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Chapter

Use of Waste Foundry Sand (WFS) as Filler in Hot-Mixed Asphalt Concrete

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Abstract

The environmental issue has become a topic of relevant discussion in modern society, given the current awareness that construction inputs are finite, and a large amount of waste can be reused as a building material in engineering works. The products used in foundry industry can be non ferrous and ferrous and the residue produced by this last one is not potentially hazardous to human health. The waste foundry sand (WFS) fits this reuse and can be employed in asphalt mixtures, in partial or complete replacement of the conventional filler, i.e. Portland cement (PC). In this sense, this work analyses five asphalt mixtures, one using 100% CP (reference mixture) as filler, and the other four using WFS in proportions of 25-100%, every 25% of the total amount, in 5% (in mass) of the maximum replacement. The mixtures were physically and mechanically characterised according to the Marshall methodology and subsequently submitted to the tests of static indirect tensile strength (static ITS), resilient modulus (RM), repeated-load indirect fatigue (fatigue life) and unconfined static creep. The results of the tests showed that all mixtures with WFS residue presented physical and mechanical parameters within Brazilian standards following the Marshall methodology.

Keywords: waste foundry sand (WFS), mineral filler, asphalt mixture, fatigue life, static creep, resilient modulus, static indirect tensile strength, Marshall stability

1. Introduction

Industries annually generate millions of metric tons of solid by-products, and most of these materials have been landfilled at considerable cost since. Modern society has been developing beneficial reuse of industrial by-products in a variety of applications [1–3]. Recycling of waste construction materials saves natural resources, saves energy, reduces solid waste, reduces air and water pollutants and reduces greenhouse gases [4, 5]. The transportation, construction and environmental industries have the greatest potential for reuse because they use vast quantities of earthen materials annually. Replacement of natural soils, aggregates and cements with solid industrial by-products is highly desirable [1, 2].

The steel industry produces a myriad of metal components for industrial chains such as the automobile industry, which in turn generates mineral discarded sand moulds (waste foundry sand/WFS) that end up occupying large volumes in

landfills [6]. The major portion of the WFS is considered as non-hazardous waste and is currently deposited in a special WFS landfill that is remote from areas of settlement [7–10].

The metal casting industry annually discards about 10% of foundry sand for production, i.e. approximately an estimated 9–10 million tons of WFS each year, in the USA [5, 10, 11]. Generally speaking, approximately 1 ton of foundry sand is needed to produce 1 ton of metal casting [8, 12]. WFS can be used as an alternative material (fine aggregate in asphalt mixtures) in highway constructions allowing the increasing of the lifespan of landfills [13].

This work analyses the physical and mechanical behaviour of asphalt mixtures, using the WFS as a mineral filler in asphalt concrete, in 5% (in mass) of maximum replacement to conventional Portland cement (CP). The waste was obtained from an industry located in the free-trade zone of Manaus city, Amazon State, Brazil. The results showed that the addition of industrial WFS in asphalt mixture resulted in adequate performance of the mixtures.

2. Literature review

Waste foundry sand is generated by industries that use sands, binders and additives to form moulds and cores for castings. Sands are chosen for several reasons; they are readily available everywhere, inexpensive, highly refractory and readily bonded by clays or other inorganic and organic materials [8, 9, 14]. The mould forms the outside of the castings; the core forms the internal shape. When the part to be made has deep recesses or hollow portions, sand cores must be provided in the mould [3]. The material to be used to form moulds and cores in a foundry should have cohesiveness and porosity properties at the same time. Adding binder (bentonite, resins, cement, sodium silicate and oils) will improve the cohesiveness of the sand grains but will tend to reduce porosity. Additives are those materials which are added to the bonded sands to improve properties, either during the moulding process or during the casting process or both [8]. The moulding processes which involve sand are (1) green sand moulding (or clay-bonded sand, [12]), (2) chemically bonded process and (3) shell moulding process [3, 5, 8, 9]. The most commonly used process is green sand moulding [15]. Green sand is composed of four major materials. Sand comprises 85–95% of the green sand mixture. Most often the sand is inert silica, but olivine and zircon sand are also used [8, 15–17]. Approximately, 4–10% of the mixture is made of some form of clay, e.g. bentonite. The clay acts as a binder for the green sand and provides strength and plasticity. Combustible additives like sea coal, cereal, fuel oil and wood flour typically make up from 2 to 10% of the green sand mixture. The final additive of green sand is water which is usually added in small percentages (2–5% by weight) [5, 8]. Chemically bonded sands are those that use furan, phenolic urethane and acid cured no-bake systems, as well as alkyd and phenolic urethane cold box processes. Shell moulding uses a mixture of sand and thermosetting resin (usually phenol formaldehyde) to form the mould [8, 17].

The physical, chemical and mechanical characteristics of virgin sand make it a popular material for construction engineering, but after several reuses in moulds and cores, it becomes WFS [7]. The grain size distribution of WFS is quite uniform, with a majority of the sizes (85–95%) falling within a narrow range between 0.6 and 0.15 mm, and 5–12% is smaller than 0.075 mm [5, 8, 10] or between 1 and 16.5% [14]. According to Tikalsky et al. [17], more than 80% of the particles by mass are concentrated by size between 0.15 and 0.70 mm, compared to 0.30–4.75 mm for conventional fine aggregate. Most of the WFS materials reported are found to be

medium to fine sand. WFS have been found to be too fine to satisfy the specifications for general fine aggregate [8, 10, 12]. WFS has uniform equidimensional subangular to rounded grains, and a few has rounded grains [8, 10, 17, 18].

For density and unit weight, the values found for the WFS were very close to conventional aggregate [13]. The bulk specific gravities reported in the literature on WFS ranged from 1.985 to 2.722 [8, 17]. In most of the cases WFS have been reported to be almost dry. The moisture content as received for WFS were reported to be in the range of 0.0–4.85% [8, 17, 18]. Concerning absorption, the values are relatively higher than those obtained for the natural aggregate, due to the presence of organic matter [6, 8]. The percentage absorption values on WFS samples have been reported to vary between 0.3 and 6.2% [3, 8, 17].

Over the past three decades, there have been several studies around the world on the use of WFS in engineering works, in different areas: base and subbase layers of highway construction [19–21], embankments [22, 23], hydraulic barriers [24], asphalt mixtures [3, 7, 16, 25, 26], etc.

Highway subbase layers using WFS have been shown to resist winter conditions (freeze–thaw cycles) better than specimens of reference materials [5, 17, 19]. If a subbase layer stabilised with WFS is compacted in field at dry of optimum content then it will have an increase in its strength [19, 20, 27].

It has been mentioned in the literature that the fines of WFS affect the properties of asphalt concrete negatively [7, 28]. The amount of WFS used in an asphalt mixture depends largely on the amount of fines in the WFS [5, 12, 14, 29]. Studies have recommended that WFS should replace successfully as much as 15% (in mass) of the conventional sand (fine) content in asphalt concrete [3, 9]; 8–10, 10–20 and 10%, respectively, in engineering practice in Pennsylvania, Michigan and Tennessee States [5]; 35% [30]; 15% [26]; 10% [7, 13]; 15% [10, 31]; 35% [27, 32]; and 15–30% [14].

Concerning physical characteristics, the densities of the mixtures decreased as the percentage of WFS in the asphalt concrete increased [7, 9, 10, 12, 13, 17, 32]. Percentage of air voids and voids in the mineral aggregate (VMA) were found to increase with blending of increased quantities of WFS [8, 9]. The optimum asphalt content (4.9–6.8%) for HMA mixtures containing various amounts of foundry sand is comparable to the content of mixes not containing foundry sand [14, 17]. The OAC increases with increase in the WFS percentage [13], although Miller et al. [14] found lower values for mixtures containing WFS, in relation to control ones. According to this author, the mixtures obtain the higher percentage of OAC with the WFS with the higher amount of particles passing the #200 sieve. This happens due to the fineness properties of material and increase of surface area [10, 32].

Regarding the mechanical characteristics, the Marshall stability of the asphalt concrete samples containing WFS decreases as the quantity of WFS is increased [3, 6–8, 10, 12, 29, 32]. The flow values of mixtures decreased with increasing percentage of WFS in the asphalt concrete mixtures [7,–10, 13]. The indirect tensile strengths of the asphalt cement mixtures decreased as the percentage of WFS material was increased [7–10, 12, 13, 32]. However, Abdulsattar and Mohammed [25] found that all the WFS mixtures that they analysed showed higher tensile strength than the control mixture. According to Tikalsky et al. [17], the level of air voids and saturation greatly influenced the indirect tension values.

In relation to moisture susceptibility, WFS has little effect on top-down fatigue cracking resistance and moisture susceptibility of the mixtures [32]. When WFS replacement is higher than 15%, asphalt mix may become more sensitive to moisture damage (i.e. stripping) due to the presence of silica [10, 27]. WFS, on average, decreases the unconditioned tensile strength and thus the durability of asphalt mixtures; on the other hand, WFS do not necessarily increase or decrease a mixture's rutting potential but do improve fatigue performance [17].

3. Materials and methods

3.1 Origin of materials

The experimental procedure of this research contemplates 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 WFS, replacing the cement gradually in proportions of 25%. This residue was produced by the foundry industrial process of a company located in free-trade zone of Manaus city, Amazon State, Brazil, which produces clutch assembly lines (pressure and friction plates, discs, outer housing, etc.) for the motorcycle industry. **Figure 1a** shows one of the several kinds of pieces that are produced in that industry, while **Figure 1b** presents the WFS studied. The annual production of WFS in that industry was about 1500 tons in 2014 (SUFRAMA, 2016). 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), but it was acquired in the local market as well. The mineral filler used was Portland cement II-Z-32 type. Finally, asphalt cement (AC) 50/70 grading was used, produced by the oil refinery of Manaus (REMAN). The materials used in this research and their respective origins are listed in **Table 1**.

3.2 Characterisation of materials

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. In relation to the asphalt cement (AC—50/70 penetrating grading), it was submitted to complete characterisation according to standards shown in **Table 3**.

In order to avoid the presence of impurities, the residue was washed in sieves Nos. 200, 300 and 400, before subjected to characterisation tests and used in asphalt mixtures. The WFS filler was subjected to chemical analysis (XRF) made by an X-Ray spectrometer equipment (720 energy dispersive, Shimadzu), through drying and subsequently pressing the sample in a disc form. The equipment can perform analyses from sodium to uranium, has a rhodium tube and is cooling by liquid nitrogen. Besides that, the WFS filler was also submitted to the X-Ray diffraction (XRD) in order to be characterised its crystalline phases. The equipment used in the analysis was
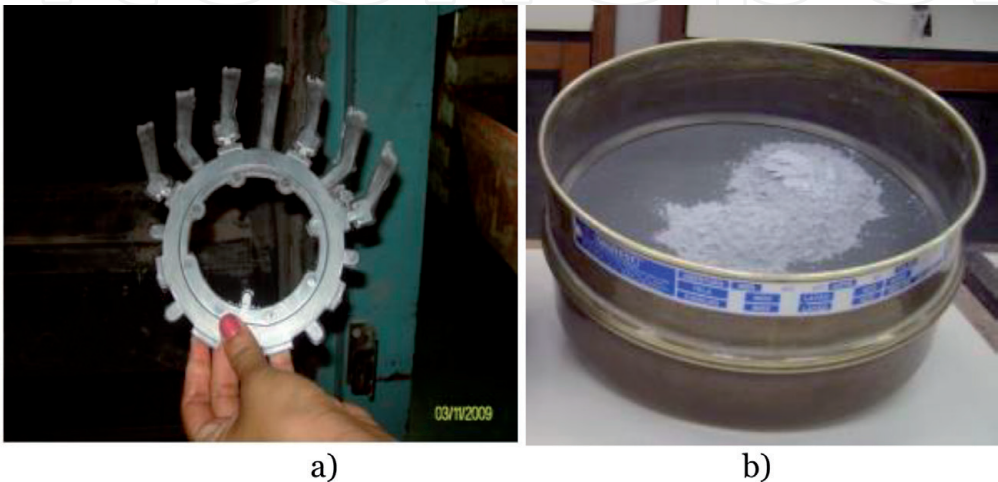
Figure 1.
(a) A piece (to be deburred) produced at the trade zone of Manaus city industry. (b) WFS to be tested.

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)
Waste foundry sand (WFS)	Industry of free-trade zone of Manaus

Table 1.
Provenance of HMAC component materials.

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 materials—determination of density	Greater than 3.00 g/cm^3	ASTM-C188–09
WFS	NBR 16137/2010	Non-destructive testing—material identification by spot test, X-ray fluorescence spectrometry and optical emission spectrometry	—	ASTM-C114–15
WFS	—	Wavelength dispersive X-ray fluorescence spectrometry	—	ASTM-C1365

Table 2.
Aggregate characterisation tests.

the D8 Focus-Bruker diffractometer, with monochromatic cuprum radiation (CuKα, λ = 1.5418 Å), operating at 35 kV and 40 mA. A laser particle size analyser was used to determine with precision the particle size of both mineral fillers (PC and WFS).

3.3 Dosage method of the SMA mixtures

Since the tests were performed 10 years ago, asphalt concrete studies were developed through the traditional Marshall method and not by current Superior

Brazilian standard	Test	Unity	Similar international standard	AC 50/75
NBR 14756	Apparent specific gravity, 25°C	g/cm^3	AASHTO T 228	1.010
NBR 6576	Penetration, 25°C, 100 g, 5 s	0.1 mm	AASHTO T 49	58
NBR 14950	SSF viscosity, 135°C	s	AASHTO T 72	160
NBR 15184	Brookfield viscosity, 135°C, sp21, rpm 20	cP	AASHTO T 316	286
NBR 6560	Softening point	°C	AASHTO T 53	53
NBR 6293	Ductility, 25°C	cm	AASHTO T 51	>120

Table 3.
Properties of asphalt cement (AC—50/70 penetrating grading) used in the mixtures.

Performing Asphalt Pavements (Superpave) methodology. After the characterisation 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 2**. The curves obtained fitted 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 (1950) based on the specific surface of the aggregates:

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

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

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

$$T_{ca} = m \sqrt[5]{S} \tag{2}$$

where T_{ca} is the OAC in relation to the mass of the aggregates (%) and m is the richness modulus of AC, varying from 3.75 (wearing course with high stiffness) to 4.00 (wearing course with low stiffness).

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:

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

where T$'_{ca}$ is the corrected OAC in relation to the mass of the aggregates (%) and δ_{am} is the mean bulk specific gravity of the total aggregate.

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

$$P_{ca} = \frac{100 \, T_{ca}}{100 + T_{ca}} \text{ or } P_{ca} = \frac{100 \, T'_{ca}}{100 + T'_{ca}} \tag{4}$$

where P$_{ca}$ is the final value of OAC in relation to the total mixture (%).

From that OAC value were adopted two points below it (each 0.5%) and two points above it (each 0.5%).
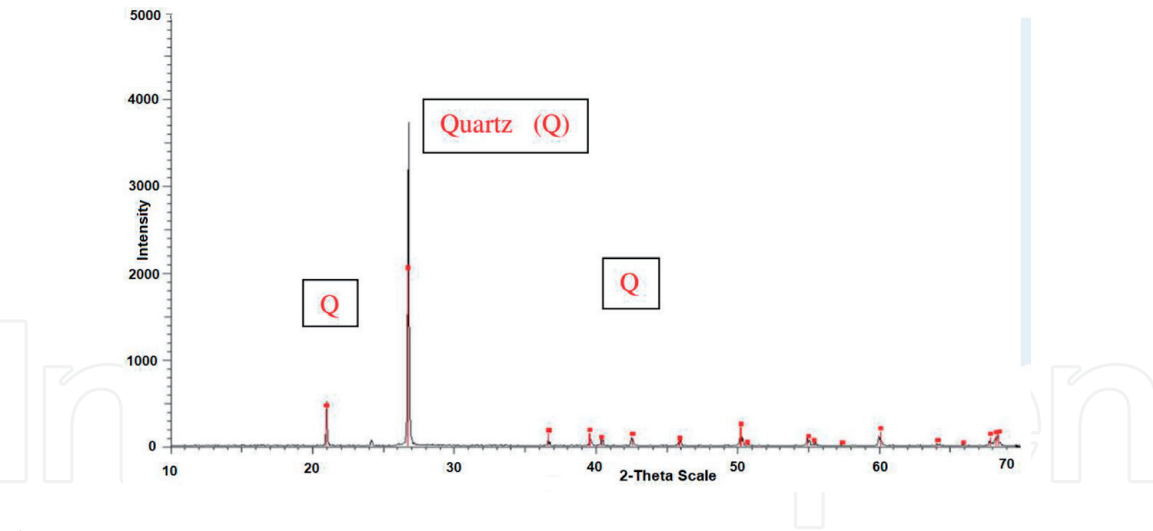
Figure 2.
XRD analysis for WFS filler.

3.4 Production of SMA samples in the laboratory

Five HMAC mixtures were analysed whose grain size proportions are shown in **Table 4**. The mixture 1 was used as reference, for 100% of Portland cement as mineral filler. The other mixtures used WFS as mineral filler, replacing Portland cement in gradual proportions each 25%. At the end, the results were compared between the mixtures with and without WFS according to the physical and mechanical tests performed.

The experimental procedures were defined as follows, for each mixture [33]: (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 2 min; (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 2 h; (vi) finally, they were placed in the compression mould and submitted to compression in order to determine the rupture load and flow value. Thus, all physical and mechanical parameters of HMAC mixtures were determined by the Marshall method.

From Eq. 4, an initial OAC value of 6.15% for mixture 1 was adopted, with m = 3.75. Nevertheless, the mixture showed excessive fluid, with AC in excess. Hence, OAC = 4.5% was considered. It is noteworthy that three specimens were cast for each AC content to find the final OAC of each the mixture (mixtures 1–5), whose range varied from 3.5 to 5.5%, at each interval of 0.5%. **Figure 3a** presents the results of OAC for each mixture.

3.5 Physical and mechanical properties of SMA mixtures

After the tests, the Marshall parameters of the mixtures were determined: bulk specific gravity (BSG), theoretical maximum specific gravity (TMG), air void volume (AVV), voids in the mineral aggregate (VMA), voids filled with asphalt

Oxide	SiO_2	Al_2O_3	SO_3	Fe_2O_3
Content (%)	93.68	3.97	1.66	0.41

Table 4.
Composition of oxides present in WFS filler.
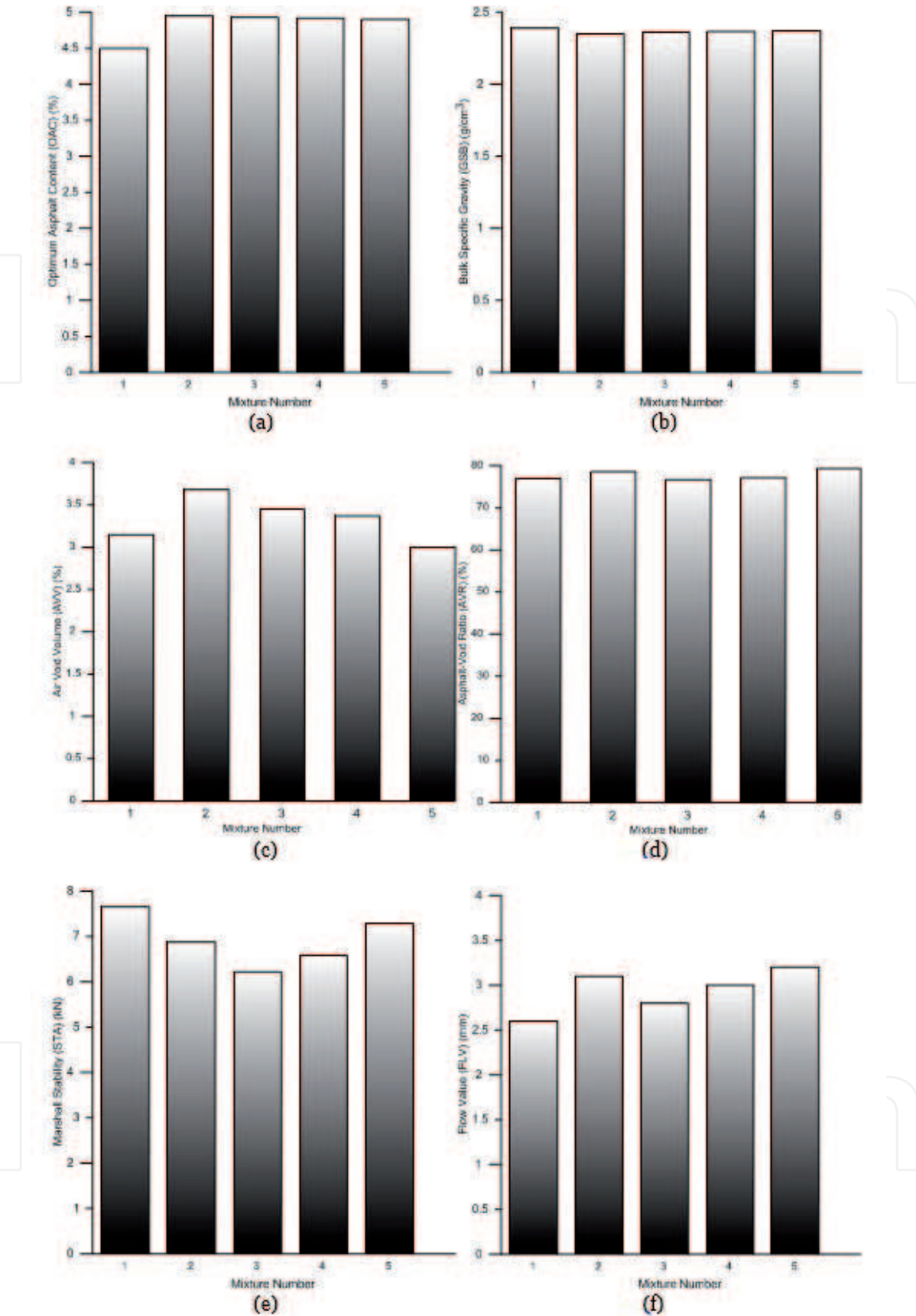
Figure 3.
Marshall physical and mechanical characteristics of studied mixtures: (a) optimum asphalt content, (b) bulk specific gravity, (c) air void volume, (d) asphalt-void ratio, (e) Marshall stability and (f) flow value.

(VFA), asphalt-void ratio (AVR), Marshall stability (STA) and flow value (FLV). 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, at each OAC. The ITS individual value was obtained through the expression

$$\sigma_t = \frac{T}{\pi rh} \qquad (5)$$

where σ_t is the individual static ITS (kPa), T is the static rupture load (kN), r is the sample radius (m) and h is the 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, the specimen were submitted to a repeatedly vertical compression load F at a maximum stress level less than or equal to 20% of the ITS. 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 [33]

$$RM = \frac{F}{\delta h} \times (0,9976\mu + 0,2692) \qquad (6)$$

where RM is the individual resilient modulus (MPa), F is the cyclic vertical load diametrically applied on specimen (N), δ is the elastic strain recorded for 200, 400 and 500 load applications (mm), h is the sample height (mm) and μ is 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 seven stress levels (7.5, 10, 15, 20, 25, 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 [34]:

$$\log(N_f) = n \times log(\sigma_f) + k \qquad (7)$$

where N_f is the fatigue life (in cycles) and 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 bilogarithmic scale, in which "n" is the gradient and "k" is the intercept.

The study of permanent deformation was made using the static creep test applying a static and continuous compression load on a specimen moulded according to the Marshall methodology. The specimen was placed in the axial position and then was subjected to an applied tension of 0.1 MPa, distributed over the entire contact surface of the specimen for a period of 60 min at a temperature of 40°C. The permanent deformations were measured continuously along that time, and then the specimen was discharged, waiting for 15 min for the stabilisation of the viscous deformations, which were measured continuously too. The total strain (D_t) after the recovery period can be obtained as:

$$D_t = \frac{\Delta h_{75}}{h_o} \qquad (8)$$

where Δh_{75} is the specimen height change after the final recovery period, i.e. 75 min after the start of the test load (mm), and h_o is the specimen initial height taken in the axial direction of loading (mm). **Table 5** shows the mechanical tests performed on HMAC mixtures, while **Figure 4** presents all tests carried out on components and 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 mixture—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 min	ASTM D 2990–09

Table 5.
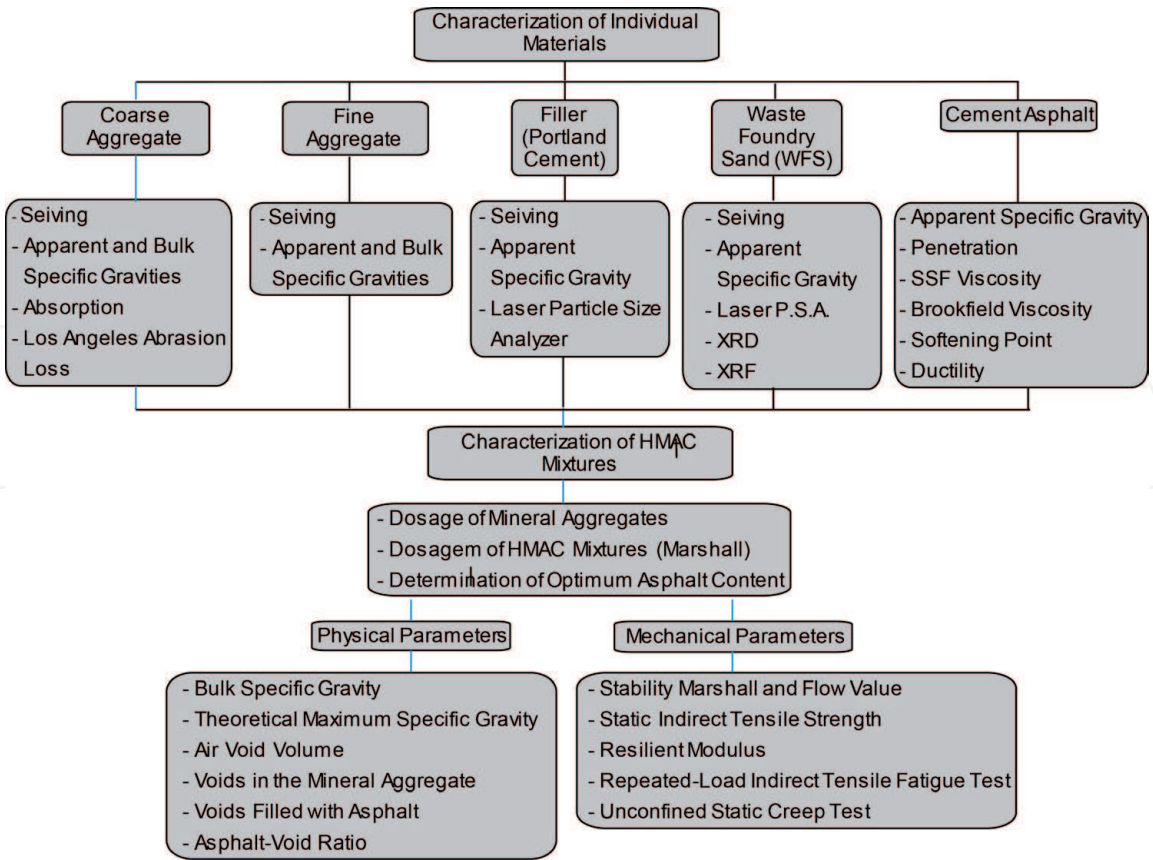*Mechanical characterisation tests carried out on HMAC mixtures.*

Figure 4.
Flowchart of the laboratory tests.

4. Results and discussion

4.1 Characterisation of materials

Figure 2 indicates the result of XRD analysis for WFS filler. As shown in the figure, WFS is essentially formed by quartz mineral, as expected. **Table 4** shows the composition of the main oxides present in the WFS filler obtained by XRF analysis. The high percentage of silica confirms the XRD analysis of the material [8, 16, 17]. **Table 6** indicates the physical characteristics of the aggregates. WFS aggregate apparent specific gravity of WFS is very close to conventional aggregates (pebble and sand) [7, 9, 10, 13] each other except for PC. Pebble had a Los Angeles abrasion loss below the maximum allowed by the Brazilian standard, which is 50%. The WFS had 76.25% of its particle sizes passing at #200 sieve and are slightly larger than that of Portland cement, i.e. it is too fine to replace part of the fine aggregate of the asphalt mixes [8, 10, 12], thus demonstrating that the residue could only replace part or total filler fraction.

Table 7 shows the resulting granulometric composition of the mineral aggregates with and without the addition of WFS. It is observed that all the mixtures were composed with the same amount of aggregates, varying only the proportion between the two types of the filler fraction. Conventional mixture 1 used PC exclusively, while mixture 2 used WFS as filler exclusively. The other mixtures had variations between permutations of PC and WFS proportions. The grain size distribution of the mineral aggregates, the "C" range maximum and minimum limits of the Brazilian highway specification and the resulting aggregates of mixtures 1 and 2 are shown in **Figure 5**.

| Aggregate	Apparent specific gravity (g/cm^3)	Absorption (%)	Los Angeles abrasion loss (%)	d_{90} (mm)	d_{50} (mm)	d_{10} (mm)
Pebble	2.66	1.92	40.0	12.0	7.0	2.5
Sand	2.63	—	—	1.5	0.35	0.12
Filler (PC)	3.03	—	—	0.063	0.020	0.004
Filler (WFS)	2.65	—	—	0.133	0.040	0.004

Notes: d_{90}, d_{50} and d_{10} are the particle size for which 90, 50 and 10% of the all particles, in mass, are finer than it.

Table 6.
Physical characteristics of aggregates.

Aggregate	Mixture designation				
	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)
Pebble	62.0	62.0	62.0	62.0	62.0
Sand	33.0	33.0	33.0	33.0	33.0
Filler (cement)	5.0	0.0	3.75	2.5	1.25
Filler (WFS)	0.0	5.0	1.250	2.5	3.75
% Total	100.0	100.0	100.0	100.0	100.0

Table 7.
Granulometric composition of mineral aggregate mixtures with and without WFS addition.
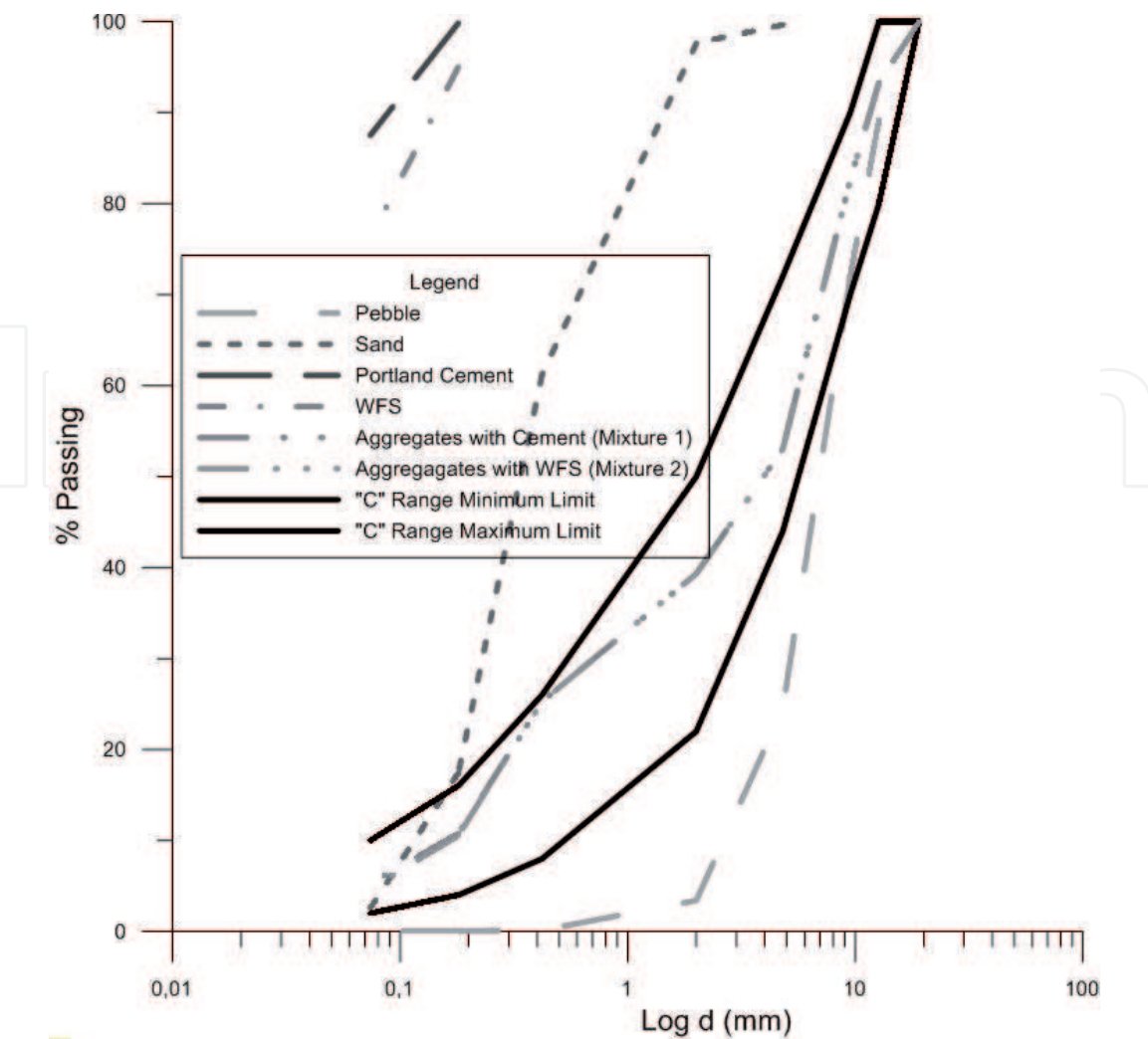
Figure 5.
Grain size distribution and limit curves of mineral aggregates.

4.2 Physical characteristics of mixtures

Figure 3 shows the main physical parameters of the mixtures, obtained through the Marshall methodology. OAC values of the mixtures containing WFS are comparable to the control in mixture 1 [14, 17]. Mixture 1 obtained the lowest OAC (4.5%), whereas mixtures with WFS had little bit higher OAC values, whose contents increased as WFS proportions were increased too [13]. This reason probably is due to the absorption characteristics of this residue, and not due to the grain size [10, 32], since CP has larger particle size and therefore smaller surface area and thus should consume less AC, at the same proportion of WFS.

It was observed that all five mixtures met the Brazilian standards regarding the physical Marshall parameters (OAC, AVV, VMA and AVR). Mixture 1 had a higher GMB values than all other mixtures with WFS and was therefore the densest. The other mixtures maintained a slight decrease of this parameter, when the proportion of WFS in the mixture was increased [7, 9, 13]. Mixture 2 (100% WFS filler) had the highest amount of AVV and the second largest AVR among all mixtures. AVV values increased when WFS content were increased in the mixtures [8–10, 32].
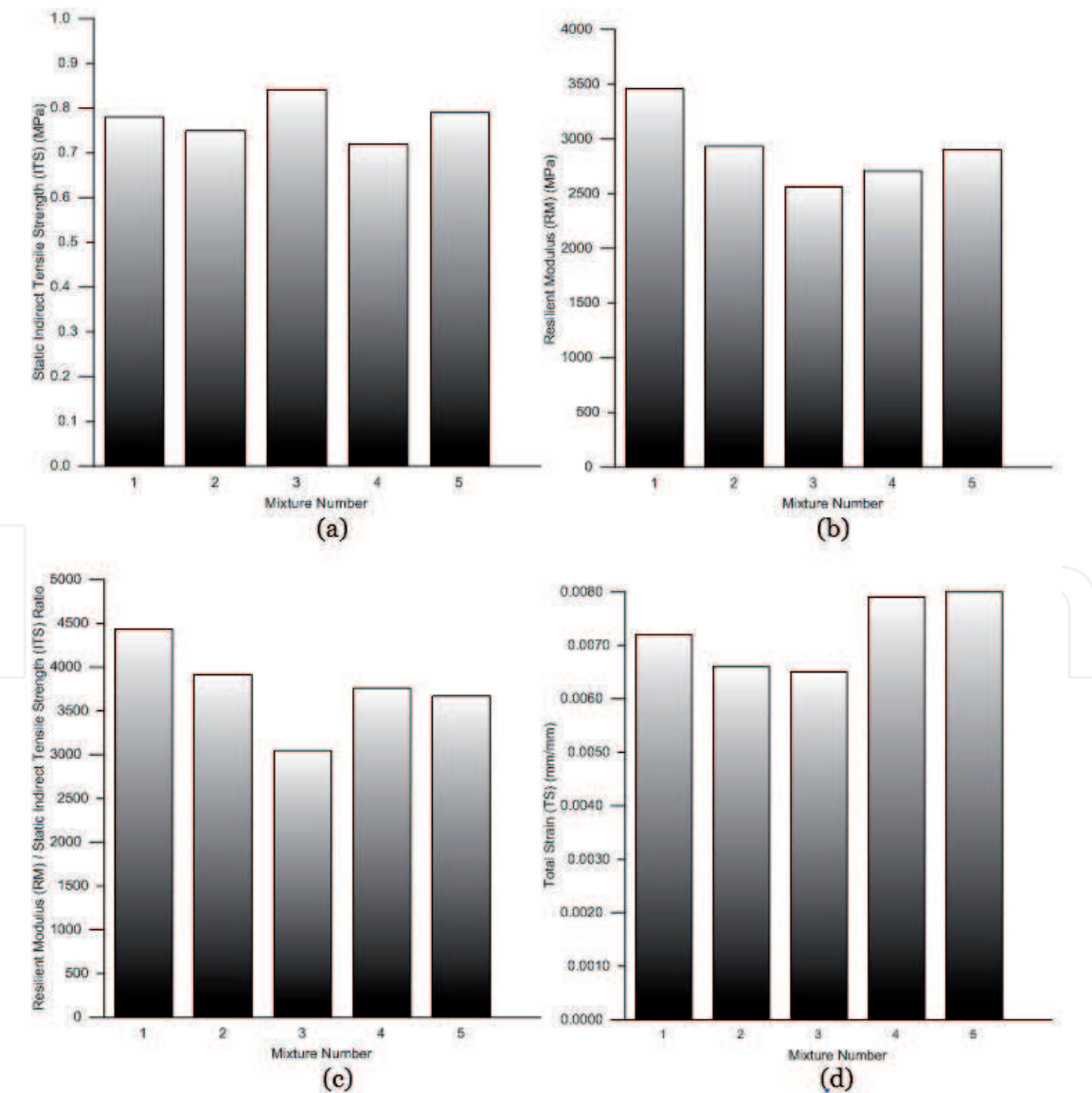
4.3 Mechanical characteristics of mixtures

High amounts of AVV and AVR tend to negatively influence STA and FLV values, given the viscous characteristic of AC. Thus, mixture 1 showed the best performance,

with the highest STA and lowest FLV values. Among the mixtures using WFS, mixture 5 (one fourth WFS + three fourths PC) was the one that presented the highest value of GMB, thus being the densest, and also presented the highest value of STA; however, it had the highest FLV value too. The FLV values of the WFS blends were higher than the PC blends, which characterises a higher AC consumption of these blends. In summary, the use of WFS decreased the stability of blends [6, 8, 10, 12, 32] while increasing their fluency. This latter is in disagreement with that observed by the author cited previously. Even so, all mixtures showed STA values higher than the minimum required (>5 kN).

There was a certain tendency that static ITS values will decrease as WFS content increased [7, 9, 10, 13, 32]. Mixtures 3 and 5 presented higher values of this parameter than control mixture 1 [25]. All asphalt mixtures presented values above the minimum value of the Brazilian standard (>0.65 MPa). This is a good indication for durability of the mixtures since fatigue life is a function of ITS. There was not an apparent correlation between AVV and static ITS values (**Figure 6**).

The use of WFS decreased the RM values. Mixture 1 presented the highest value, followed by mixture 2. In Brazil, the relationship 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
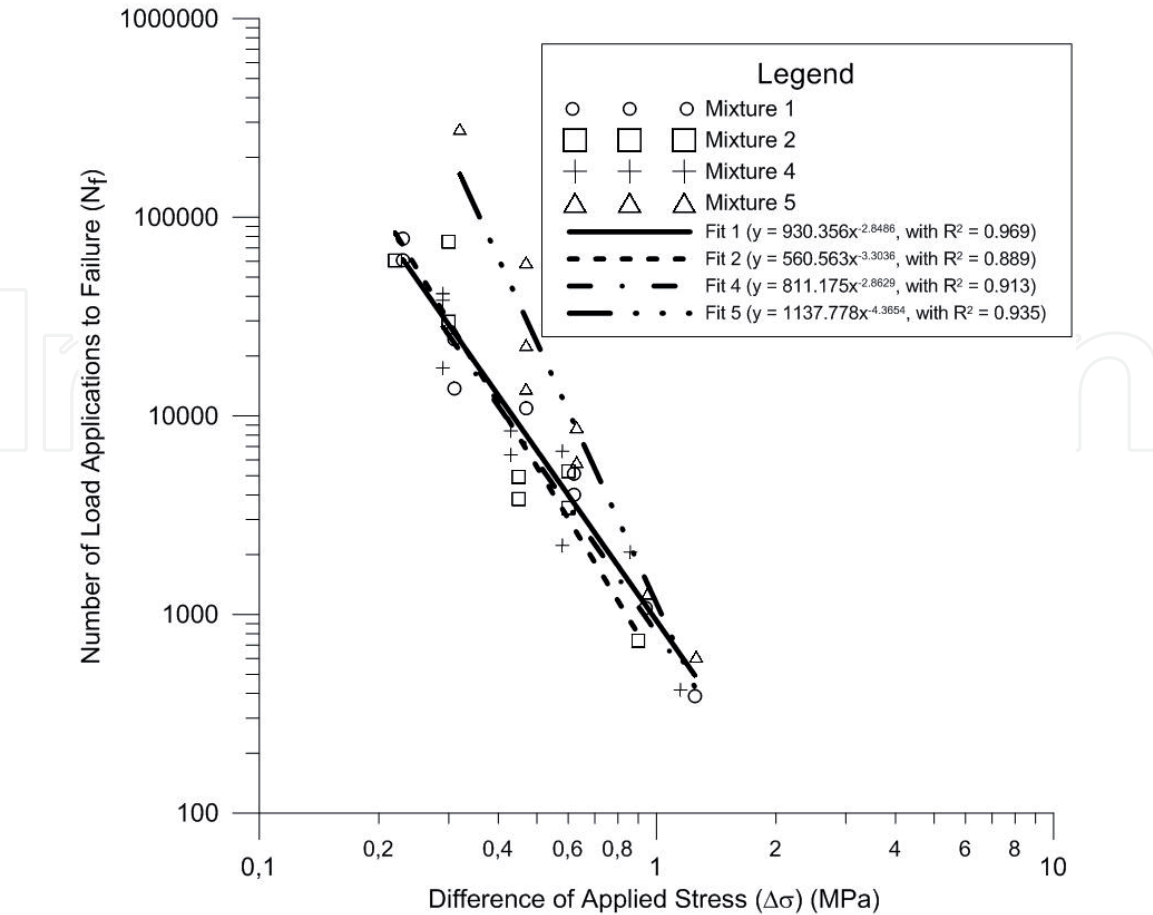

Figure 6.
Mechanical characteristics of studied mixtures: (a) static indirect tensile strength, (b) resilient modulus, (c) RM/ITS ratio and (d) total strain (static creep).

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. In this sense, mixture 3 was the only one that met this criterion. On the other hand, the conventional mixture 1 presented the highest value of this ratio, thus indicating a more rigid behaviour.

Figure 7 shows the comparison between asphalt mixtures in relation to the stress-controlled fatigue test. For the acquisition of fatigue curves, the average value of the RM and the static ITS of each mixture were used. Between Mixtures 1 and 4, the best-fitting straight lines were very close to each other, with a parallelism between the line slopes, and both mixtures can be considered to have practically the same fatigue life. Mixture 2 presented the shortest fatigue life, while mixture 5 presented the longest fatigue life, standing out among the others. For applied stress differences up to 0.4 MPa, Mixtures 1, 2 and 4 behave similarly.

It should be noted that mixture 5 presented the second best ITS result and the second closest value of the RM/ITS ratio around 3000, thus justifying the use of this parameter as a quantitative indicator of fatigue life of asphalt mixtures. The fatigue life test on mixture 3 was not performed.

Regarding the permanent deformation, Mixtures 2 and 3 presented lower values than mixture 1, while mixture 5 presented the highest value among the others. There was no direct relationship with AVV, since, of all of them, mixture 5 presented the lowest value of voids. Mixture 3 presented the lowest value of permanent deformation, confirming again the good indicative of the RM/ITS ratio around 3000 in predicting the behaviour of asphalt mixtures for fatigue and permanent deformations. All mixtures presented permanent deformation values below the

Figure 7.
Fatigue life for the mixtures with and without WFS content.

conventional criterion of 0.020 mm/mm and do not have the tendency to be susceptible to premature permanent deformations.

5. Conclusions

This work analysed five asphalt mixtures, one using 100% CP as a filler and the other four using WFS, with a maximum proportion of 5% (by weight) of the total aggregate. The WFS residue used consisted of almost 94% silica, without organic compounds, with apparent specific gravity similar to clean sand and slightly coarser than CP.

All mixtures with WFS residue presented physical and mechanical parameters within the Brazilian standards, following the Marshall methodology, although with lower STA and higher FLV values. The use of WFS increased static ITS values, while decreased MR values. The mixtures with WFS showed total permanent deformation values less than 2% after 75 min of the test. The RM/ITS ratio around 3000 proved to be a good indication of mixtures with better performance against fatigue life and permanent deformation.

Finally, the use of WFS as a mineral filer in asphalt mixtures proved to be adequate, meeting the criteria of Brazilian standards in physical and mechanical tests.

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