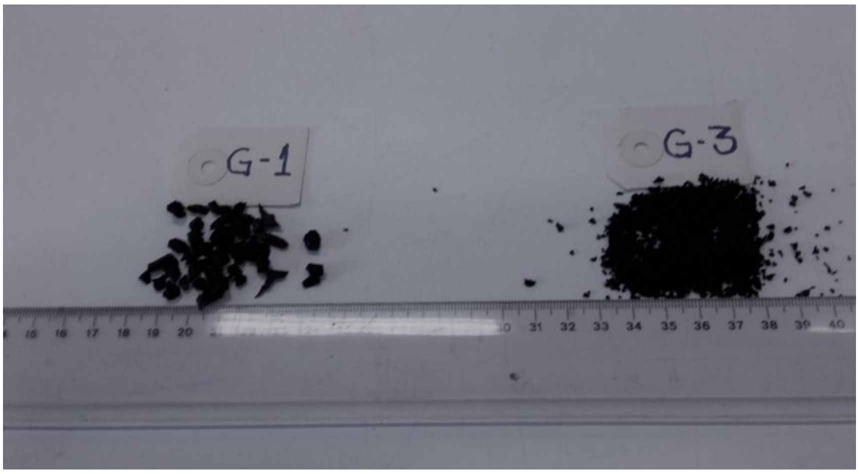

Figure 1. G1 and G3 crumb rubber particle sizes

Table 1. Provenance of SMA component materials.

Material	Origin
#1-CA (coarse)	Quarry “Pedreira 29” (22°03’37,8”S / 47°52’40,52”W)
#2-CA (coarse)	Quarry “Pedreira 29” (22°03’37,8”S / 47°52’40,52”W)
#3-CA (coarse)	Quarry “Pedreira 29” (22°03’37,8”S / 47°52’40,52”W)
#1-FA (fine)	Quarry “Pedreira 29” (22°03’37,8”S / 47°52’40,52”W)
#2-FA (fine)	Quarry “Pedreira 29” (22°03’37,8”S / 47°52’40,52”W)
MF (filler)	Quarry “Pedreira 29” (22°03’37,8”S / 47°52’40,52”W)
G1/G3 (crumb rubber)	Utep Brasil (23°28'13.73"S / 46°28'50.37"W)
Asphalt cement (AC 30/45 grading)	REPLAN Refinery (22°43'46.18"S / 47° 8'52.63"W)

2.2. Characterization of Materials.

Two equal grain-size proportions were adopted with CR - named the MA-G1 and MA-G3 mixtures, using G1 and G3 crumb rubber, respectively - and one without CR, named the MA mixture (this analysis as reference), all with the same amount of asphalt cement (AC). In the moulding of the samples, the CR replaced part of the mineral aggregates in a fixed amount of 2% of the total mass of the mixture. No natural fibres were used since the work experience in the field of a similar SMA mixture showed good workability and no draindown, even without the addition of the natural or synthetic fibres in the blends. At the end, the results were compared between the mixtures with and without CR according to the physical and mechanical tests performed.

From the size particle analysis of each aggregate, the Bailey method was used to determine the optimum composition of each mixture (MA, MA-G1 and MA-G3). All aggregates used in the asphalt mixtures were tested according to the standards described in Table 2, mainly the Brazilian highway standards, which are most similar to known international standards. In relation to CRs, these materials were submitted to sieve analysis and apparent specific gravity, while CA was submitted to complete characterization (penetration, Saybolt-Furol and Brookfield viscosities, ductility, specific gravity, etc.). Table 3 shows the AC properties used in the mixtures.

Table 2. Aggregate characterization tests.

Material	Brazilian Standard	Title	Acceptance Parameter	Similar International Standard
Coarse Aggregate	NBR NM 53/2009	Coarse aggregate - Determination of the bulk specific gravity, apparent specific gravity and water absorption	Greater than 1,80 and 2,70 g/cm^3;less than 1%, respectively	ASTM-T-85
Coarse/Fine Aggregate	NBR NM 248/2003	Aggregates - Sieve analysis of fine and coarse aggregates	Within granulometric range	ASTM-C136 / C136M-14
Fine Aggregate	NBR NM 52/2009	Fine aggregate - Determination of the bulk specific gravity and apparent specific gravity	Greater than 1,60 and 2,60 g/cm^3, respectively	ASTM-C128-01
Filler	NBR NM 23/2001	Portland cement and other powdered material - Determination of apparent specific gravity	Greater than 3,00 g/cm^3	ASTM-C188-09

Table 3. Properties of asphalt cement (AC – 30/45 penetrating grading) used in the mixtures.

Brazilian Standard	Test	Unity	Similar International Standard	AC 30/45
NBR 14756	Apparent specific gravity, 25 °C	g/cm^3	AASHTO T 228	1.003
NBR 6576	Penetration, 25 ºC, 100 g, 5 s	0.1 mm	AASHTO T 49	35
NBR 14950	SSF Viscosity, 135 ºC	s	AASHTO T 72	192
NBR 14950	SSF Viscosity, 150 ºC	s	AASHTO T 72	90
NBR 15184	Brookfield Viscosity, 135 ºC, sp21, rpm 20	cP	AASHTO T 316	374
NBR 15184	Brookfield Viscosity, 150 ºC, sp21, rpm 20	cP	AASHTO T 316	203
NBR 6560	Softening point	ºC	AASHTO T 53	52
NBR 6293	Ductility, 25 ºC	cm	AASHTO T 51	60

2.3. Dosage Method of the SMA Mixtures.

In Brazil, the Superior Performing Asphalt Pavements (Superpave) methodology is still not sufficiently widespread in everyday practical pavement services. Therefore, asphalt concrete studies were developed through the traditional Marshall method. After the characterization of all components of asphalt concrete, the materials were classified in the "C" granulometric range limits of Brazilian highway specifications following the Marshall dosage method, as shown in Figure 3. The Bailey method was adopted to calculate percentages of each aggregate that must be mixed to obtain the proportion of the resulting mixture that satisfies those limits.

The curves obtained were in the area defined by the two curve limits of the "C" range, minimum and maximum. After fixing the particle size distribution of aggregates of the mixture, the probable optimum asphalt content (OAC) was estimated by the expression derived from the work of Duriez [35] based on the specific surface of the aggregates:

$$S = \frac{0.17G + 0.33g + 2.30A + 12a + 135f}{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where: S = specific surface area of aggregate (m^2/kg); G = percentage retained on sieve 9.5 mm; g = percentage passing on sieve #9.5 mm e retained on sieve 4.8 mm; A = percentage passing on sieve #4.8 mm e retained on sieve 0.3 mm; a = percentage passing on sieve #0.3 mm e retained on sieve 0.074 mm; f = percentage passing on sieve 0.074 mm.

Then, the probable OAC was calculated, using the following expression:

$$T_{ca} = m\sqrt[5]{S} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where Tca = OAC in relation to the mass of the aggregates (%); m = richness modulus of asphalt cement, varying from 3.75 (wearing course more rigidus) to 4.00 (wearing course more flexible).

If the mean bulk specific gravity of the total aggregate is less than 2.60 or greater than 2.70, then the content obtained in the previous item should be corrected by the following expression:

$$T'_{ca} = \frac{2{,}65 T_{ca}}{\delta_{am}} \quad (3)$$

where T´ca = corrected OAC in relation to the mass of the aggregates (%); δ_{am} = mean bulk specific gravity of the total aggregate.

Finally, the OAC is calculated in relation to the entire mixture:

$$P_{ca} = \frac{100 T_{ca}}{100 + T_{ca}} \quad \text{or} \quad P_{ca} = \frac{100 T'_{ca}}{100 + T'_{ca}} \quad (4)$$

where P_{ca} = final value of OAC in relation to the total mixture (%).

In the Bailey Method [36-37], the sieve that defines coarse and fine aggregate is known as the primary control sieve (PCS), and the PCS is based on the nominal maximum particle size (NMPS) of the aggregate blend.

$$PCS = NMPS \ x \ 0.22 \quad (5)$$

where NMPS = one sieve larger than the first sieve that retains more than 10%.

The fine aggregate is broken down and evaluated as two portions. To determine where to split the fine aggregate, the same 0.22 factor used on the entire gradation is applied to the PCS to determine a secondary control sieve (SCS). The SCS then becomes the break between coarse sand and fine sand. The fine sand is further evaluated by determining the tertiary control sieve (TCS), which is determined by multiplying the SCS by the 0.22 factor.

An analysis is performed using ratios that evaluate packing within each of the three portions of the combined aggregate gradation. Three ratios are defined: Coarse Aggregate Ratio (CA Ratio), Fine Aggregate Coarse Ratio (FA_c Ratio), and Fine Aggregate Fine Ratio (FA_f Ratio). Equations 6, 7 and 8 indicate expressions to calculate those ratios, and Table 4 shows the recommended ranges of those ratios.

$$CA \ Ratio = \frac{(\% \ passing \ \ HS - \% \ passing \ \ PCS)}{(100\% - \% \ passing \ \ HS)} \quad (6)$$

where HS (half sieve) = one half the NMPS.

$$FA_c \ Ratio = \frac{(\% \ passing \ \ SCS)}{(\% \ passing \ \ PCS)} \quad (7)$$

$$FA_f \ Ratio = \frac{(\% \ passing \ \ TCS)}{(\% \ passing \ \ SCS)} \quad (8)$$

Table 4. Recommended ranges of aggregate ratios.

Ratio	NMPS (mm)					
	37.5	25.0	19.0	12.5	9.5	4.75
CA	0.80-0.95	0.80-0.85	0.60-0.75	0.50-0.65	0.40-0.55	0.30-0.45
FA_c	0.35-0.50	0.35-0.50	0.35-0.50	0.35-0.50	0.35-0.50	0.35-0.50
FA_f	0.35-0.50	0.35-0.50	0.35-0.50	0.35-0.50	0.35-0.50	0.35-0.50

The mixtures were carried out with and without CR from the use of an excel spreadsheet, which calculated the proportions between each aggregate to reach the desired grain size curve (Figures 3 and 4) by the Bailey method.

2.4. Production of SMA samples in the Laboratory.

The incorporation of two CR (G1 and G3) was made by the dry process in an amount of 2%, replacing part of the mineral aggregates. The two CR mixtures were compared with a conventional blend (without CR) using the same proportion of aggregates.

Based on the Saybolt-Furol viscosity test, working temperatures of the AC and aggregates were found for each mixture, taking care to observe the limits set out in the Brazilian highway standards, which admits as an AC heating temperature that corresponds to (85 ± 10) SSF (seconds Saybolt-Furol) and as a compaction temperature of the mixture one in which the AC exhibits a viscosity of (140 ± 15) SSF. In addition, the working temperature of the aggregates should be 10 °C to 15 °C higher than that of the AC.

Each specific amount of aggregate was weighed individually, mixed and heated in a pot at a temperature of 170 °C. Furthermore, the added AC was also weighed as the amount found in each mixture at a temperature of 155 °C. The procedure was to mix the components (aggregates + AC) at a temperature of 146 °C for approximately two minutes (without curing time) until completely covering the aggregates with AC. This mixture was then placed in the mould and compacted mechanically with 75 blows on each side of the specimen. Next, the specimens were left at rest for 24 h at room temperature. After that, the specimens were immersed in a water bath at 60 °C for two hours. Then, they were placed in the compression mould and positioned in the

Marshall machine, and both rupture load and flow value were determined. Thus, all physical and mechanical parameters of SMA mixtures were determined by the Marshall method.

It is noteworthy that three specimens were cast for each AC content to find the optimum asphalt content (OAC) of each mixture (MA, MA-G1 and MA-G3), whose range varied from 4.9% to 6.9%, at each interval of 0.5%.

2.5. Physical and Mechanical Properties of SMAs Mixtures.

The arithmetic mean values of physical and mechanical Marshall parameters of the mixtures were determined, i.e., bulk specific gravity (GMB), theoretical maximum specific gravity (TMG), air void volume (AVV), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), asphalt-void ratio (AVR), Marshall stability (STA) and flow value (FLV). The test results were plotted in graphs as a function of the variation of AC content obtaining the characteristic curves of the Marshall test. The optimum contents of AC adopted were those with an AVV value of 4%.

Three samples with cylindrical forms were moulded for the determination of the static indirect tensile strength (ITS) by diametrical compression for each type of mixture. The ITS individual value was obtained through the expression:

$$\sigma_t = \frac{\mathrm{T}}{\pi \mathrm{rh}} \qquad (9)$$

where σ_t = individual static ITS (kPa); T = static rupture load (kN); r = sample radius (m); h = sample height (m).

Three samples were moulded for determining the resilient modulus (RM) of each mixture. This mixture was then placed in the mould and compacted mechanically with 75 blows on each side of the sample. Then, a vertical load F was applied repeatedly until achieving a stress less than or equal to 20% of the ITS with a frequency of 60 cycles per minute and a duration of 0.10 s with 0.9 s of rest. The horizontal displacements were recorded during the load application F. The RM adopted was the arithmetical mean value determined at 300, 400 and 500 load application F.

Hence, the value of the RM was determined by the expression:

$$\mathrm{RM} = \frac{F}{\delta h} \times (0{,}9976\mu + 0{,}2692) \qquad (10)$$

where RM = individual resilient modulus (MPa); F = cyclic vertical load diametrically applied on specimen (N); δ = elastic strain recorded for 200, 400 and 500 load applications (mm); h = sample height (mm); μ = Poisson's ratio.

The fatigue test was performed to define the number of loading repetitions as a function of controlled stresses in diametrical compression samples with the load applied at a frequency of 1 Hz, with 0.10 s of repeated loading duration through the same resilient modulus equipment, increasing in tensile strain until the specimen is completely disrupted at a constant temperature of 25 °C. The fatigue curve was determined in four stress levels (10%, 20%, 30% and 40% of the static ITS) with two specimens per level. The fatigue resistance was evaluated according to the fatigue curves generated by testing, which introduces the relationship between fatigue strength and fatigue life. The fatigue equation in this study was calculated using the formula given in the following equation [14]:

$$\log(N_f) = n \times log(\sigma_f) + k \qquad (11)$$

where N_f is the fatigue life (in cycles); σ_f is the fatigue stress (MPa), i.e., the tension stress applied during the test. The equation provides a linear relationship between them using a denary logarithm, in which 'n' is the gradient and 'k' is the intercept. High values of n indicate greater sensitivity to cracking, which infers poor fatigue resistance. Conversely, the larger k is, the higher the fatigue life is and the longer the fatigue life.

The moisture induced damage test was carried out using the modified Lottman method by moulding six similar samples at the OAC, with AVV of 7%; initially, a first set of three specimens were separated and placed in plastic bags for protection and immersion in a 25 °C water bath for 2 h; a second set of three of these samples was placed in a vessel with distilled water and vacuum being applied at a pressure of 250-650 mm Hg for 5 to 10 min in order to obtain a degree of saturation between 70% and 80%; the tensile strength test was performed on both the groups of three unconditioned (TS_u) and conditioned (TS_c) samples. Finally, the tensile strength ratio (TSR) was determined, which is the ratio between TS_c and TS_u. A minimum TSR value between 0.7 and 0.80 is often used as a standard. Table 5 describes the Brazilian standards used in the tests and their correspondents to international standards; nevertheless, it should be considered that specific SMA mixtures have not yet been standardized in Brazil; because of this, technical specifications of SMA mixtures recommended by NAPA [38] were used. Figure 2 shows the flowchart of laboratory activities developed to determine the physical and mechanical properties of SMA mixtures.

Table 5. Mechanical characterization tests carried out on SMA asphalt mixtures.

Brazilian Standard	Title	Acceptance Parameter(*)	Similar International Standard
DNER – ME 043/1995	Asphalt mixtures - Marshall test	OAC≥ 6% STA ≥ 6 kN 3% <AVV< 4%	ASTM D5581-07a
NBR 16018/2011	Asphalt mixtures - Stiffness determination by repeated load indirect tension test	--	ASTM D4123-82
NBR 15087/2012	Asphalt mixtures — Determination of tensile strength by diametrical compression	≥ 0,65 MPa	ASTM D 6931-17
DNER-ME (provisional standard)/2017	Hot mixed asphalt concrete - fatigue under repeated loading, constant tension, using the indirect tension test	--	ASTM D4123-82
NBR 15617/2015	Asphalt mixtures - Determination of moisture induced damage	TSR≥ 70%	AASHTO T 283

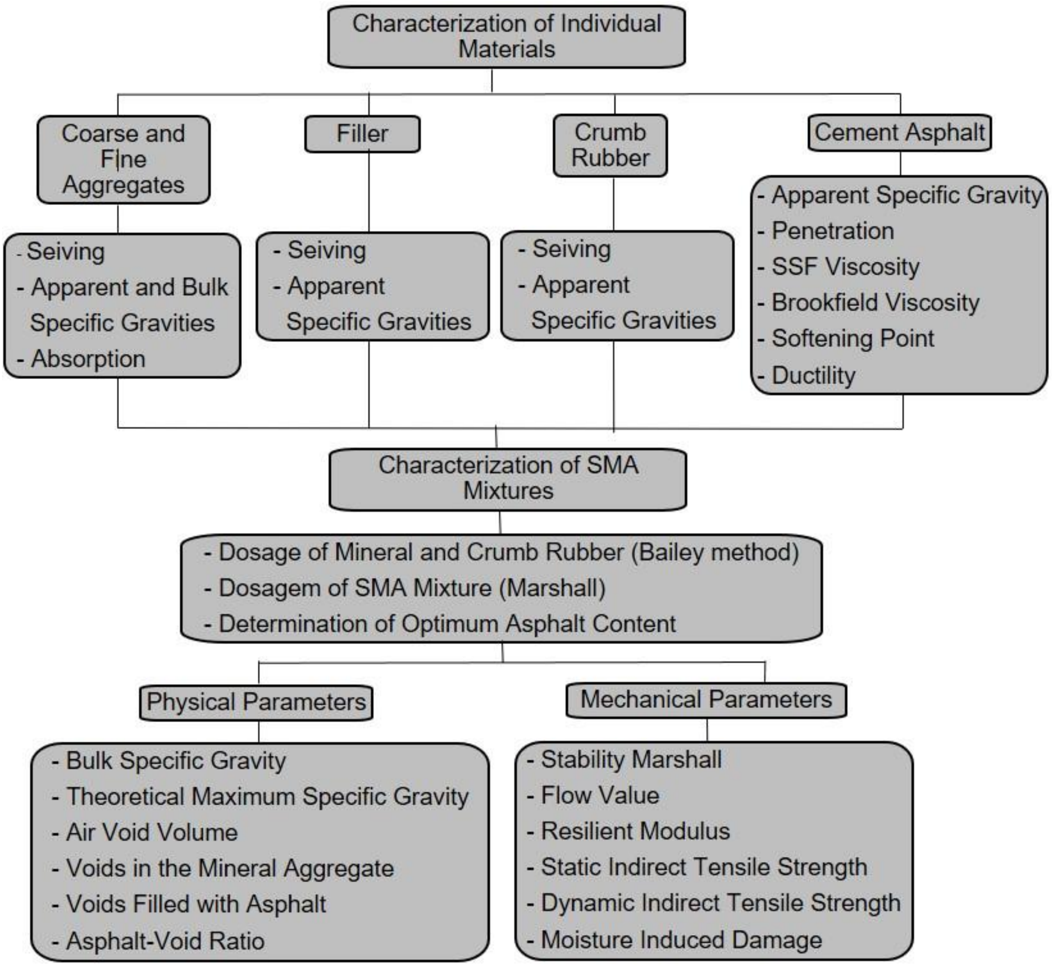

Figure 2. Flowchart of the laboratory tests.

III. RESULTS AND DISCUSSIONS

3.1. Characterization of Materials.

The granulometric curves of the mineral aggregates, the "C" range maximum and minimum limits of the Brazilian highway specification and the resulting aggregates mixture by the Bailey method are shown in Figure 3. Table 6 shows the resulting granulometric composition of the mineral aggregates with and without the addition of CR. Table 7 presents the bulk, apparent and effective specific gravities and the aggregate absorption.

Table 6. Granulometric composition of mineral aggregate mixtures with and without CR addition.

Aggregate	Mixture Designation		
	MA (%)	MA-G1 (%)	MA-G3 (%)
#1-CA	0,0	0,0	0,0
#2-CA	24,3	24,3	24,3
#3-CA	11,2	11,2	11,2
#1-FA	17,7	17,7	17,7
#2-FA	44,8	44,8	44,8
MF (Hydrated Lime)	2,0	0,0	0,0
CR G1/G3	0,0	2,0	2,0
% Total	100	100	100

Table 7. Bulk, apparent and effective specific gravities and absorptions of mineral aggregates and CR.

Aggregate	Specific Gravity (g/cm^3)			Absorption (%)
	Bulk	Apparent	Effective	
#1-CA	2,835	2,987	2,911	1,8
#2-CA	2,840	3,006	2,923	2,0
#3-CA	2,837	2,993	2,915	1,8
#1-FA	2,754	3,011	2,882	3,1
#2-FA	2,827	2,987	2,907	1,9
MF	--	3,000	--	--
CR G1/G3	1,150	--	--	--

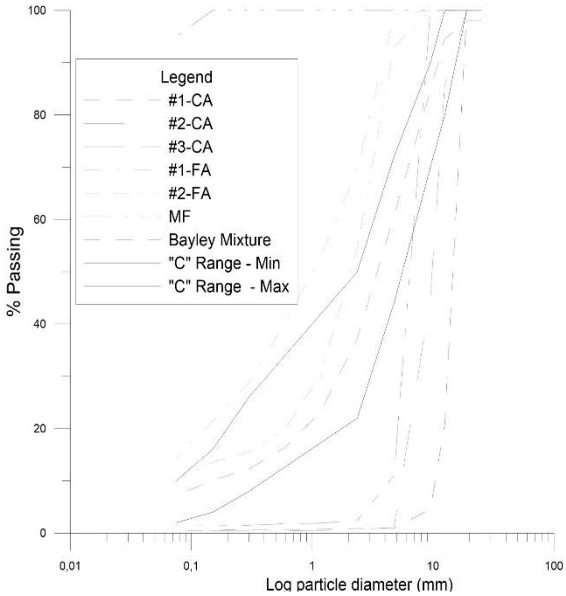

Figure 3. Grain-size distribution and limits curves of mineral aggregates.

It should be noted that CR mixtures have the same granulometric composition, differing only in the grain size of the CR, G1 and G3, the first one having a slightly coarser size. Figure 4 shows the control points of the combined mixture, followed by the Bailey method, which serves as delimiters to establish the number of voids resulting from the blending, in addition to the restriction zone that has a delimitation between 4.75 and 0.3 mm in diameter, in which the resulting curve should avoid going through it due to the large amount of fine sand causing a sensitive structure and the high permanent deformation, making it difficult to be compacted in the field.

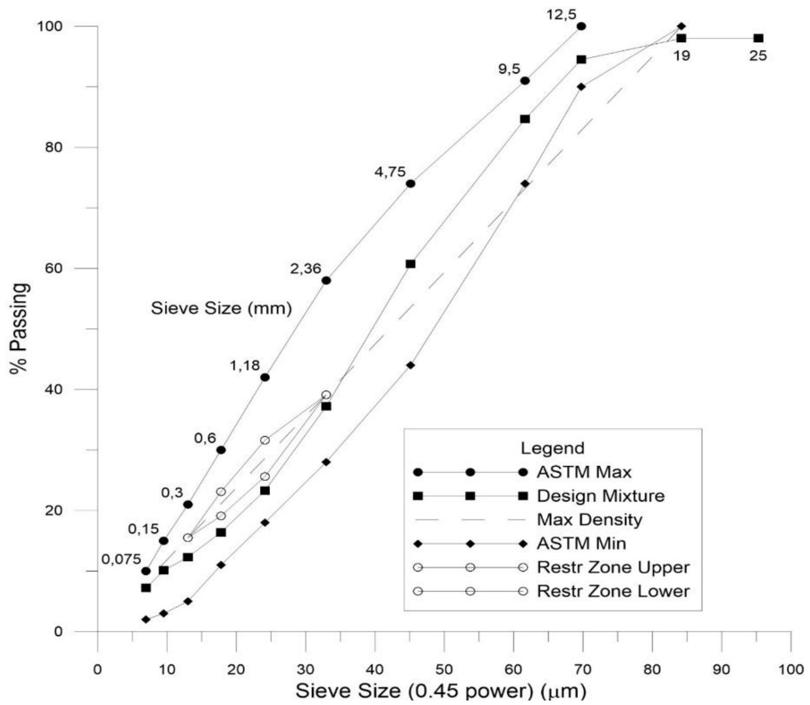

Figure 4. Granulometric distribution of the resulting mixture by the Bailey method.

3.2. Physical and Mechanical Characteristics of Mixtures.

Tables 8 to 10 show the results for the Marshall parameters of the SMA mixtures, without (control) and with CR (RSMA), referring to the GSA, GSB, STA, FLV, AVV, AVR, VMA and VFA, as a function of AC content. As a general rule, OAC corresponds to an AVV of 4.0%. Thus, the OAC of the MA, MA-G1 and MA-G3 mixtures are 5.4%, 6.0% and 5.9%, respectively; that is, RSMA mixes have higher OAC content than control mixtures (as corroborated by [3, 13, 14, 15,16]). In relation to both RSMA mixes, the coarser RPS (MA-G1) led to a slightly higher AC content than the finer (MA-G3) in the blend.

It is verified that increasing OAC, FLV, AVR, VMA and VFA also increase continuously; in contrast, GSA and AVV decrease continuously. However, in the case of GSB and STA, they increase to the point where the OAC is reached and then decrease. All these tendencies were verified in all mixtures. It can be observed that the addition of CR to the blend diminished the bulk and apparent specific gravity [17]. STA values of the control mix were higher than RSMA blends [2-3, 9, 13, 15, 17-18], and between both RSMA mixes, the coarser RPS exhibited the higher STA value, contrary to [9]. For the RSMA mixes, AVV values were higher than control values: ranging upward between 16% and 50% for the coarser and between 13% and 46% for the finer blend in relation to the corresponding AC content. These AVV increases in RSMA mixes by the dry process were expected and can be explained by poorer compaction in the mixtures [23] or by a lack of curing time needed to complete the swelling and stabilization process of the CR in the asphalt mixture [2]. The high AVV values in the RSMA blends will reflect the mechanical properties of the mixtures, as will be observed later. In the case of FLV, the control mix had a lower value than the RSMA mixes, as confirmed by[17].

Table 8. Marshall parameters for SMA mixtures without CR as aggregate (MA).

OAC (%)	GSA (g/cm^3)	GSB (g/cm^3)	STA (kN)	FLV (mm)	AVV (%)	AVR (%)	VMA (%)	VFA (%)
4.4	2.659	2.495	11.7	2.46	6.2	63.9	17.1	10.92
4.9	2.635	2.513	12.3	2.64	4.6	72.6	16.9	12.27
5.4	2.625	2.520	14.0	2.70	4.0	77.2	17.6	13.59
5.9	2.607	2.518	10.4	2.85	3.4	81.3	18.2	14.80
6.4	2.578	2.516	8.8	3.00	2.4	86.9	18.5	16.08

Table 9. Marshall parameters for SMA mixtures with CR (G1) as aggregate (MA-G1).

OAC (%)	GSA (g/cm^3)	GSB (g/cm^3)	STA (kN)	FLV (mm)	AVV (%)	AVR (%)	VMA (%)	VFA (%)
4.4	2.604	2.417	8.0	4.24	7.2	59.9	17.8	10.66
4.9	2.579	2.430	8.5	4.27	5.8	67.2	17.7	11.90

5.4	2.567	2.442	8.8	4.30	4.9	73.0	18.0	13.14
5.9	2.549	2.445	9.0	4.61	4.1	77.9	18.5	14.41
6.4	2.533	2.441	6.6	5.13	3.6	81.1	19.2	15.57

Table 10. Marshall parameters for SMA mixtures with CR (G3) as aggregate (MA-G3).

OAC (%)	GSA (g/cm^3)	GSB (g/cm^3)	STA (kN)	FLV (mm)	AVV (%)	AVR (%)	VMA (%)	VFA (%)
4.4	2.597	2.414	6.8	4.24	7.0	60.0	17.6	10.56
4.9	2.576	2.428	7.6	4.27	5.8	67.3	17.6	11.79
5.4	2.553	2.435	8.0	4.30	4.6	73.0	17.9	13.07
5.9	2.541	2.440	8.1	4.61	4.0	78.3	18.3	14.33
6.4	2.520	2.432	7.7	5.13	3.5	81.7	19.0	15.52

The test results for MR are presented in Table 11, including the average values (MR_{avr}). The highest values found were for the condition without rubber addition [3, 6, 13, 28, 30], unlike most works reported in the literature. Regarding the results with RSMA blends, the finer RPS presented higher MR values than the coarser[15, 28]. The large reduction of MR between the control mix and RSMA mixes should be recorded, reaching close to 50% and 37% for the coarser and finer RPS mixtures, respectively. The results of ITS are presented in Table 12, including the average values (ITS_{avr}), showing higher values for the control mix, followed by the finer RPS and, finally, the coarser in RSMA mixes [13, 20, 24, 28, 30]. Again, the elevated decrease of ITS values between the control mix and RSMA mixes, which are equal to 47% and 32% for coarser and finer RPS, respectively, should be noted.

Table 13 shows the results of the fatigue life tests for the samples with and without rubber, carried out under controlled tension, where one can read the fatigue tensions (σ_f) and the respective load cycles. Figure 5 shows the graphs originating from the data of Table 13, where it can be verified that the fatigue life is higher for the mixture without CR content – in the contrary sense to that found in the literature - followed by the mixture with the finer and coarser RPS, respectively. In relation to the latter case, the result is different from that found by [15] because this author found a shorter fatigue life for the finer RPS.

Table 14 shows the results of the moisture-induced damage through the Modified Lottman Test (AASHTO T283) on unconditioned and conditioned samples of mixtures with and without rubber content. The ITS values for the conditioned (ITS_c) and unconditioned samples (ITS_u), as well as the Tensile Strength Ratio (TSR) of each sample, are shown. It was verified that all the mixtures reached TSR values higher than the minimum (0.70), with the RSMA mixtures showing the highest values in relation to the control one, unlike that reported by [22], [28] and [30] but in the same sense found by [6], [33] and [34] However, it should be noted that control mixtures presented higher individual values (ITS_c and ITS_u) and average values (TS_{avg}) than RSMA mixtures.

Table 11. Resilient modulus (MR) for the mixtures with and without rubber content.

Mixture Designation	Sample No.	MR (MPa)	MR_{avr} (MPa)
MA	1	4809	5654
	2	6012	
	3	6141	
MA-G1	1	2588	2773
	2	2816	
	3	2915	
MA-G3	1	3509	3540
	2	3636	
	3	3476	

Table 12. Indirect tensile strength (ITS) for the mixtures with and without rubber content.

Mixture Designation	Sample No.	Height (cm)	Diameter (cm)	Tension Force (kgf)	ITS (MPa)	ITS_{avr} (MPa)
MA	1	6.04	10.17	1789	1.9	1.9
	2	6.02	10.16	1816	1.9	
	3	6.05	10.16	1974	2.0	
MA-G1	1	6.60	10.17	975	0.9	1.0
	2	6.50	10.23	1073	1.0	
	3	6.54	10.17	1045	1.0	
MA-G3	1	6.45	10.19	1326	1.3	1.3
	2	6.49	10.18	1344	1.3	

3	6.39	10.25	1221	1.2

Table 13. Tensile stresses and corresponding number of cycles of the mixtures in fatigue life tests.

MA		MA-G1		MA-G3	
σ_f (MPa)	Cycles	σ_f (MPa)	Cycles	σ_f (MPa)	Cycles
3,01	457	1,53	849	1,94	593
3,01	454	1,52	795	1,97	930
2,28	1454	1,17	3760	1,49	2264
2,26	956	1,13	2455	1,49	2047
1,52	3970	0,75	9171	0,98	5601
1,51	4704	0,76	8343	0,98	7530
0,75	62792	0,38	64812	0,48	55126
0,76	61325	0,37	63565	0,49	56525

In the analyses it was verified that the control mixtures presented higher values of GSA, GSB, VFA, STA, MR, ITS and FL, while RSMA mixtures showed higher values of AVV, VMA, FLV and TSR. Among the RSMA mixtures, the ones with the finer RPS showed higher values of MR, ITS, FL and TSR, in relation to those coarser grain size.

Some inconsistencies need to be registered. The first is the shorter FL for rubber mixtures, which is nonsense in relation to almost all studies in the literature; second is the great reductions in MR and ITS values, in relation to the control mixture.

It can be argued by citing, for example, that the absence of a curing time in the drying process is critical to complete the swelling and stabilization process of the CR in the mixture [2, 22]; in addition, there may have been greater difficulty in the compaction of mixtures with the addition of CR [23] relative to the reference mixture; according to [13], the CR in the dry process mixes seems to reduce the stiffness of the resulting mixes, and according to [22], when compared to long-term ageing, short-term ageing is more significant in the mixture's stiffness. Finally, according to [15], the modulus and fatigue of CR asphalt mixes depends on rubber gradation, aggregate gradation, and rubber content; that is, the grading of the mixtures performed by the Bailey method and the determination of the content of 2% CR may not have been the best possible combination to produce satisfactory results in the mechanical parameters of RSMA mixtures.

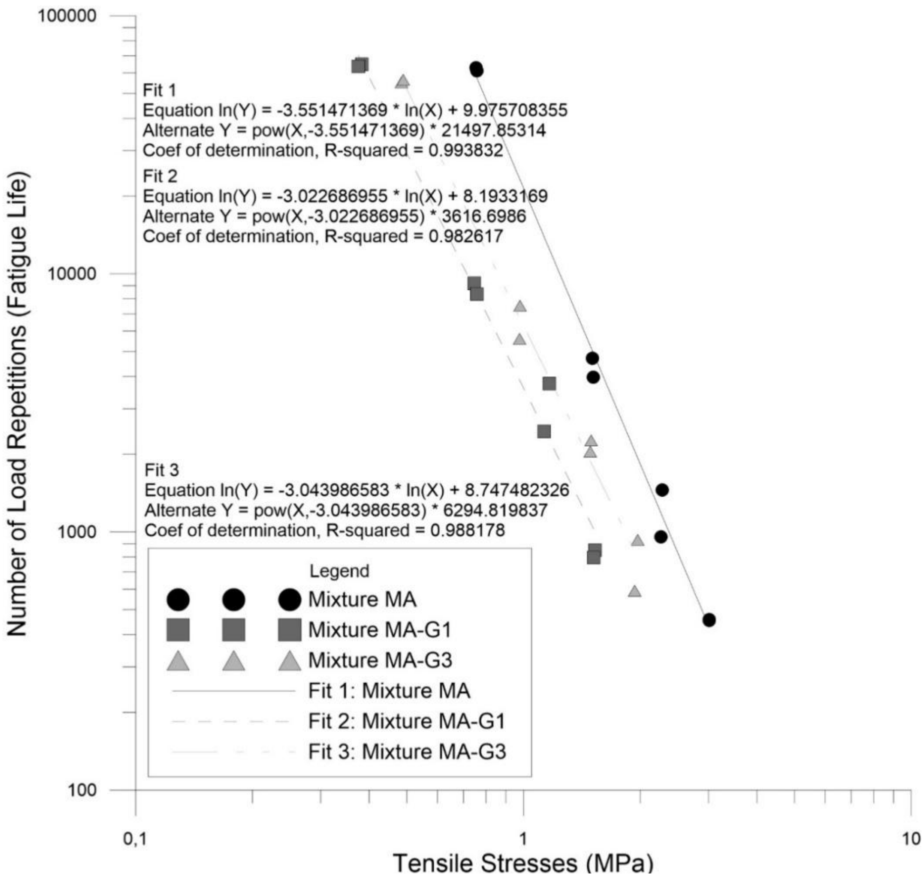

Figure 5. Fatigue life for the mixtures with and without rubber content.

Table 14. Moisture-induced damage through the Modified Lottman Test for the mixtures with and without rubber content.

Mixture Designation	Sample Conditions	Sample No.	Type	ITS (MPa)	ITS_{avg} (MPa)	TSR
MA	Conditioned	1	ITS_c	1.62	1.57	0.86
		2		1.60		
		3		1.50		
	Uncoditioned	4	ITS_u	1.95	1.82	
		5		1.80		
		6		1.72		
MA-G1	Conditioned	1	ITS_c	0.85	0.91	0.97
		2		0.95		
		3		0.94		
	Uncoditioned	4	ITS_u	0.96	0.94	
		5		0.89		
		6		0.96		
MA-G3	Conditioned	1	ITS_c	1.10	1.05	0.93
		2		1.02		
		3		1.02		
	Uncoditioned	4	ITS_u	1.09	1.13	
		5		1.17		
		6		1.14		

IV. CONCLUSIONS AND RECOMMENDATIONS

This study addresses the use of Rubberized Stone Matrix Asphalt (RSMA) using dry process to mix the CR and mineral aggregates through the Bailey method of aggregates dosage. Two rubber particle sizes were used ranging from 4.75 to 2.40 mm and from 2.40 to 0.60 mm at the same 2% (in mass) content in the mixtures. The mixes with (RSMA) and without CR (control one) were submitted to laboratorial tests in order to determine Marshall parameters, resilient modulus, fatigue life and moisture susceptibility.

The results indicated that the control mixtures presented higher values of GSA, GSB, VFA, STA, MR, ITS and FL, while RSMA mixtures showed higher values of AVV, VMA, FLV and TSR. Among the RSMA mixtures, the ones with the finer RPS showed higher values of MR, ITS, FL and TSR, in relation to those coarser grain size.

On the other hand, there was a higher FL for the control mixture as well as higher values of MR and ITS, when compared to RSMA values. The differences in the MR and ITS values found were close to 50% and 37% and to 47% and 32%, for coarser and finer RPS, respectively.

The absence of a curing time in a dry process, higher AVV values (between 13% and 50), the setting of a constant CR value of 2% in the blend, even the grading through bailey method can try to justify those abnormal behaviours of RSMA mixtures in relation to control mixtures.

Finally, RSMA blend had better performance than control mixture in the case of MS.

ACKNOWLEDGEMENTS.

The authors would like to thank the laboratory technicians of the Pavement Laboratory of the University of São Paulo at São Carlos, Mrs. Antonio Carlos “Gigante” (in memoriam), Paulo Toyama and João Domingos Pereira Filho, for their assistance in carrying out the laboratory tests.

REFERENCES

[1]. Lo Presti, D. Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review. Construction and Building Materials, 49 (2013) 863–881, Elsevier, http://dx.doi.org/10.1016/j.conbuildmat.2013.09.007.

[2]. Hernández-Olivares, F.; Witoszek-Schultz, B.; Alonso-Fernández, M. and Benito-Moro, C. Rubber modified hot-mix asphalt pavement by dry process. International Journal of Pavement Engineering, 2009, 10:4, 277-288, DOI: 10.1080/10298430802169416.

[3]. Cao, W. Study on properties of recycled tire rubber modified asphalt mixtures using dry process. Construction and Building Materials, 21, (2007) 1011–1015, Elsevier.

[4]. Shu, X. and Huang, B. Recycling of waste tire rubber in asphalt and portland cement concrete: An overview. Construction and Building Materials (2013), http://dx.doi.org/10.1016/j.conbuildmat.2013.11.027

[5]. Hassan, N.A.; . Airey, G.D.; Jayaa, R.P.; Mashrosa, N.; Aziz, M.A. A Review of Crumb Rubber Modification in Dry Mixed Rubberised Asphalt Mixtures. www.jurnalteknologi.utm.my, 70:4 (2014) 127–134.

[6]. Venudharana, V.; Biligiria, K.P.; Sousa, J.B. and Way, G.B. Asphalt-rubber gap-graded mixture design practices: a state-of-the-art research review and future perspective. Road Materials and Pavement Design, 2016, http://dx.doi.org/10.1080/14680629.2016.1182060, Taylor & Francis Group.

[7]. Mashaan, N.S. and Karim, M.R. Evaluation of Permanent Deformation of CRM-Reinforced SMA and Its Correlation with Dynamic Stiffness and Dynamic Creep. The Scientific World Journal, Vol. 2013, Art. ID 981637, 7 pages, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2013/981637.

[8]. Hassan, N.A.; Hainin, M.D.; Yaacob, H.; Ismailc, C.R.; Yunus, N.Z.M. Evaluation on Mix Design and Rutting Resistance of Dry Mixed Rubberised Asphalt Mixtures. www.jurnalteknologi.utm.my, 65:3 (2013) 115–120.

[9]. Al Qadi, A.N.S; Alhasanat, M.B.A; Haddad, M. Effect of Crumb Rubber as Coarse and Fine Aggregates on the Properties of Asphalt Concrete. American Journal of Engineering and Applied Sciences 2016, 9 (3): 558-564, DOI: 10.3844/ajeassp.2016.558.564.

[10]. Mashaan, N.S.; Ali, A.H.; Karim, M.R. and Abdelaziz, M. A. Review on Using Crumb Rubber in Reinforcement of Asphalt Pavement. Thee Scientific World Journal, Vol. 2014, Art. ID 214612, 21 pages, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2014/214612.

[11]. Rahman, M.M. Airey, G.D. and Collop, A.C. The mechanical properties of the dry process CRM asphalt mixtures following short-term and long-term ageing. 7th International Conference on the Bearing Capacity of Roads and Airfields, Tondheim, Norway, 2005.

[12]. Ghabchi, R.; Zaman, M.; Arshadi, A. Use of ground tire rubber (GTR) in asphalt pavements: literature review and dot survey. Final report, School of Civil Engineering and Environmental Science (CEES), The University of Oklahoma, Sep. 2016.

[13]. Gallego, J.; Del Val, M.A. and Tomás, R.A. Spanish Experience with Asphalt Pavements Modified with Tire Rubber. Proc. of the Asphalt Rubber Conference. Portugal. 2000.

[14]. Gowda, G.V.; Hall, K.D.; Elliott, R.P. Arkansas. Experience with crumb rubber modified mixes using marshall and shrp level 1 design methods. 75th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1996.

[15]. Liu, Y.; Han, S.; Zhang, Z. and Xu, O. Design and evaluation of gap-graded asphalt rubber mixtures. Materials and Design, 35 (2012) 873–877, Elsevier Ltd., doi:10.1016/j.matdes.2011.08.047.

[16]. Takallou. H.B. and Hicks, R.G. Development of improved mix and construction guidelines for rubber modified asphalt pavements. 1988 Annual Meeting of Transportation Research Board Washington, D.C., March, Transportation Research Record, 1171, p. 113-120.

[17]. Mashaan, N.S.; Ali, A.H.; Karim, M.R.; Abdelaziz, M. A.; Ibrahim, M.R.; Katman, H.Y. and Koting, S. Evaluation of Fatigue Life of CRM-Reinforced SMA and Its Relationship to Dynamic Stiffness. The Scientific World Journal, Vol. 2014, Art. ID 968075, 11 pages, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2014/968075.

[18]. Eme, D.B. and Nwofor, T.C. INVESTIGATING THE MARSHALL STABILITY REQUIREMENTS OF ASPHALT CONCRETE MIX WITH GROUND SCRAP TYRES AS AGGREGATE. International Journal of Civil Engineering and Technology (IJCIET), Vol. 6, Issue 9, Sep 2015, pp. 01-07, Article ID: IJCIET_06_09_001.

[19]. Karacasu, M.; Okur, V.; Er, A. A Study on the Rheological Properties of Recycled Rubber-Modified Asphalt Mixtures. Scientific World Journal, Vol. 2015, Art. ID 258586, 9 pages, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2015/258586.

[20]. Xie, Z. and Shen, J. Performance of porous European mix (PEM) pavements added with crumb rubbers in dry process, International Journal of Pavement Engineering, 2015, DOI: 10.1080/10298436.2015.1011783

[21]. Moreno-Navarro, F. and Rubio-Gámez, M.C. Influence of Crumb Rubber on the Indirect Tensile Strength and Stiffness Modulus of Hot Bituminous Mixes. J. Mater. Civ. Eng., 2012, 24(6): 715-724, ASCE, DOI: 10.1061/(ASCE)MT.1943-5533

[22]. Xuanrui, G. Research on the influence factors of asphalt rubber mixture fatigue performance. Proceedings of ICOACS 2016.

[23]. Rahman, M.M; Airey, G.D. and Collop, A.C. Moisture susceptibility of high and low compaction dry process crumb rubber modified asphalt mixtures. Journal of the Transportation Research Board, Volume: 2180 issue: 1, page(s): 121-129, 2010. https://doi.org/10.3141/2180-14.

[24]. Jones, D.; Liang, Y. and Harvey, J. Literature Review on Increasing Crumb Rubber Usage by Adding Small Amounts of Crumb Rubber Modifier in Hot Mix Asphalt. REPORT NO. UCPRC-TM-2017-05, 2017. University of California Pavement Research Center.

[25]. Nguyen, H.T.T. and Tran, T.N. Effects of crumb rubber content and curing time on the properties of asphalt concrete and stone mastic asphalt using dry process. International Journal of Pavement Research and Technology 11, (2018) 236–244, https://doi.org/10.1016/j.ijprt.2017.09.014, Elsevier.

[26]. Xie, Z. and Shen, J. Long-Term Performance of SMA Mixtures Added with Crumb Rubbers in Dry Process. Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements, ASCE, 2013 p. 1145-1155.

[27]. Moreno-Navarro, F., Rubio-Gámez, M.C.; Tomás-Fortún, E.; Valor-Hernández, F and Ramírez-Rodriguez, A. Evaluation of the fatigue macro-cracking behavior of crumb rubber modified bituminous mixes. Materiales de ConstruCCión, Vol. 64, Issue 315, July–September 2014, http://dx.doi.org/10.3989/mc.2014.07913.

[28]. Mashaan, N.S.; Ali, A.H.; Koting, S. and Karim, M.R. Performance Evaluation of Crumb Rubber Modified Stone Mastic Asphalt Pavement in Malaysia. Advances in Materials Science and Engineering, Vol. 2013, Art. ID 304676, 8 pages, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2013/304676.

[29]. Cetin, A. Effects of Crumb Rubber Size and Concentration on Performance of Porous Asphalt Mixtures. International Journal of Polymer Science, Vol. 2013, Art. ID 789612, 10 pages, http://dx.doi.org/10.1155/2013/789612. Hindawi Publishing Corporation.

[30]. Mashaan, N.S.; Ali, A.H.; Koting, S. and Karim, M.R. Dynamic Properties and Fatigue Life of Stone Mastic Asphalt Mixtures Reinforced with Waste Tyre Rubber. Advances in Materials Science and Engineering, Vol. 2013, Art. ID 319259, 9 pages, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2013/319259.

[31]. Stroup-Gardiner, M.; Chadbourn, B. and Newcomb, D.E. Babbitt, Minnesota: Case Study of Pretreated Crumb Rubber Modified Asphalt Concrete. Transportation Research Record, 1530.

[32]. Di Mino, G.; Di Liberto, M.; Noto, S.; Soto, F.M. The resistance to fatigue of dry asphalt rubber concrete for sub-ballast layer. 15th International Conference of Railway Engineering, 2015.

[33]. Diab, A.; Singh, D. and Pais, J.C.Moisture Susceptibility of Asphalt Mixtures: A Literature Review. 4th Conference of Transportation Research Group of India (CTRG), 2017.

[34]. Muniandy, R. and Aburkaba, E.E. Effect of Filler Type and Particle Size on Moisture Susceptibility of Stone Mastic Asphalt Mixtures. Australian Journal of Basic and Applied Sciences, 4(11): 5522-5532, 2010. INSInet Publication.

[35]. Chiu, C.T. and Lu, L.C. A laboratory study on stone matrix asphalt using ground tire rubber. Construction and Building Materials 21 (2007) 1027–1033.

[36]. Duriez, M. Traité de matériaux de construction, EditionsDunod, 1950.

[37]. Vavrik, W.R.; Huber, G.; Pine, W.J.; Carpenter, S.H. and Bailey, R. Bailey Method for Gradation Selection in Hot-Mix Asphalt Mixture Design. Transportation Research Circular, Number E-C044 October 2002.

[38]. Aurilio, V.; Pine, W.J. and Lum, P. The bailey method achieving volumetrics and HMA compatibility. Fiftieth Annual Conference of the Canadian Technical Asphalt Association (CTAA), Victoria British Columbia, Canada, Nov. 2005.

[39]. National Asphalt Pavement Association (NAPA). Designing and Constructing SMA Mixtures - State-of-the-Practice. Quality Improvement Series 122, 2002, 47 pages.

[40]. Mamlouk, S.M. and Sarofim, R.T. Modulus of asphalt mixtures: an unresolved dilemma. Washington: Transportation Research Board, 1988.