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Research Article

Use of Wastewater Treatment Sludge (WTS) as Filler in Hot-Mixed Asphalt Concrete

Nilton de Souza Campelo[1]*, José Francisco Aleixo da Silva[2], João Bosco Ladislau de Andade[1]

[1]*Program in Civil Engineering, Federal University of Amazonas, Av. Gen. Rodrigo Otávio Ramos, No. 6200-Coroado I, Ziz Code 69067-005, Manaus, AM, Brazil*

[2]*Department of Civil Engineering, Superior School of Technology, State of Amazonas University, Av. Darcy Vargas, 1.200-Parque Dez de Novembro, Manaus-AM, Zip Code 69050-020, Manaus, AM, Brazil*

ABSTRACT

Nowadays, society is increasingly aware that consumer goods are limited, and that waste produced in industrial and residential activities need to be reused. In doing so, the use of new materials is reduced and there is no need for large accumulations of waste in landfills; therefore, the noble destination of a waste brings numerous technical, economic and environmental advantages. This research deals with the use of sludge from the Water Treatment Plant of Ponta do Ismael, in the city of Manaus, state of Amazonas, Brazil, as a filler fraction in hot-mixed asphalt concrete, replacing the mineral filler traditionally used in this region (Portland cement). Five asphalt mixtures were analysed, one as reference (100% Portland cement) and four others, using sludge in the proportions of 25%, 50%, 75% and 100%, by mass, reaching a maximum of 5%, in relation to the total mass of the mixture. Specimens of the five asphalt mixtures were moulded and the results according to Marshall stability, flow value, static indirect tensile strength, resilient modulus and repeated-load indirect fatigue (fatigue life) were analysed. All the physical and mechanical properties of the five mixtures met the specifications of Brazilian standards, having mixtures with sludge showing better performances than the reference mixture. Thus, the use of sludge in the asphalt mixtures proved to be highly satisfactory, and even greater than 5%, by mass, may have been incorporated.

Keywords: Sludge; Wastewater treatment plant; Mineral filler; Asphalt mixture; Fatigue life, Resilient modulus; Static indirect tensile strength; Marshall stability

INTRODUCTION

The Negro River has its source in the Colombian Andes and its mouth in the city of Manaus, capital of the State of Amazonas, Brazil, with an extension of 2,250 km, and an average flow rate of 28,400 m^3/s. During this journey, the Negro River is enriched with dissolved organic matter from the decomposition of the forest itself. Its predominantly dark in colour is mainly due to this fact. The water in this river originates from glacial melting in the Andes and rain in the spring and flows through land that does not contain significant salts or suspended matter, such as clays, even during the flood season, resulting in water that is low in dissolved substances, of low conductivity (in the mean of 10 S/cm) and turbidity from 5 UNT to 20 UNT. The water is characteristically acidic, with pH ranging between 4.5 and 5.9, without alkalinity and very low levels of calcium and hardness. The temperature varies between 26°C and 35°C. Due to its acidity and almost no existence of urban and industrial activities upstream with an enormous dilution capacity and self-purification, it presents very low pollution values, and almost no faecal contamination.

According to the municipal water utility [1], the water supply system in the city of Manaus is composed of four Water Treatment Plants (WTPs). In the Ponta do Ismael WTP, in the West zone of the city, located in an area of 18 hectares, are located ETA-1 and ETA-2 (Figure 1), responsible for supplying 80% of the city's population. The two other WTPs are located in the South and East of the city. Currently, more than 630 million litres of water are extracted daily from the Negro River and produced under strict quality control carried out by the concessionaire. Approximately 30 thousand analyses are carried out monthly, in a production process that involves more than 600 collection points, among hospitals, dental clinics, schools, restaurants and other specific places, where there is a greater concentration of population and groups with greater impact by direct consumption of water. Altogether there are more than 80 parameters determined and monitored, from

***Correspondence to:** Nilton de Souza Campelo, Program in Civil Engineering, Federal University of Amazonas, Av. Gen. Rodrigo Otávio Ramos, No. 6200-Coroado I, Ziz Code 69067-005, Manaus, AM, Brazil, Tel: 55-92992299550; E-mail: ncampelo@ufam.edu.br

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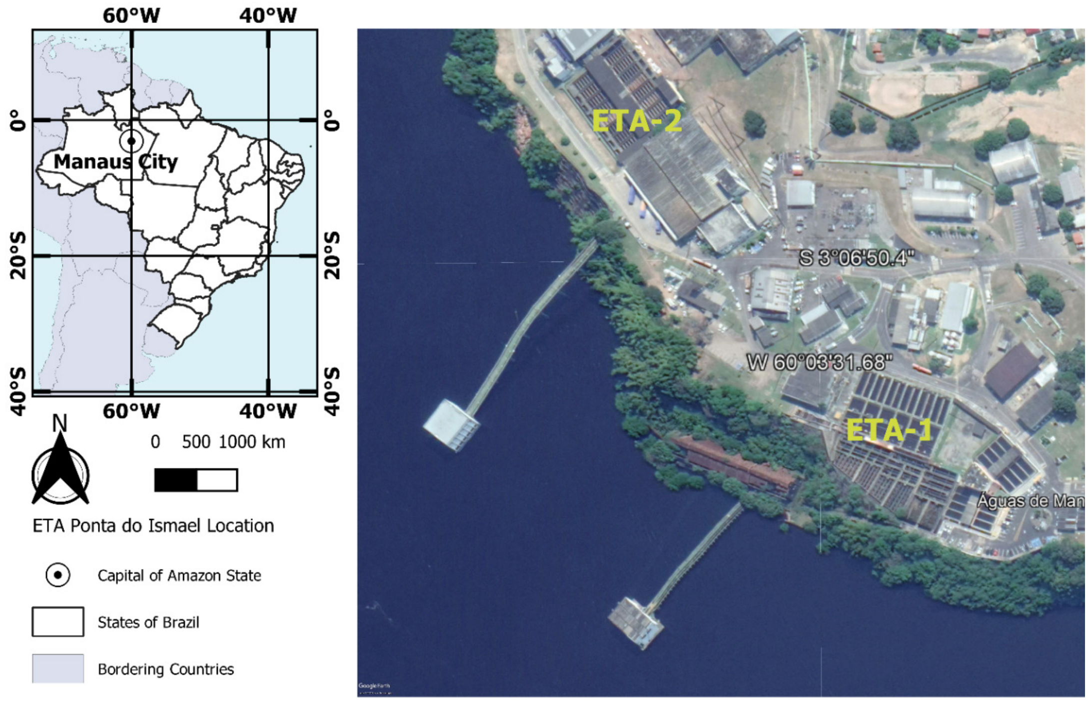

Figure 1: Sludge collection site at ETA-2, in Ponta do Ismael WTP, city of Manaus.

the characteristic that measures the degree of colour and turbidity (transparency) of the water, up to the presence of heavy metals and bacteria (it's absence, guaranteeing the potability standard). The raw water extraction from the Negro River is subjected to a treatment process before being released for consumption.

This process involves the following steps: i) raw water extraction from the Negro River, in which the water is fed to the WTP by means of vertical axis pumps, which lift the liquid to the station's loading chamber by means of a tube; ii) pre-alkalization: one of the characteristics of raw water from the Negro River is its dark colour, caused by organic colloids resulting from the decomposition of plant materials, containing very low salt content and high acidity; this condition requires the application of lime to increase alkalinity and correct the acidity of the water; iii) coagulation: addition of aluminium sulphate to the water to coagulate the dissolved impurities; iv) flocculation: agitation of water to flocculate impurities, facilitating their removal; v) decantation and flotation: removal of impurities by physical forces (separation of mixtures); vi) filtration: retention of the finest impurities in a sand and anthracite filter; vii) disinfection: addition of chlorine, ensuring that the water distributed does not contain microorganisms; viii) fluoridation: adding a small amount of fluoride to prevent cavities; ix) final pH adjustment: second acidity correction for the distribution of neutral water.

Treated water is pumped to the city of Manaus, by means of large hydraulic pumps, through underground pipelines to the reservoirs, to be subsequently distributed to users.

In the flotation tanks, the sludge is thickened and should go to the dehydration tanks, and from there, for final disposal, however, the water supply company does not carry out dehydration and the residual sludge is released into a small water course behind the company's station, contributing, hence, to pollution of the local environment.

Thus, an attempt was made to reuse sludge to mitigate the environmental impact of these products on the environment. As the sludge has a large number of fine-grained solids, it was decided to analyse the use of sludge in asphalt mixtures as partial replacement to the conventional filler, which is Portland cement. Therefore, the present work deals with the comparison between asphalt mixtures with conventional filler (reference) with ETA-2 sludge filler, in terms of physical and mechanical properties, in order to know the viability of the waste for such use.

LITERATURE REVIEW

According to EC [2], sludge is a by-product of the water clean-up process. There are three main categories of sludge: i) sludge originating from the treatment of urban wastewater, consisting of domestic wastewater or the mixture of domestic wastewater with industrial wastewater and/or run-off rain water; ii) sludge originating from the treatment of industrial wastewater, i.e., water used in industrial processes; iii) sludge from drinking water treatment. Water has to be treated before its consumption. The amount of sludge generated from drinking water treatment is significantly lower than that generated from wastewater treatment. The characteristics of sludge depend on the original pollution load of the treated water, and on the technical characteristics of the treatment carried out. Water treatment concentrates on the pollution present in water and therefore sludge contains a wide variety of matter, suspended or dissolved. Some compounds may be usefully reused (organic matter, nitrogen, phosphorus, potassium, calcium, etc.) whereas other compounds are pollutants (such as heavy metals, organic pollutants, and pathogens). Sludge from conventional wastewater treatment plants is derived from primary, secondary and tertiary treatment processes. Primary sludge is produced following primary treatment. This step consists of physical or chemical treatments to remove matter in suspension (e.g. solids, grease and scum). The most common physical treatment is sedimentation. Sedimentation is the removal of suspended solids from liquids by gravitational settling. Sedimentation is usually considered first because it is a simple and cost-effective method. Another physical treatment is flotation. Air is introduced into the wastewater in the form of fine bubbles, which attach themselves to the particles to be removed. The particles then rise to the surface and are removed by skimming.

Thermal treatment nowadays has become one of the major technologies for sewage sludge treatment to produce secure final products. Thermal treatment processes including incinerating and high temperature melting are the latest advanced treatment processes in which safe, high, quality and non-leachable end products are achieved [3].

For years, scientists and researchers have been searching for possible solutions to environmental waste production and pollution concerns. Many have found that replacing raw materials with recycled materials reduces our dependency on raw materials in the construction industry.

Many researcher have used sludge for several applications in Civil Engineering: for example, Portland cement concrete materials [4,5], asphalt mixtures [6-8], base and sub-base pavement layers [9] red ceramic tiles [10,11], among others. Nevertheless, most of those applications refer to sewage sludge.

In the specific case of asphalt mixture applications, there are many contradictory results. For example, Ghazawi et al. [7] found that stability, flow, and air voids increase with greater amounts of sludge waste in the mix, while voids in mineral aggregate decrease with increasing percentage of sludge in the mix, while Al Sayed et al. [6] and Abiero et al. [12] found that, for the same optimum asphalt content, stability in sludge mixture were lower than their corresponding control mixes. Ingunza et al. [8] found that mixtures with calcined sludge had better stability than that of the mixtures with the same proportion of cement. Flow values were greater for mixtures with sludge than mixtures with Portland cement [7,6].

In relation to specific gravities, Ingunza et al. [8] and Al Sayed et al. [6] found that mixtures with calcined sludge tended to be slightly greater than those of the mixtures containing the same proportion of cement. The cement mixtures had lower air voids content than those with the same proportion of calcined sludge. The mean voids filled with asphalt values of the sludge were lower than those of cement in the same proportion.

Tenza-Abril et al. [13] affirmed that the permanent deformations in the mixes made with sludge were similar to those produced in mixes made with cement. The resilient modulus of mixes made with sludge was slightly less than mixes made with other types of filler. Shirodkar et al. [14] found that the laboratory rutting performance of asphalt mixtures with sludge is found to be slightly higher for the mix with sludge. All researches showed that sludge can be used successfully as a component of structural concrete, asphalt concrete, mortars, tiles, etc.

MATERIALS AND METHODS

Origin of materials

The experimental procedure of this research contemplated the dosage and physical and mechanical tests on five hot-mixed asphalt concrete (HMAC) mixtures using the conventional Portland cement filler (as reference) and four other mixtures using Wastewater Treatment Sludge (WTS), replacing the cement gradually in proportions of 25%, by mass.

That residue was collected from the "Águas de Manaus" private concessionaire responsible for water supply and sewerage system in the city of Manaus. The WTS residue (from drinking water treatment) was collected in a suspension form (Figure 2), from ETA-2 (Figure 1). The coarse aggregate (natural pebble) came from the "Japurá" River (an Amazon River affluent) riverbeds and was extracted by dredging, but it was acquired in the local market. The fine aggregate (clean sand) came from mining extraction in the vicinity of the city (about 30-50 km) – it has better size distribution than sand extracted from riverbed - and it was acquired in the local market as well. The mineral filler used was Portland cement (PC) II-Z-32 type. An asphalt cement (AC) 50/70 grading, produced by the Oil Refinery of Manaus (REMAN) was used as a binder in the mixture. The materials used in this research and their respective origins are listed in Table 1.

The WTS residue was taken from ETA-2 to the Pavement Laboratory of the Federal University of Amazonas and dried firstly at room temperature and then dried in the oven at 100 oC, for 24 h. After that, the residue was disintegrated, pulverized, homogenized, quartered and calcined at 300°C to burn organic matter, and after that, stored in plastic bags to maintain its original properties after processing.

Characterization of materials

Mineral aggregates (coarse, fine and filler) were subjected to physical and mechanical tests of particle size analysis, bulk and apparent specific gravities, water absorption, Los Angeles abrasion and asphalt adhesion, according to the desired purpose. The sludge was subjected to physical tests of particle size analysis and apparent specific gravity, in addition to chemical and mineralogical tests for its characterization, such as Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) on samples calcined at temperature of 300 °C.

Figure 2: View of ETA-2, from where the WTS sample was collected; b) Detail of WTS collection.

Chemical characterization was performed by X-Ray dispersive energy spectrometry (Thermo Electron System Six) coupled to the Scanning Electron Microscope (JSM-6460LV JEOL). The images were made with secondary electrons and chemical analysis with Energy Dispersive Spectrometry (EDS) to quantify oxides. The equipment can perform analyses from Sodium to Uranium, having a Rhodium tube and is cooled by liquid nitrogen.

The XRD mineralogical analyses were performed on pulverized samples to be manipulated by the dry method, using the LabX_XRD-600 Shimadzu diffractometer, with monochromatic Cuprum radiation (CuKα, λ=1.5418 Å), operating at 35 kV and 40 mA. The method used was for random non-oriented samples, without dust pre-treatment, avoiding the preferential orientation effect as much as possible.

The AC was submitted to complete physical characterization. All mineral aggregates used in the asphalt mixtures were tested according to the standards described in Table 2, mainly by the Brazilian highway standards, which are most similar to known international standards.

Dosage method of the SMA mixtures

The study compared conventional asphalt mixtures made with Portland cement as filler with those prepared with ETA-2 sludge, replacing cement in the proportions of 25%, 50%, 75% and 100%, by mass, using the Marshall dosage method.

After the characterization of all components of asphalt concrete mixtures, the materials were classified in the "C" granulometric range limits of Brazilian highway specifications, as shown in Figure 6. The trial and error 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 experience of the authors working with those kinds of aggregates and AC.

Production of SMA samples in the laboratory

The incorporation of the WTS residue in the concrete asphalt was made by addition every 25% (in mass) amount, replacing part of the mineral filler (Portland cement) until reach 100%. Those mixtures (designed mixtures 2 to 5) were compared with a conventional blend (without WTS, named mixture 1) using the same proportion of aggregates.

The experimental procedures were defined as follows, for each mixture (Campelo et al, 2019): i) determination of the AC working temperatures from Saybolt-Furol viscosity test in the range of 85 ± 10 and 140 ± 15 SSF for mixing and compaction, respectively; ii) the components (aggregates + AC) were mixed at a temperature of 146 °C for approximately two minutes; iii) the mix was placed in the Marshall mould and compacted mechanically with 75 blows on each side of the specimen; iv) the specimen were left at rest for 24 h at room temperature; v) after that, the specimens were left in a water bath at 60 °C for two hours; vi) finally, they were placed in the compression mould and submitted to compression in order to be determined the rupture load and flow value. Thus, all physical and mechanical parameters of HMAC 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 (mixtures 1 to 5), whose range varied from 4.5% to 6.5%, at each interval of 0.5%.

Table 1: Provenance of SMA component materials.

Material	Origin
Sand	Market of Manaus
Pebble	Market of Manaus
Portland Cement (PC) II-Z-32 (mineral filler)	Market of Manaus
Asphalt Cement (AC) (50/70 grading)	Oil Refinery of Manaus (REMAN)
Wastewater Treatment Sludge (WTS)	ETA-2 "Águas de Manaus" water utility

Table 2: Aggregate characterization tests.

Material	Brazilian Standard	Title	Acceptance Parameters (Brazilian Standard)	Similar International Standard
Pebble	NBR NM 53/2009	Coarse aggregate - Determination of the bulk specific gravity, apparent specific gravity and water absorption	Greater than 0,88 and 2,00 g/cm^3; less than 18 %, respectively	ASTM-T-85
Pebble	NBR NM 51/2001	Coarse aggregate - Test method for resistance to degradation by Los Angeles machine	Less than 50 %	AASHTO-T-96
Pebble, Sand, Fillers	NBR NM 248/2003	Aggregates - Sieve analysis of fine and coarse aggregates	Within granulometric range	ASTM-C136 / C136M-14
Pebble	NBR 12583/1992	Coarse aggregate - Coating to bituminous binder	Qualitative test (visual analysis)	--
Sand	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
Fillers	NBR NM 23/2001	Portland cement and other powdered material - Determination of density	Greater than 3,00 g/cm^3	ASTM-C188-09
WTS	NBR 16137/2010	Nondestructive testing - Material Identification by spot test, X-ray fluorescency spectrometry and optical emission spectrometry	--	ASTM-C114-15
WTS	--	Wavelength dispersive X-ray fluorescence spectrometry	--	ASTM-C1365

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:

$$\sigma_t = \frac{T}{\pi rh} \quad (1)$$

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 (Curvelo Júnior et al, 2020).

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

$$\mathrm{RM} = \frac{F}{\delta h} \times (0,9976\mu + 0,2692) \quad (2)$$

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 [15]:

$$\log\left(N_f\right) = n \times log\left(\sigma_f\right) + k \quad (3)$$

where N_f is the fatigue life (FL) (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.

Table 3 shows the mechanical characterization tests carried out on mixtures and their respective standards. Figure 3 presents the flowchart with the laboratory tests carried out on the components and respective asphalt mixtures.

RESULTS AND DISCUSSION

Characterization of materials

The ETA-2 sludge, after calcination at 300°C, was prepared in two samples and subsequently submitted to Scanning Electron Microscopy (SEM) imaging, accompanied by chemical analysis. Table 4 illustrates the chemical element contents present in samples 1 and 2. Table 5 presents the oxides composition found int the WTS filler in both samples, mainly silicate, aluminate and sulphate. Note the great proportion of aluminium oxides in the residue samples. The presence of more aluminium oxide was already expected due to the use of aluminium sulphate as a coagulant element in the water treatment in Ponta do Ismael WTP.

Figure 4a shows one of the images obtained by SEM indicating the presence of quartz particles. Figure 4b indicates the chemical elements represented in the Table 4.

Mineralogical analysis by X-ray diffraction of the ETA-2 sludge after calcination fits with SEM images due to the fact that was detected the presence of main mineralogical elements quartz (Q) and kaolinite (K) in the residue mass, according to Figure 5. The element quartz represents the coarser fraction of the residue, while the element kaolinite represents the finer fraction (clay).

Table 6 presents the apparent specific gravities, water absorption and Los Angeles abrasion mass loss of the aggregates. The WTS residue has a lower value of specific gravity than the conventional

Table 3: Mechanical characterization tests carried out on HMAC mixtures.

Brazilian Standard	Title	Acceptance Parameter (Brazilian Standard)	Similar International Standard
DNER – ME 043/1995	Asphalt mixtures - Marshall test	OAC ≥ 6% STA ≥ 5 kN 3% < AVV < 5%	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	-	FHWA-Protocol P07/2001
-	Standard test methods for tensile, compressive, and flexural creep and creep - rupture of plastics	D_t ≤ 0.02 mm/mm in 75 minutes	ASTM D 2990-09

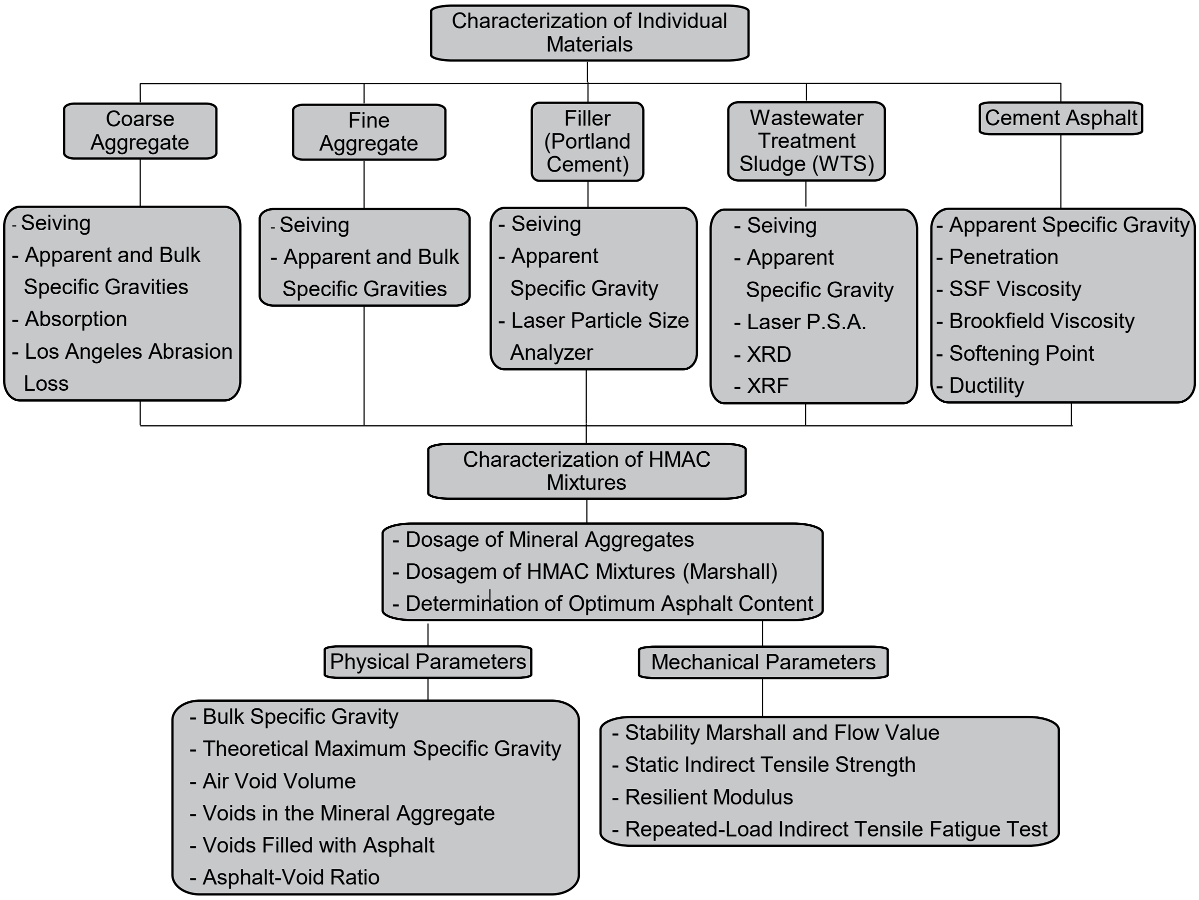

Figure 3: Flowchart of the laboratory tests.

Table 4: Chemical composition of elements presents in WTS filler.

Oxide	Sample	O	Al	Si	S	Ca	Fe
Content (%)	1	46.28	32.05	10.28	1.13	0.81	9.46
	2	41.34	21.99	8.48	-	-	28.2

Table 5: Composition of oxides present in WTS filler.

Oxide	Sample	SiO2	Al2O3	SO3	CaO	Fe2O3
Content (%)	1	21.98	60.55	2.81	1.14	13.52
	2	18.13	41.55	-	-	40.31

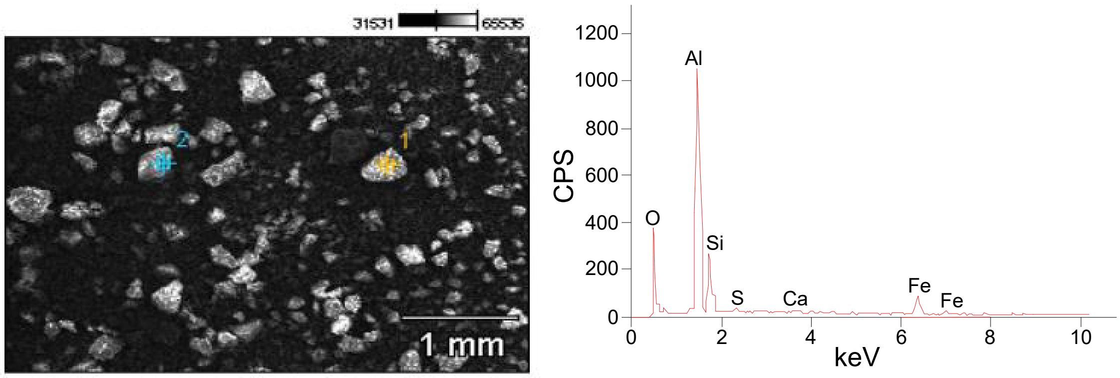

Figure 4: a) image obtained by scanning electron microscopy (SEM); b) chemical composition of the elements.

filler, then this fact will impact on the asphalt mixture densities using the residue.

The granulometric curves of the mineral aggregates, the "C" range maximum and minimum limits of the Brazilian highway specification and the resulting aggregates mixture are shown in Figure 6. Table 7 shows the resulting granulometric composition of the mineral aggregates with and without the addition of WTS. The range maximum and minimum limits resulted in 67% pebble, 28% sand and 5% filler (Portland cement) proportions in the aggregate mixture.

For all the mixtures the same OAC equal to 5.0% was considered, since the difference between the mixture with and without WTS residue was about 0.3%. Hence, the comparison between the mixtures could be better. The temperatures found for the AC was 157 °C, 170°C for the aggregates and 146°C for the asphalt mixture.

Physical and mechanical characteristics of mixtures

Table 8 and Figure 7 indicate the main physical and mechanical Marshall parameters. It was observed that all five mixtures met the

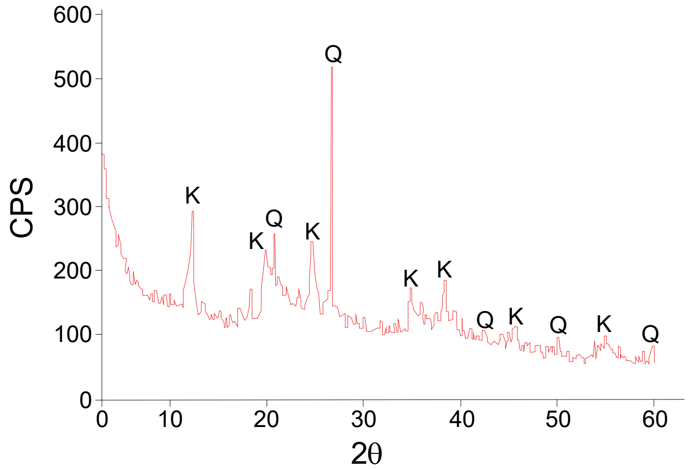

Figure 5: WTS sample diffractogram.

Table 6: Main physical parameter of aggregates.

Aggregate	Specific Gravity		Water Absorption (%)	Los Angeles Abrasion Mass Loss (%)
	Apparent	Bulk		
Pebble	2.73	2.63	1.32	19.6
Sand	2.63	-	-	-
Cement Portland	3.109	-	-	-
WTS	2.49	-	-	-

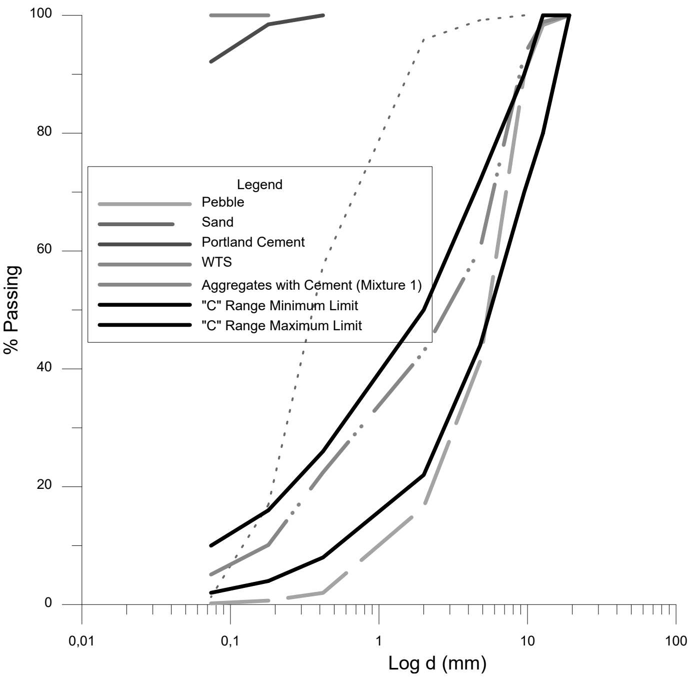

Figure 6: Grain-size distribution and limits curves of mineral aggregates.

Brazilian standards regarding the physical Marshall parameters. It was noted that increasing the proportion of residue in the mixture, the apparent and real specific masses, the void volume, the bitumen-voids ratio, the void volume in the mineral aggregate and voids filled with bitumen decreased; in the opposite direction, stability and fluency have increased. Even having the lowest void volume, mixture 5 (100% sludge residue) had the lowest specific mass, mainly due to the fact that the sludge density is much lower than the density of Portland cement.

The results found for the specific masses are at odds with the work of Ingunza et al. [8] and Al Sayed et al. [6]; in relation to the volume

Table 7: Granulometric composition of mineral aggregate mixtures with and without WTS addition.

Aggregate	Mixture Designation (%)				
	1	2	3	4	5
Pebble	63.65	63.65	63.65	63.65	63.65
Sand	26.6	26.6	26.6	26.6	26.6
Filler (Portland Cement)	4.75	3.56	2.38	1.19	0
Filler (WTS)	0	1.19	2.37	3.56	4.75
Asphalt Cement (AC) (50/70 grading)	5	5	5	5	5
% Total	100	100	100	100	100

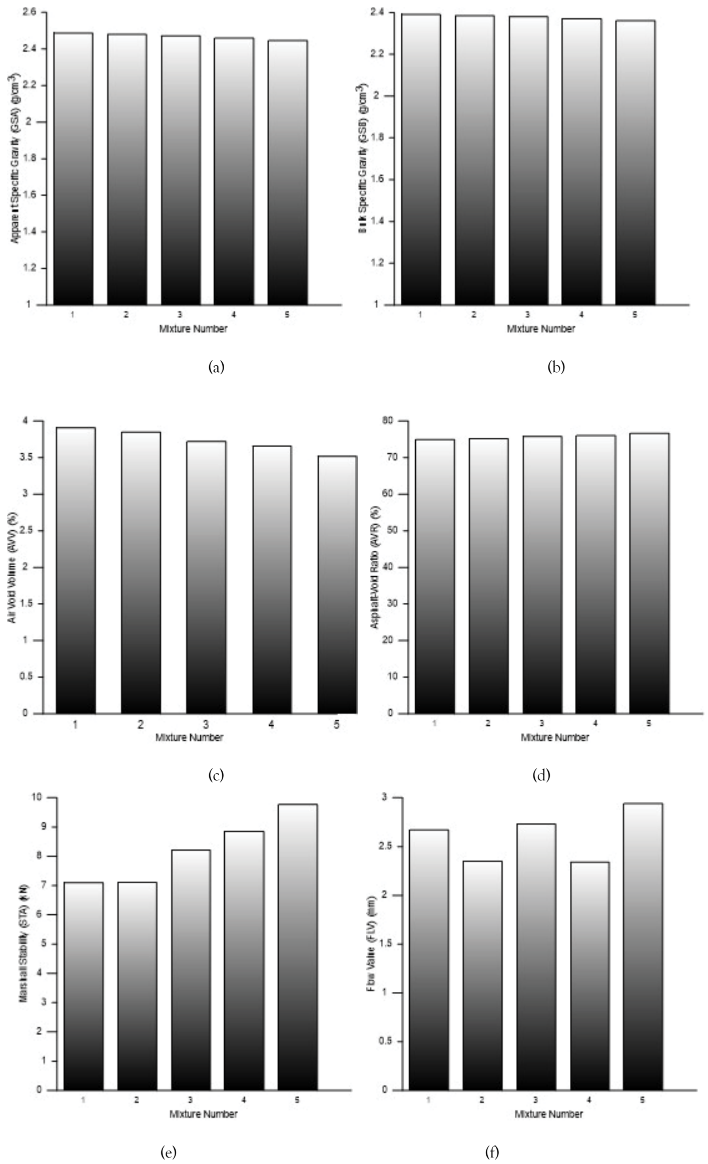

Figure 7: Marshall physical and mechanical characteristics of studied mixtures: (a) apparent specific gravity (GSA); (b) bulk specific gravity (GSB); (c) air void volume (AVV); (d) asphalt-void ratio (AVR); (e) stability (STA); (f) flow value (FLV).

of voids, the results are in agreement with Al Sayed et al. [6]; in the case of stability and fluency, the results are also similar to the trend found by Ingunza et al. [8] and Ghazawi et al. [7]. High amounts of AVV and AVR tend to negatively influence STA values, given the viscous characteristic of AC. Thus, mixture 5 showed the best performance between all of them, in terms of Marshall parameters.

Figure 8 presents the mechanical characteristics of studied mixtures.

Table 8: Marshall parameters for mixtures with and without WTS residue.

Mixture	GSA (g/cm³)	GSB (g/cm³)	STA (kN)	FLV (mm)	AVV (%)	AVR (%)	VMA (%)	VFA (%)
1	2.487	2.390	0.70	2.67	3.91	74.97	15.63	11.72
2	2.480	2.385	0.71	2.35	3.85	75.23	15.64	11.69
3	2.472	2.380	0.82	2.73	3.72	75.82	15.39	11.67
4	2.460	2.370	0.88	2.34	3.66	76.04	15.28	11.62
5	2.446	2.360	0.98	2.94	3.52	76.67	15.09	11,57

Figure 8a shows that all asphalt mixtures presented values above the minimum value of the Brazilian standard (> 0.65 MPa). It was observed that in all mixtures in which ETA-2 sludge was added, there was an improvement in static ITS values. For example, the total replacement of cement by sludge provided a maximum static ITS gain corresponding to 45.6%. Again, the best performance was reached by mixture 5. This is a good indication for durability of the mixtures since fatigue life is a function of ITS. However, if the tensile strength is too high, this may imply the need to increase the thickness of the wearing course depending on the other layers as it becomes more rigid, decreasing its flexibility. Very hard wearing courses with low thickness tend to crack. In the asphalt mixture the tensile strength and hence the modulus of elasticity can be increased, provided that the thickness of the pavement layer is increased. That is, the resilience module and the tensile strength influence the pavement thickness and the asphalt mixture dosage.

Figure 8b shows that the use of WTS increased the RM values and mixture 5 presented the highest value. This result is on the contrary to that found by Tenza-Abril et al. [13]. A possible explanation for the increase in RT and RM when adding the ETA sludge is the fact that, because it is very thin, it hardens the mixture by modifying the CA ductility. As the ambient temperature in the city of Manaus is high because it is close to the Equator line, the sludge filler makes the mixture less viscous and less subject to permanent deformation. Thus, the increase in stiffness due the incorporating of the residue in the mixture becomes a better improvement in this particular case.

In Brazil, the ratio between RM and static ITS (RM/ITS) has been used as an analysis parameter to evaluate the behaviour of asphalt mixtures related to fatigue life. As a rule, mixtures with RM/ITS ratio around 3000 exhibit good structural behaviour because they allow the use of thinner asphalt wearing layers for the same fatigue life; that is, they characterise mixtures that are not susceptible to early development of permanent deformations because they are not rigid enough [6]. In this sense, Figure 8c shows that none of the mixture reached that ratio, but both mixtures (3 and 5) which have incorporated sludge in their mass presented the lower values, when compared to the mixture 1. That is, besides the fact that the mixtures 3 and 5 had high RM values, nevertheless they also had high static ITS values, which, at the end, compensated the ratio RM/ITS values.

Figure 9 shows the results of fatigue life tests. It can be seen that mixture 5 has a straight line slope greater than the line of mixture 3 which, in turn, has a slope greater than that of the line of mixture 1. Therefore, the fatigue life of mixtures with sludge is greater than that of mixture without adding the residue. Higher fatigue life was reached by mixture 5. These results corroborate the results obtained with the ratio between RM and static ITS (RM/ITS). With respect to the elastic deformation, the ETA-2 sludge mixture increased its modulus by about 14.30%, passing from 7 x 10^{-5} to 8 x 10^{-5}, whose result is in accordance with the work of Shirodkar

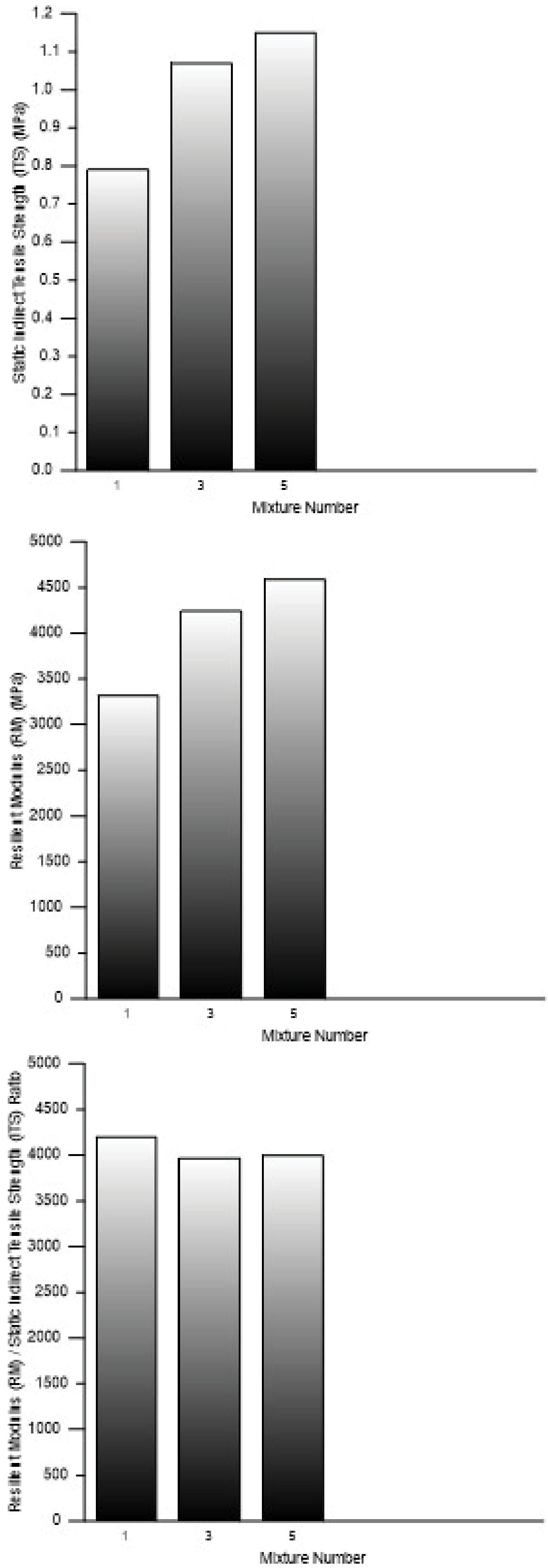

Figure 8: Mechanical characteristics of studied mixtures: (a) static indirect tensile strength (ITS); (b) resilient modulus (RM); (c) RM/ITS ratio.

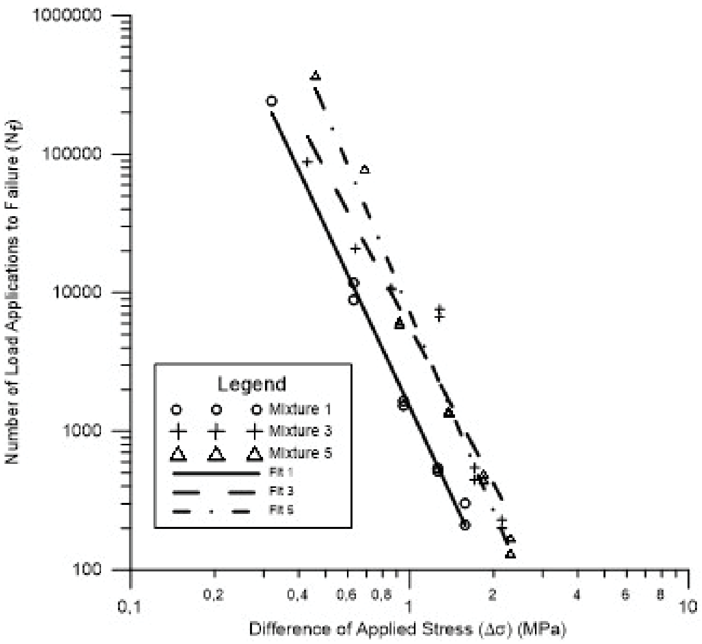

Figure 9: Fatigue life for the mixtures with and without WTS.

et al. [14]. Again, for regions with high ambient temperature, this increase in resilient deformation allows to obtain wearing courses with a longer fatigue life [16].

It was observed that in all mixtures in which the ETA sludge was added, there were improvement in all mechanical properties such as STA, ITS, RM, FL and resilient deformation.

CONCLUSIONS

This study addresses the use of Wastewater Treatment Sludge (WTS) from drinking water treatment in five hot-mixed asphalt mixtures as a filler material, replacing conventional Portland cement in proportions of 25%, 50%, 75% and 100%, by mass, reaching a total replacement of 5%, in relation to the total mass of the mixtures.

The sludge residue had its particle dimensions passing 100% through the sieve number 200 and contributed to increase the stiffness of the asphalt mixtures. Due to that, the physical and mechanical properties of the mixtures with sludge incorporated had a better improvement when compared to the reference (conventional) mixture, using Portland cement as mineral filler. In addition, all five mixtures had their main parameter within the Brazilian specifications.

Hence, the mixtures with WTS had their STA maximum increased in 40.0%, while had their stiffness (expressed by RM values) maximum increased in 45.6%; and finally, had their permanent deformation increased in 14.3%. In addition, the fatigue life of the mixtures using sludge increased as well.

The stiffening of the mixtures using WTS can be considered positive, in the case of Manaus, because the CA 50/70 grading used in the region is soft, for the high temperatures of the place (sometimes, more than 40°C, in some months of the year), decreasing the stiffness of the mixture in the hottest hours of the day.

It is believed that a replacement of Portland cement by sludge could be even greater than 5%, by mass, without the asphalt mixtures losing their qualitative properties.

It is hoped that the results obtained may contribute to the use of these sludge residues, as raw materials in the noblest possible applications, minimizing local environmental impacts and increasing the profitability of the company that generates this type of waste.

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REFERENCES

1. http://www.aguasdemanaus.com.br/agua/
2. EC - European Communities, DG Environment - B/2. Disposal and recycling routes for sewage sludge Part 3 - Scientific and technical report. Luxembourg: Office for Official Publications of the European Communities. 2001:70.
3. Jakarni FM, Yusoff NIM, Wu J, Aziz MMA. Utilization of sewage sludge molten slag as aggregate substitute in asphalt mixtures. Jurnal Teknologi. 2015;73:105-110.
4. Barbuta M, Bucur RD, Cimpeanu SM, Paraschiv G, Bucur D. Wastes in building materials industry. Agroecology. IntechOpen. 2015:81-99.
5. Cheng WN, Yi H, Yu Cf, Wong HF, Wang G, Kwon EE, et al. Biorefining waste sludge from water and sewage treatment plants into eco-construction material. Frontiers in Energy Research. 2019;22:1-9.
6. Al Sayed MH, Madany IM, Buali ARM. Use of sewage sludge ash in asphaltic paving mixes in hot regions. Construction and Building Materials. 1995; 9:19-23.
7. Ghazawi Z, Khedaywi T, Gouneem A. Pollution reduction and reuse of sludge waste in asphalt paving mixtures. Proceedings of the 4th International Conference on Energy Systems, Environment, Entrepreneurship and Innovation (ICESEEI '15) Dubai, United Arab Emirates February 22-24. 2015: 395-400.
8. Ingunza MPD, Santos Junior OF, Medeiros SA. Sewage sludge as raw-material in asphalt mixtures. Advanced Materials Research. 2013;664:638-643.
9. Lucena LCFL, Jucá JFT, Soares JB, Marinho Filho PGT. Use of wastewater sludge for base and subbase of road pavements. Transportation Research Part D. 2014;33:210-219.
10. Amin SK Hamid EMA, El-Sherbiny SA, Sibak HA, Abadir MF. The use of sewage sludge in the production of ceramic floor tiles. Housing and Building National Research Center. 2018;14:309-315.
11. Jordán MM, Almendro-Candela MB, Romero M, Rincón JM. Application of sewage sludge in the manufacturing of ceramic tile bodies. Applied Clay Science. 2005;30:219-224.
12. Abiero ZG, Owili D. Suitability of sewage sludge ash as a filler material in asphalt concrete. Journal of Multidisciplinary Engineering Science Studies (JMESS). 2016;2.
13. Tenza-Abril A, Saval JM, Cuenca A. Using sewage-sludge ash as filler in bituminous mixes. Journal of Materials in Civil Engineering, ASCE. 2013:1-9.
14. Shirodkar P, Sonpal K, Norton A, Weaver R, Tomlinson C, Nolan A, et al. Evaluation of fatigue and rutting performance of sewage sludge ash (SSA) in asphalt concrete. Journal of Solid Waste Technology and Management. 2011;37:55-60.
15. Liu Y, Han S, Zhang Z, Xu O. Design and evaluation of gap-graded asphalt rubber mixtures. Materials and Design, Elsevier Ltd. 2012;35:873-877.
16. Campelo NS, Campos AMLS, Aragão AF. Comparative analysis of

asphalt concrete mixtures employing pebbles and synthetic coarse aggregate of calcined clay in the Amazon region. International Journal of Pavement Engineering. 2017;20(5):507-518.

17. De Souza Campelo Nilton, Jussara Sá da Costa Karine, Kennedy Vieira Raimundo, Kennedy Vieira, Adalena. Use of Waste Foundry Sand (WFS) as Filler in Hot-Mixed Asphalt Concrete. Use of Sandy Materials in Civil Engineering, IntechOpen. 2019:1-18.

18. Curvelo Júnior JC, Campelo NS, Vieira AK, Fernandes Júnior JL, Souza ES. Dosage of Dry Mixed Rubberized SMA by Bailey Method. International Journal of Modern Engineering Research. 2020;10:25-38.