Sustainability & Environment

Mechanical behavior of asphalt concrete containing waste foundry sand

Paulo Paiva Oliveira Leite Dyer[1], Luis Miguel Gutiérrez Klinsky[2], Silvelene Alessandra Silva[3], Maryangela Geimba de Lima[4]

[1]Instituto Tecnológico de Aeronáutica, [2]Grupo CCR Centro de Pesquisas Rodoviárias, [3] Instituto de Estudos Avançados, [4]Instituto Tecnológico de Aeronautica

Abstract

Currently, the concerns about sustainable development made many traditional industrial sectors rethink their production methodologies and raw materials used. At the road projects this vision is no different since, this sector requires the consumption of large amounts of exhaustible natural resources. In the same way, the industrial sectors that manufacture consumer goods produce huge quantities of industrial waste; highlighted are the steel industries, responsible to produce metallic parts using the casting process, were the main by-products are the Waste Foundry Sand (WFS). The WFS is considered a non-hazardous by the major environmental agencies worldwide, however it is disposed in industrial landfills, reducing their service life. This scenario created a motivation for the development of this study. Samples of WFS were obtained from a sanitary landfill and characterized according to the road engineering standards parameters. The WFS was used to replace 50% of fine aggregates in a hot mix asphalt, produced with a bitumen characterized as 30-45 pen-grade. Specimens were produced in Superpave Gyratory Compactor to assess the mechanical parameters of splitting tensile strength (STS), indirect tension test for resilient modulus (ITTRM), dynamic modulus (E*) and flow number. An asphalt mix without waste foundry sand was used as a control mix. Results in the laboratory test program showed that there is no statistical difference between the control and the asphalt mix containing WFS. The mixture with WFS was also analyzed using environmental tests. Results indicate that the substances from the residues remained encapsulated in the asphalt matrix showing that this concrete have almost no environmental risk if applied in the construction of a highway. It is concluded that there is a technical environmental viability to reuse the waste foundry sand in asphalt mixes. As a result, the society would need to use less the landfills to dispose the WFS.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

The use of alternative building materials has been consolidated in the current practices and research, this affirmation is based on the growing environmental concerns and the high costs of conventional raw materials due to the demands for construction. Similarly, by-products of industry and society, so-called waste, they are produced in large volumes, requiring more and more landfills or polluting the environment (when disposed of illegally).

Among these residues there are those which do not represent a risk to human health and environment due to the low concentration of pollutants; such wastes are classified by US Environmental Protection Agency (EPA) [1] as non-hazardous wastes which are those considered as non-inert or inert.

This high availability of unwanted by-products (non-hazardous waste) and enhancement of exhaustible mineral resources costs has aroused the interest of researchers and research entities to reuse wastes in civil construction since these have close physical-chemical similarities with mineral aggregates [2].

Whether it's fly ash from auto furnaces [3], wastes of construction and demolition (WCD) [4], granite or marble dust (also known as manufactured sand) [5], plastic waste (such as high density polypropylene and polyethylene terephthalate) [6], phosphate gypsum [7], discarded and shredded tires [8], waste foundry sand [2], among others, Many studies have been performed on non-hazardous residues to assess its reuse in the construction of a variety of infrastructures such as: granular mixtures for slope construction, base layers and sub-base in road projects and landfill cover [9, 10]; hydraulic mixtures with Portland cement, mortars, masonry blocks and paving blocks [3, 11-13]; and asphalt [6, 8, 14-17].

These studies show promising results in terms of the technical feasibility of the infrastructure when compared to conventional materials, as well as with the parameters of the current technical standards. However, few studies regarding an environmental investigation and its life cycle in this infrastructure are analysed, about physical and environmental parameters over time; since they are still waste containing levels of toxic substances even at low concentrations.

One of the industrial by-products that arouses much interest on the part of the academic community is the waste foundry sand (WFS) which is a residue produced in large quantities, daily by steelmakers; and because it cannot be disposed of in an unsuitable location [1], because it contains hazardous substances even at levels which place it in the non-hazardous classification [4], rapidly depletes the capacity of industrial landfills [2]. Its reuse, similar to other types of waste, extends to a diverse modality of types of infrastructures highlighting the road projects with flexible pavements. This is due to such projects consume large quantities of mineral resources in the construction of the project layers (layer of subgrade reinforcement, subbase, base and asphalt course). It is important to say that road transport is the main means of transportation in the world [18, 19] and the high availability of waste (more than 115 million tons of ADF produced worldwide each year [20, 21]).

Therefore, the development of methodologies for reuse of WFS in flexible road projects acting as a component of the asphalt is a measure consistent with the production of the waste and the necessity of this type of infrastructure for materials employees. However, it is still necessary the technical and environmental understanding of its behaviour over time over time subject to the efforts of traffic when inserted to the asphalt matrix to evaluate if this practice brings really economic (in terms of durability) and environmental benefits in terms of polluting potential that this pavement could have.

2. MICROESTRUCTURAL AND ENVIRONMENTAL ASSAYS

For the microstructural tests, asphalt containing WFS as fine aggregate in the form of specimens were analysed in an optical stereoscope in increments of 10 and 40 times, obtaining enlarged images to study the microstructures of the asphalt. This procedure was repeated on samples that did not contain WFS that is, control samples.

The environmental tests were developed according to the adapted procedures of EPA 3500c [22] standard, which determines the methods for obtaining solubilized solid waste extract.

In this development the specimens for each type of asphalt (control and containing WFS) were tested. Small portions crushed of specimens (54 ± 0.3 g of each asphalt) were submerged in 430 ± 0.3 ml of distilled water and remained submerged for 7 days after this period the liquid phase was extracted with a 200 μm paper filter. These liquids were oven dried to obtain evaporated extracts which were analysed in a scanning electron microscope equipped with an energy dispersive spectroscope (SEM / EDS) obtaining magnified images of 80 and 2000 times and the elemental composition (% by weight). These same procedures were repeated with WFS in nature to quantify the substances present in the liquid phase of the asphalt containing the residue determining if this asphalt offers environmental risks.

3. EXPERIMENTAL DATA

In this study, mineral aggregates, waste foundry sand, mineral additive and bitumen were used. The materials and their physical properties will be further detailed in accordance with the criteria of the technical specifications.

3.1. Materials

The WFS used was obtained by sampling according to the procedures defined by EN 14899 (2006) [23] standard in an industrial waste landfill located in the City of São José dos Campos/Brazil. In this place the WFS is grounded for more than 30 years under a layer of three meters of compacted soil. The residue originates from the foundry processes of an automobile industry located in the same city as the landfill. To that end, a site at this sanitary landfill was random selected and excavated at a depth of three meters, the debris and soil material were removed and discarded followed by a useful portion of WFS that was sieved in the range of 11.2 mm. The passing material produced a pile of three meters in height by 1.5 meters in diameter. From this pile 2 kg parts at a time were removed from the waste according to the solid waste sampling procedures [23] obtaining a total sample of 150 kg.
The mineral aggregates gravel Gc 90/20, gravel Gc 85/35 [24] and manufactured sand were obtained from a granitic rock mining company located in the City of Jambeiro/Brazil. In this case the procedure of mineral aggregates sampling [25] was conducted, producing a total sample of 150 kg of each material.
For all the granular materials used in this present study (aggregates and WFS) the procedure of reducing samples for laboratory [26] was adopted. The main physical properties of these materials are shown in Table 1 and Figure 1.

Table 1. Aggregates and WFS main physical properties

Test method	Properties	Aggregate/Residue			
		WFS	Manufactured sand	Gc80/20	Gc90/20
EN 1097-7 [27]	Water absorption (%)	0.6 ± 0.01	1.6 ± 0.05	0.6 ± 0.08	0.5 ± 0.07
	Density (g/cm³)	2.2 ± 0.07	2.4 ± 0.08	2.7 ± 0.07	2.7 ± 0.08
EN 1097-3 [28]	Bulk density (kg/m³)	1,489 ± 65	1,776 ± 87	1,765 ± 98	1,943 ± 21
EN 933-1 [29]	Finer than 0.063 (%)	6.4 ± 0.09	13 ± 0.08	1.4 ± 0.1	0.7 ± 0.09
EN 13055-2 [30]	Lightweight (%)	2.86 ± 0.08	0.67 ± 0.06	-	-
EN 933-8 [31]	Sand Equivalent (%)	37.6 ± 0.08	32 ± 0.09	-	-

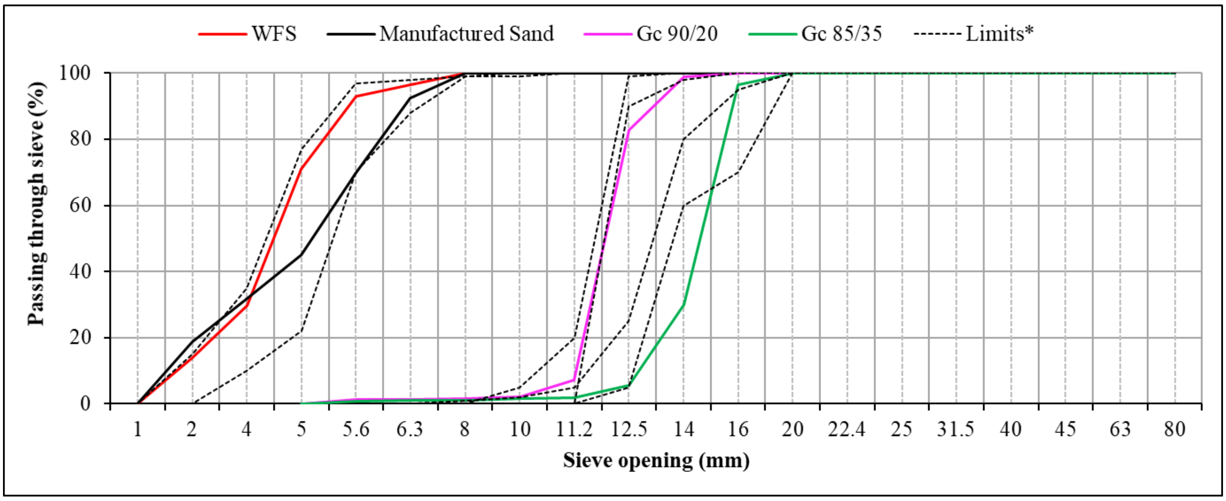
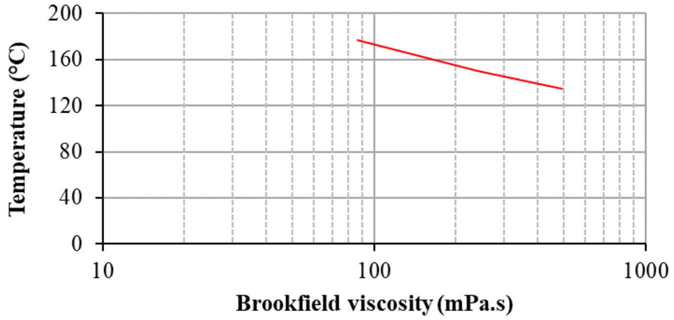


Figure 1: Aggregate and WFS determination of particle size distribution by sieving method [29], (*) according to classification limits [24]

The bitumen used was characterized as 30-45 pen-grade and the mineral additive used was the hydrated lime or With at least 45% of CaO, both of which were purchased from specialized suppliers. The properties of bitumen are shown in Figure 2.



Parameter	Max	Min
Mixture temperature (C°):	162	156
Compaction temperature (C°):	150	145
Brookfield Viscosity mixture (mPa.s):	95	458

Figure 2: Brookfield viscosity of bitumen by ASTM D2983 - 17 (2017) [32]

3.2. Asphalt preparation and compacting

Asphalts control and containing WFS at the 50% substitution rate over manufactured sand were produced by hot blending in a small-scale asphalt plant as shown in Figure 3. The mixtures of aggregates used were determined according to State of São Paulo/Brazil regulation: ET-DE-P00/27 (2005) [33] 12.5 mm for dense Hot Mix Asphalt (HMA), which is the type of asphalt most used in highways in Brazil; the granulometry of these aggregate blends is shown in Figure 4 and the composition by weight of aggregates types are shown at Table 2. The bitumen content of these two mixtures was determined according to the Marshall procedure [34] and these have physical properties presented in Table 2; the same Table also contemplates the terminologies of each mixture being that mixture containing WFS is designated as "50WFS" and control as "Ctr".

Figure 3: Illustrated photographic of procedures for obtaining asphalt

Table 2. Composition of aggregate mixtures

Blends	Proportions of aggregates / WFS (% by weight)				
	WFS	Manufactured sand	Gravel Gc 90/20	Gravel Gc 85/35	$Ca(OH)_2$
50WFS	25.7	25.2	27.6	15.2	1.4
Ctr	0.0	50.9	27.6	15.2	1.4

Table 3. Asphalt main physical properties

Physical properties	50WFS	Ctr	Test method
Optimum asphalt contents (%) by Marshall method	4.8 ± 0.09	4.7 ± 0.05	EN 12697-34 [34]
Bituminous void content (%)	4.2 ± 0.06	4.5 ± 0.01	EN 12697-8 [35]
Bulk density (g/cm³)	2.6 ± 0.02	2.6 ± 0.03	EN 12697-6 [36]
Maximum density (g/cm³)	2.4 ± 0.2	2.5 ± 0.2	EN 12697-5 [37]
Indirect tensile strength at Marshall – ITS or ITS (MPa)	2.2 ± 0.3	2.2 ± 0.4	EN 12697-23 [38]

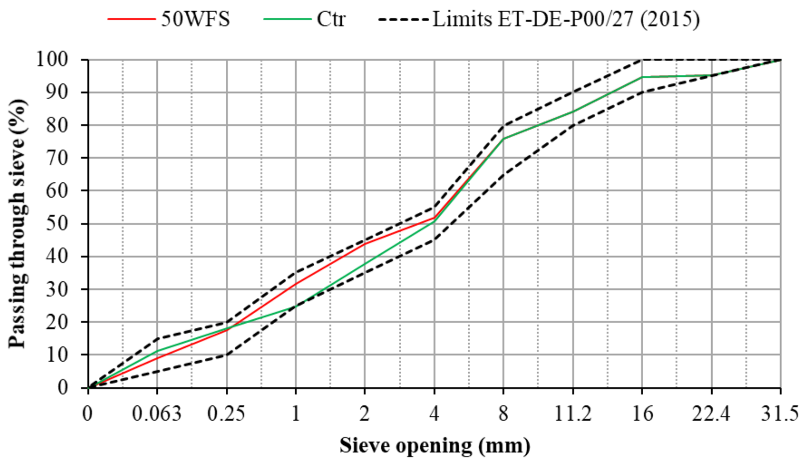


Figure 4: Aggregate and WFS mix particle size distribution according to ET-DE-P00/27 (2005) [33]

The production of cylindrical specimens was conducted according to the SUPERPAVE compaction procedures [39]. The Figure 5 illustrate this procedure, in this stage the equipment used recorded the properties of the asphalt during compaction. These characteristics and quantities of specimens per mixture by mechanical assays that were made are presented in Figure 6. The cylindrical specimens for the flow number [40] and dynamic modulus [41] (FN, DM) tests were compacted in the dimensions of 176 mm in height by 150 mm in diameter; already the cylindrical specimens for stiffness assay (also called indirect tension test for resilient modulus – ITTRM assay) [42] were compacted in the dimensions of 67 mm of height by 100 mm of diameter (same specimens used in ITS assay). The cylindrical specimens for the FN and DM tests were sectioned or extracted in cylinders according to the standards [40, 41].

Figure 5: Illustrated photos about the compacting process

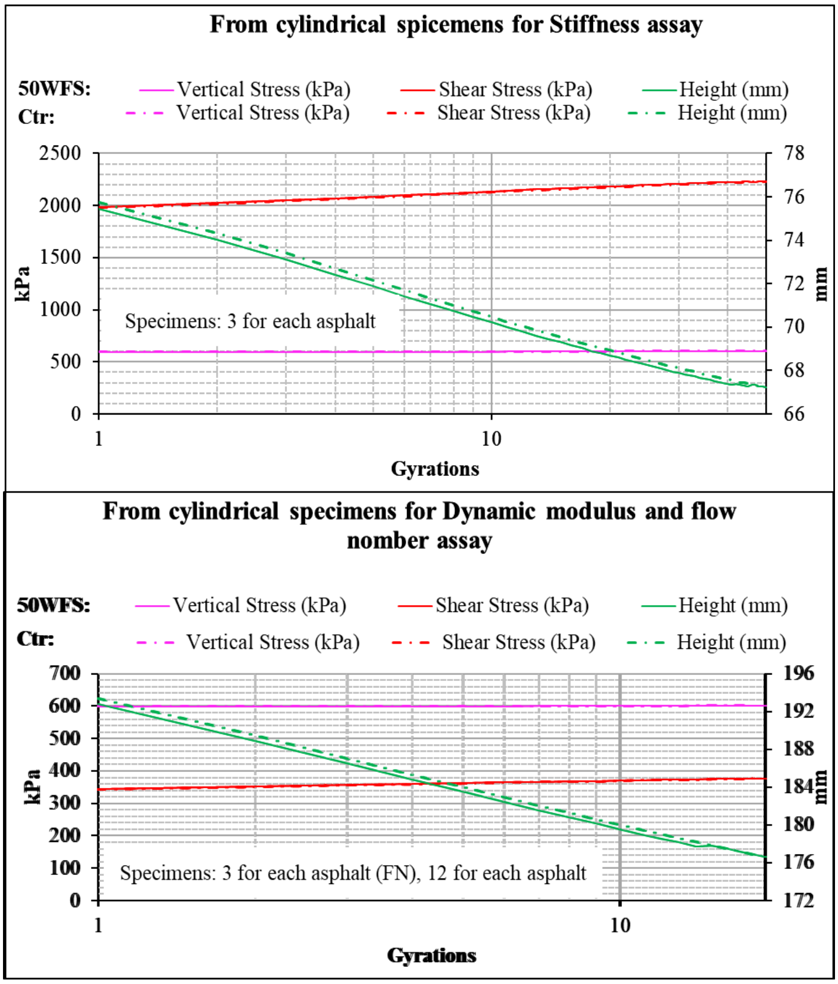


Figure 6: Asphalt behaviour at compacting of specimens

3.3. Mechanical tests

In order to evaluate the mechanical assessment of asphalt containing WFS as an aggregate the 50WFS and Ctr mixtures were tested, in the light of road tests, in order to evaluate resistance to repeated loads such as those from vehicle traffic. The Table 4 presents the tests performed as well as the methods adopted. The environmental and microstructure analysis were performed as shown in Chapter 2 of this paper.

Table 4. Mechanical tests according to standards procedures

Experiment	Test method
Indirect tensile strength (ITS)	EN 12697-23 [38]
Stiffness (ITSRM)	EN 12697 -26 [42]
Dynamic modulus (DM)	ASTM D 3497-03 [41]
Flow number (FN)	AASHTO T 378 [40]

For the stiffness and Indirect tensile strength tests, input parameters were taken for the asphalts, these boundary conditions and other ones were also fixed for the DM and FN being that in these tests the temperatures were varied as specified by the respective standards [40, 41]; except for the temperature of -10 ° C which had not been analysed because it did not correspond to real weather conditions Brazil.
The development of the mechanical tests followed the methodology by the international standards that determine these experimental procedures [40, 41]. The Million Equivalent Single Axle Loads (MESAL) variable which estimates the traffic of vehicles that will produce a wheel tracking rutting (WTR) of 12 mm is also calculated by the flow number test using equation (1). Rutting resistance is known by the flow number test [40] under conditions determined by the National Cooperative Highway Research Program Report 691 [43].

$$MESAL = \frac{F_n^{\,0,9}}{6,2} \tag{1}$$

Where MESAL is the estimated traffic that will produce a 12 mm WTR on the asphalt after a period of 20 years (in millions of repetitions) and *Fn* is the number of cycles for the sample failure or the asphalt flow number. The Table 6 contemplates the criteria for evaluation of *Fn* and *MESAL* according to the AASHTO method [40, 43, 44].

Table 6. Parameters for MESAL according to NCHRP 691 (2011) [43]

Traffic (MESAL)	**Minumum Flow Number (cycles)**
	NCHRP 691 Recommendations
< 3	-
3 to < 10	53
10 to < 30	190
> 30	740

4. RESULTS AND DISCUSSIONS

The results of this present study will be presented according to the methodology. Initially the results of the environmental and microstructural assays of the specimens then the results mechanical assays.

4.1. Microstructural and environmental properties of asphalts containing WFS

Using a Zeiss stereoscope, 10- and 40-fold enlarged images were made of the tops of asphalt specimens (50WFS and Ctr). In the observed region, many images (a total of 10 images for each increase in each asphalt) were acquired in an attempt to obtain a representative of this region. Of all the acquired images the best ones were selected being two images (one for each increase) for each type of asphalt (50WFS and Ctr). Figure 7 presents these images.

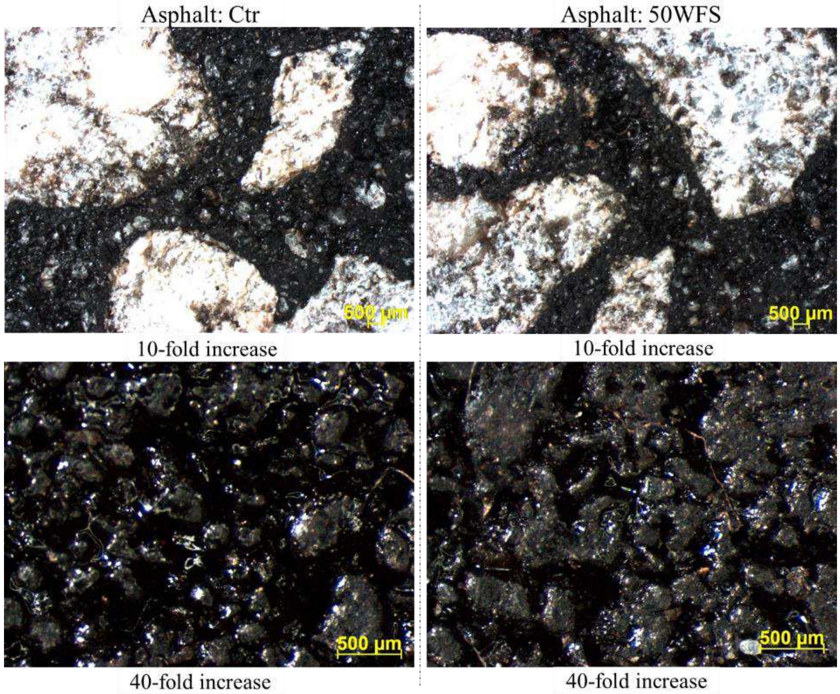


Figure 7: Asphalt microstructure at 10 and 40-fold increases

After a more detailed observation of Figure 6 some considerations, about the microstructure of the 50WFS asphalt, can be made. In the 10-fold increase few differences can be noted with respect to the asphalt Ctr as an apparent superior porosity of the 50WFS asphalt. At the 40-fold increase it is evident that the 50WFS asphalt is a little more frosted than the control suggesting that this blend has a slightly less efficient bitumen coating of the aggregates.
In the environmental assay, after the drying of the aqueous extracts, the substrates obtained were studied with a the MEV / EDS Tecsan. For this purpose, small powder samples (about 0.1 + 0.01 g each) of the initial substrates of 50WFS, Ctr and WFS were glued onto carbon ribbons, as shown in Figure 8. The carbon and sample set were analysed in the SEM / EDS obtaining images of 2000-fold increases, produced by the bombardment of electrons at 15 keV. Figure 9 shows these images.

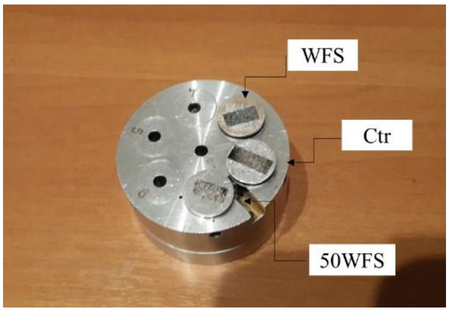


Figure 8: Sampler with dried extracts of asphalt for SEM/EDS analyses

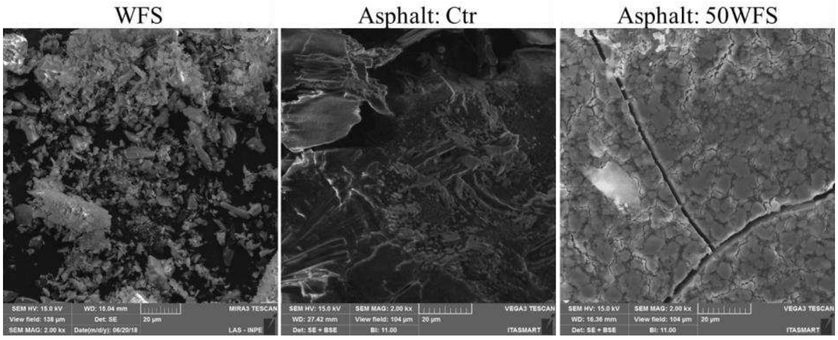


Figure 9: Microstructures at 2000-fold increments by SEM of Dried extracts of Asphalt

In these images microstructures similar to "flakes" are identified in the WFS, they probably refer to the micro-grains that passed through the 200 µm filter. From the dried extracts obtained from Ctr and 50WFS, it is noted that the image of 50WFS is brighter than Ctr this is also noticed in the WFS image, this occurs when there are conductive materials of electric energy in the samples like metals or quartz. Evidence that in the 50WFS and WFS samples are found conductors elements such as metals. Such assumption is ratified when the EDS sensor quantifies the elemental composition (% by weight) of the samples as shown in Table 5.

Table 5. Elemental composition by weight of dried extracts of asphalts by EDS.

Elements	WFS	Ctr	50WFS
C	5.7 ± 0.2	94.68 ± 0.24	93,53 ± 0.18
Al	8.4 ± 0.1	1.12 ± 0.1	-
Fe	7.5 ± 0.03	-	-
K	5.7 ± 0.04	-	-
Na	2.3 ± 0.03	-	-
Ca	2.1 ± 0.04	-	-
Mg	2 ± 0.01	-	-
O	41.7 ± 0.1	-	6,08 ± 0.16
Si	24.6 ± 0.05	2.03 ± 0.13	0,39 ± 0.08
S	-	2.17 ± 0.19	-
Cl	0.5 ± 0.02	-	-

The elemental composition of the dry extracts obtained from the analysed asphalts showed few chemical elements from the WFS in free state, indicating that the asphalt matrix plays the role of encapsulation of these substances in an efficient way. This result is verified by comparing the results of the solubilization test conducted on 50WFS and Ctr asphalts compared to WFS; the results showed a very close elemental composition between the two asphalts and a significant reduction of the elements found in WFS. These results of this environmental test prove the potential of WFS use as an aggregate in paving demonstrating environmental safety of this practice.

4.2. Mechanical behaviour of asphalt containing WFS

The 50WFS asphalt presented diametral compression strength [38] very similar to the result of this test performed in Marshall dosage [34]. For the asphalt containing WFS this resistance was of 2.3 ± 0.3 MPa against 2.5 ± 0.4 MPa of the control, a loss of resistance of the order of 10%. However, according to the criteria of Brazilian transport department (0.65 MPa) [45], this resistance is adequate.

In the stiffness test at 25°C [42] the resilience modules of the asphalts were obtained. For the asphalt 50WFS, maximum values (in average) of 11,240.3 ± 129.1 MPa were obtained against 7,678.7 ± 204.9 MPa of the Ctr (a 30% gain). During the test the equipment used recorded deformation patterns per cycle of application of repeated loads. The Figure 10 shows the graph of recoverable deformations as a function of the application of repeated load cycles during the stiffness assay.

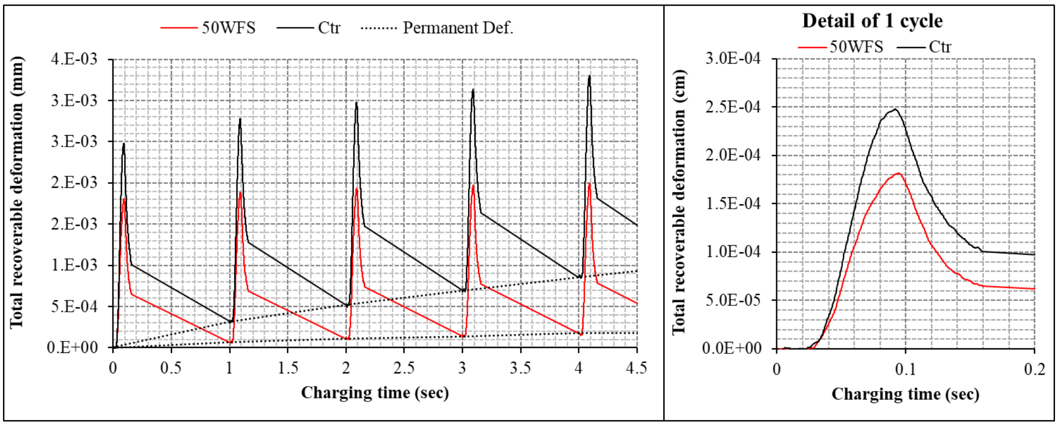


Figure 10: Graph of the total recoverable deformations of the asphalt as a function of the cycles of application of loads in the stiffness assay

In these graphs it is possible to observe that the recoverable deformations in the 50WFS asphalt are smaller than in the Ctr, showing that this asphalt has a greater rigidity modulus than the control. Following the results of the mechanical tests, during the DM test [41] (which was performed on the same equipment used in the stiffness assay) the angle phase curves vs reduced frequency were obtained in the different temperatures of the test, as shown in Figure 11; in the same way the curve of the dynamic modulus values (E *) was obtained as a function of the frequencies for the different test temperatures, as shown in Figure 12.

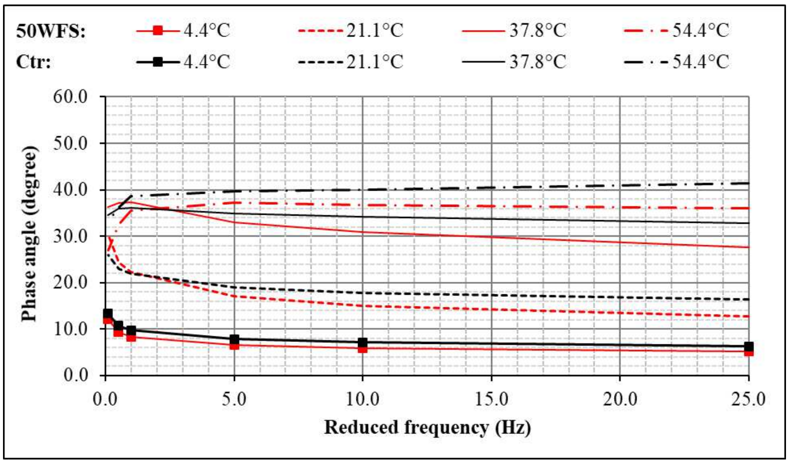


Figure 11: Angle phase curves vs reduced frequency during DM assay

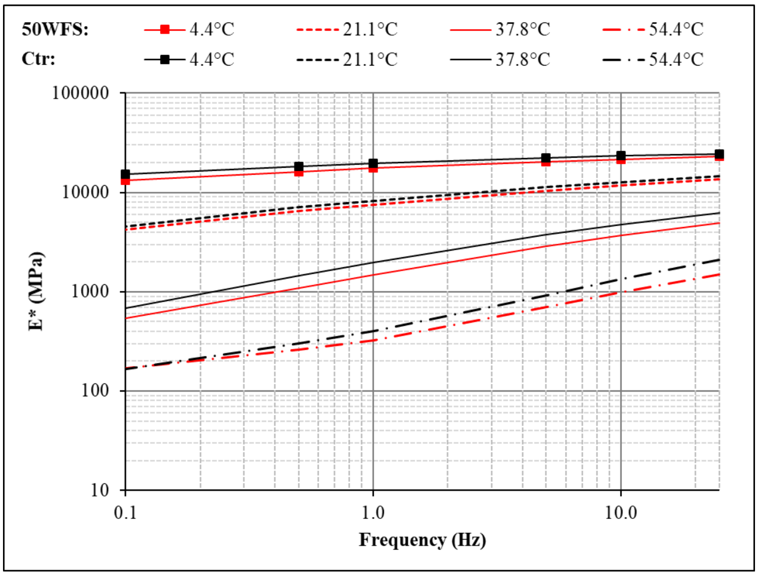


Figure 12: Dynamic modules (E*) vs frequency during DM assay

From these preliminary results of DM test, it is noted that mixtures containing 50% of WFS have lower stiffness, when compared to control asphalt mixes. However, the result obtained by the master curve of the DM test reveals that such property does not influence since the curves of the two asphalts are so similar that it overlaps, as shown in Figure 13. This graph and Table values was plotted using a mathematical approaching, with the E * results, by Witczac [46] model obtaining adjusted values for E*. In the same way so that each result of each temperature remained in the same curve a shift factor, initially developed for the study of viscoelastic or viscoplastic materials [47], was applied.

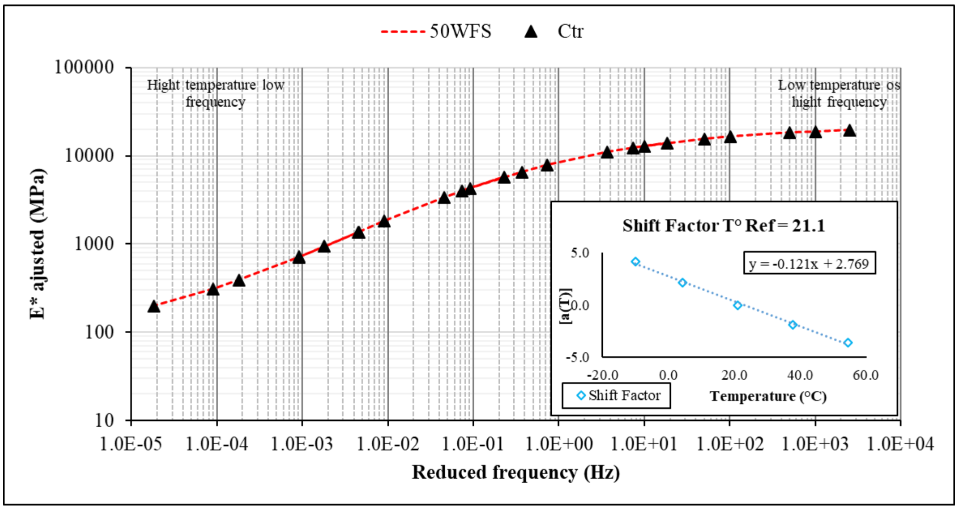


Figure 13: Master curve of DM test

After the non-destructive DM test, the specimens subjected to a temperature of 54.4 ° C continued in the equipment (at the same temperature) and were submitted to a vertical pressure of 600 kPa in charge cycles and without confinement until the failure. This test, according to the standardized methodologies [40], is the flow number test (FN); during the test the equipment registered the permanent deformations in macrostrain (µε) as a function of the load application cycle. The Figure 14 shown these preliminary results.

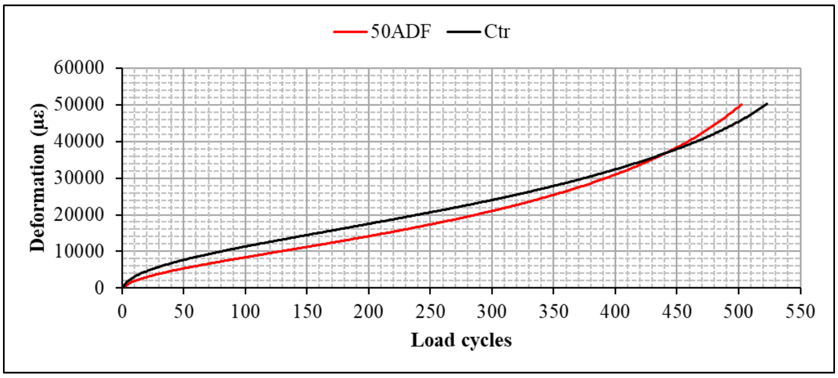


Figure 14: Preliminary results obtained in FN test

The Figure 14 shows that the mechanical behavior against the application of loads cycles of the two asphalts is very similar between them. However, the Ctr asphalt obtained an FN (corresponding to the failure cycle of the specimen) of 193 and MESAL of 16 (millions of repetitions) about twice as high as the 50WFS asphalt (FN = 99, MESAL = 9). Nevertheless, both asphalts remain within the criteria [43].
The FN was the last mechanical test to technically evaluate the asphalt containing WFS, once this test was finished the technical advice about the asphalt with WFS was concluded. And then, these results were compared with the current literature and criteria for asphalt pavements, as presented in Table 6.
It is verified that in all studies and standards the values obtained in results of this paper remain within the parameters showing higher values in the ITS and ITTRM assays compared to the literature however, in the FN assay the cycles required for the specimen failure are much lower than the one found; according to the author [49] the analysis was performed using steel slag residues (this study was chosen at the level of comparison, since no references of FN tests were found in asphalt mixtures containing WFS).

Table 6. Comparative analysis of the results obtained with the current literature and criteria.

WFS cont* (%)	Asphalt concrete type	Bitumen		Origin** (WFS)	Results of references, this paper and standards				References / results / criteria ***
		Grade	Cont (%)		ITS (MPa)	ITTRM (MPa)	FN		
							Cycles	MESAL	
100	SAHM[iv]	30/45	5.0	Steelmakers	0.4	1,385.0	NR[v]	NR	[48]
77	HMA	30/45	6.0	Landfill	1.6	9,031.3	370	28	[49]
50	HMA	30/45	4.8	Landfill	2.2	11,240.3	99	9	Results
30	HMA	50/60	5.4	Landfill	1.1	5700,0	NR	NR	[50]
10	HMA	50/60	5.3	Landfill	0.9	3987,0	NR	NR	[51]
					0.6 < and fc_{max2}[vi]	S_{max} $_{11,000}$[vii]	53 <	3 to < 10	Criteria
					[45 and 48]	[48]	[43]		Standard

Obs: (*) Content bitumen (or WFS) by weight (%); (**) origin of WFS, steelmakers industries or landfill; (***) results found in the current literature and standardized criteria of the mechanical tests performed in this paper; (iv) Sand asphalt hot mix; (v) assay Not Realized in this reference; asphalt classification (criteria) of ITS (vi) and ITTRM (vii) assays by EN 13108-1 (2006) standard [48].

5. CONCLUSIONS

During the experimental program presented in this paper it was possible to reach important conclusions about the mechanical and environmental behaviour of asphalt containing WFS. In the environmental test it was possible to determine that the residue used as fine aggregate in the asphalt matrix does not compromise the environmental safety to the surroundings of the paving project since, asphalt 50WFS did not show release of substances from the WFS in free state, making this asphalt safe to the environment. The mechanical test results confirm the technical feasibility of using WFS in asphalt demonstrating that this asphalt is within the required criteria by standards as well, complying with similar studies found in the current literature.
With this, it is concluded that the use of WFS as an aggregate in asphalt is a technical and environmentally viable technique that can reduce the costs in the asphalt paving projects, as well as bring benefits to the environment such as the reduction of exhaustible natural resources.

ACKNOWLEDGEMENTS

The acknowledgments for the accomplishment of this study go to the Coordination of Improvement of Higher-Level Personnel (CAPES) by the financing. To the Essencis Ecosystems LTDA (A Solvi group enterprise) by supplying WFS from one of its industrial landfills (São José dos Campos / Brazil). To Technological Institute of Aeronautics (ITA) for the technical support of the Laboratory of Aeronautical Infrastructure and its technical team, especially to Rodolfo Belasco. To the Institute of Advanced Studies (IEAv) for the technical support of the Photonic Laboratory (EFO). To the Consortium CCR Nova Dutra for the technical support of the Centre for Road Research (CPR-CCR Nova Dutra).

REFERENCES

[1] The CFR collection of all federal regulations codified and enforced by all federal agencies (2019). Title 40 – Protection of the Environment. [Available at: https://www.govinfo.gov/app/details/CFR-2012-title40-vol27/CFR-2012-title40-vol27-part260, last accessed June 2019]
[2] Bhardwaj B, Kumar P. Waste foundry sand in concrete: A review, Construction and Building Materials, v. 156, 2017, pp. 661-674, DOI: 10.1016/j.conbuildmat.2017.09.010
[3] Halit Y, Hüseyin Y, et al. (2008). Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete, Fuel, v. 87, 2008, pp. 2401-2407, DOI: 10.1016/j.fuel.2008.03.005.
[4] Youyun L, Hui Z, et al., Investigation into the Application of Construction and Demolition Waste in Urban Roads, Advances in Materials Science and Engineering, v. 2017, 2017, pp. 1-12, DOI: 10.1155/2017/9510212.
[5] Chirag M, A review on need of manufactured sand in concrete as a replacement of river sand. Paripex Indian journal of research, v. 3, 2014, pp. 72-74.
[6] Appiah, J K, Berko-Boateng, V N, et al., Use of waste plastic materials for road construction in Ghana, Case Studies in Construction Materials, v. 6, 2017, pp. 1-7, DOI: 10.1016/j.cscm.2016.11.001.
[7] Bandgar G S, Kumthekar M B, et al., A review of effective utilization of waste phosphogypsum as a building material, International Journal of Engineering Research, v. 5, 2016, pp. 277-280, DOI: 10.17950/ijer/v5is1/065

[8] Neil E N, Ahmed S, Use of scrap tires in road construction. Journal of Construction Engineering and Management – ASCE, v. 118, 1992, pp. 561-576, DOI: 10.1061/(ASCE)0733-9364(1992)118:3(561)

[9] Yazoghi-marzouk, Y O, Greullet, N V, et al. Recycling foundry sand in road construction–field assessment, Journal of Construction and Building Materials, v. 61, 2014, pp. 69-78, DOI: 10.1016/j.conbuildmat.2014.02.055

[10] Klinsky L M G, Fabbri G T P, et al., Reuse of waste foundry sand mixed with lateritic clayey soils in pavement bases and sub-bases courses, In: 8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials, v. 11, 2016, DOI: 10.1007/978-94-017-7342-3_46

[11] Saveria M, Daniela S, et al., Used foundry sand in cement mortars and concrete production, The Open Waste Management Journal, v. 3, 2010, pp. 18-25, DOI: 10.2174/1876400201003010018

[12] Mahima G, Salim R, et al., Waste foundry sand as a replacement for fine aggregate in high strength solid masonry blocks, International Journal of Innovative Research in Science, Engineering and Technology, v. 5, 2016, pp. 6878-6886, DOI: 10.15680/IJIRSET.2016.0505037

[13] Yamini S, Behaviour of paver blocks with partial replacement of sand using quarry dust, International Journal of Engineering Research and Modern Education, 2017, pp. 34-38.

[14] Dyer P P O L, de Lima M G, et al., Environmental characterization of Foundry Waste Sand (WFS) in hot mix asphalt (HMA) mixtures, Construction and Building Materials, v. 171, 2018, pp. 474-484, DOI: 10.1016/j.conbuildmat.2018.03.151

[15] Recep B, Hakan K, et al., An investigation of waste foundry sand in asphalt concrete mixtures. Waste management & research, The journal of the International Solid Wastes and Public Cleansing Association – ISWA, v. 24, 2006, pp. 269-74, DOI: 10.1177/0734242X06064822

[16] Dyer P P O L, Klinsky L M G, et al., Macro and microstructural characterisation of waste foundry sand reused as aggregate, Road Materials and Pavement Design, v. 20, 2019, pp. 1-14, DOI: 10.1080/14680629.2019.1625807

[17] Basar H M, Deveci A N, The effect of waste foundry sand (WFS) as partial replacement of sand on the mechanical, leaching and micro-structural characteristics of ready-mixed concrete, Construction and Building Materials, v. 35, 2012, pp. 508–515. DOI: 10.1016/j.conbuildmat.2012.04.078

[18] Traffic Census Map (2015). United Nations Economic Commission for Europe. [Available at: https://www.unece.org/trans/areas-of-work/transport-statistics/statistics-and-data-online/e-roads/traffic-census-map.html, last accessed July 2019]

[19] Our nation's transportation infrastructure (2009). United States Census Bureau. [Available at: https://www.census.gov/newsroom/cspan/transportation/20111209_infrastructure_dot.pdf last accessed July 2019]

[20] Modern Casting Magazine: Global Casting Production Pag. 26 (2017). American Society of Foundry. [Available at: http://content.digitalpub.blue-soho.com/web/y5b2/0A1snzj/ModernCastingDec2017/html/index.html?page=26, last accessed July 2019]

[21] Brazilian Association of Foundry ABIFA (2018). Sectoral Indices - Performance of the Foundry Sector of 2012 to 2018. [Available at: <http://www.abifa.org.br/indices-setoriais/, last accessed December 2018]

[22] United States Environmental Protection Agency (2007). Organic Extraction and Sample Preparation – Test method. EPA 3500c: 2007. Washington D. C.: EPA Standards.

[23] Comité Européen de Normalisation (2006). Sampling of waste material. EN 14899:2006. European Standards Institution

[24] Comité Européen de Normalisation (2013). Bituminous mixtures – Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas. BS EN 13043:2013. London: British Standards Institution

[25] Comité Européen de Normalisation (1997). Aggregates – Tests for general properties of aggregates – Methods for sampling. BS EN 932-1:1997. London: British Standards Institution

[26] Comité Européen de Normalisation (1999). Tests for general properties of aggregates – Methods for reducing laboratory samples. EN 932-2:1999. London: British Standards Institution

[27] Comité Européen de Normalisation (2008). Tests for mechanical and physical properties of aggregates – Part 7: Determination of the particle density of filler - Pycnometer method. DIN EN 1097-7:2008. Berlin: Germany Standards Institution

[28] Comité Européen de Normalisation (1998). Tests for mechanical and physical properties of aggregates. Determination of loose bulk density and voids. BS EN 1097-3:1998. London: British Standards Institution

[29] Comité Européen de Normalisation (1997). Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. DIN EN 933-1:1997. Berlin: Germany Standards Institution

[30] Comité Européen de Normalisation (2016). Lightweight aggregates. BS EN 13055:2016. London: British Standards Institution

[31] Comité Européen de Normalisation (1999). Tests for geometrical properties of aggregates – Part 8: Assessment of fines – Sand equivalent test. BS EN 933-8:1999. London: British Standards Institution

[32] American Society for Testing and Materials (2017). Standard Test Method for Low-Temperature Viscosity of Automatic Transmission Fluids – Hydraulic Fluids, and Lubricants using a Rotational Viscometer. ASTM D 2983-17:2017. West Conshohocken: PA, 2017. DOI: 10.1520/D2983-17

[33] Road Development S.A. – DERSA (2005). Technical specification for asphalt concrete. ET-DE-P00/27: (2005). Sao Paulo: Brazil.

[34] Comité Européen de Normalisation (2004). Bituminous mixtures - Test methods for hot mix asphalt - Part 34: Marshall test. BS 12697-34:2004. Berlin: Germany Standards Institution
[35] Comité Européen de Normalisation (2016). Bituminous mixtures - Material specifications - Part 20: Type Testing. DIN EN 13108-20:2016. Berlin: Germany Standards Institution
[36] Comité Européen de Normalisation (2012). Bituminous mixtures - Test methods for hot mix asphalt - Part 6: Determination of bulk density of bituminous specimens. DIN EN 12697-6:2012. Berlin: Germany Standards Institution
[37] Comité Européen de Normalisation (2018). Bituminous mixtures - Test methods - Part 5: Determination of the maximum density. DIN EN 12697-5:2018. Berlin: Germany Standards Institution
[38] Comité Européen de Normalisation (2017). Bituminous mixtures - Test methods - Part 23: Determination of the indirect tensile strength of bituminous specimens. EN 12697-23:2017. Standards Institution
[39] Comité Européen de Normalisation (2019). Bituminous mixtures - Test methods for hot mix asphalt - Part 31: Specimen preparation by gyratory compactor. EN 12697-31:2019. Standards Institution
[40] American Association of State Highway and Transportation Officials (2017). Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT). AASHTO T-378:2017. Washington D. C.: American Standards Institution
[41] American Society for Testing and Materials (2003). Standard Test Method for Dynamic Modulus of Asphalt Mixtures (Withdrawn 2009). ASTM D 3497-03:2003. West Conshohocken: PA. DOI: 10.1520/D3497-79R03
[42] Comité Européen de Normalisation (2012). Bituminous mixtures – Test methods for hot mix asphalt – Test methods for hot mix asphalt – Part 26: Stiffnes. DIN EN 12697 -26:2012. Berlin: Germany Standards Institution
[43] National Cooperative Highway Research Program (2011). Mix Design Practices for Warm Mix Asphalt. NCHP 691:2011. Washington, D.C.
[44] McGennis, R B, Anderson, R M, et al., Background of SUPERPAVE asphalt mixture design and analysis, 2nd ed., Technology Applications: Innovation Through Partnerships, FHWA-SA-95-003:1995, 172 p., 1995.
[45] Department of Infrastructure of Traffic DNIT (2006). Paving Manual. DNIT ME 031 IPR-719:2006. Publication: Rio de Janeiro, Brazil
[46] Witczak, M. (2005). Simple performance tests: summary of recommended methods and database. NCHRP 547:2005. Transportation Research Board, Washington, DC.
[47] Ferry, J D, Viscoelastic properties of polymer solutions, National bureau of standards – Journal of research, v. 41, 1948, pp. 53-62.
[48] Klinsky, L M G, Bardini, V S S, et al., Re-use of residual cast sand in blends of hot-rolled asphalt sand, Transportes, v. 20, 2012, pp. 27-34, DOI: 10.4237/transportes.v20i4.614
[49] Tavares, D., S. Laboratory evaluation of SMA asphalt mixture with aggregates of steel slag aggregates. Dissertation (Master in Civil Engineering) - Federal University of Rio de Janeiro UFRJ/COPE, 2012, 137 p., Rio de Janeiro, Brazil.
[50] Wesseling, D., H. A study of mechanical behaviour of asphalt concrete with industrial residues incorporated. Dissertation (Master in Civil Engineering) - Federal University of Rio Grande do Sul UFRGS/PPGEC, 2005, 143 p., Porto Alegre, Brazil.
[51] COSTA, C. Casting sand discarded in substitution of fine aggregate in asphalt mixes for paving. Military Engineering Institute, 2008, 16 p., Rio de Janeiro, Brazil.