Mechanical behaviour of asphalt mixtures with steel slag aggregate for construction to be used in road pavement layers

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ABSTRACT

Most transport infrastructures, in particular road and airport pavements, include bituminous mixtures which allow a good performance and an adequate durability under service conditions.
On the other hand, and considering that the current EU policy for residues is based on the guiding principle of hierarchy, supported by an integrated system of waste management, giving priority to prevention, recycling and, only as a final solution disposal, and knowing beforehand that preventing the production of steel slag is not feasible, the waste management strategy should focus on its recovery, mainly through valorisation and recycling solutions.
The incorporation of steel slag aggregates in bituminous mixtures will contribute to a sustainable development, reducing the amount of waste disposal in landfills, hence creating a new national market and therefore preserving the environment by reducing aggregate exploitation and associated energy consumption.
Based on the European standards for natural materials, laboratory tests were performed to characterize and classify this type of material. The definition of the laboratory tests to be carried out, as well as the selection of the most appropriate techniques must be supported on existing experience related to natural materials but with the necessary adaptations to steel slag characteristics.
As a methodology to study the mechanical behaviour of bituminous mixtures with steel slag aggregates, laboratory repeated loading tests were performed, in particular four-point bending tests (4PBT) to determine stiffness and fatigue behaviour, and wheel-tracking tests to evaluate the permanent deformation behaviour.
The fatigue behaviour of studied bituminous mixture was evaluated by the 4PBT, under controlled strain and the application of a sinusoidal loading with different frequencies, according to EN 12697-24. The permanent deformation behaviour of the mixture was determined in accordance with EN 12697-22. Water sensitivity tests according to method A of EN 12697-12 were conducted to evaluate mixture behaviour under water conditions.
The results obtained have shown that the studied mixture AC20 base 50/70 (MB) to be applied as a macadam layer presents an adequate behaviour, namely regarding fatigue and permanent deformation.

Keywords: Aggregate, Environment, Mechanical Properties, Slag

1. INTRODUCTION

Considering that the current EU policy for residues is based on the guiding principle of hierarchy, supported by an integrated system of waste management, giving priority to prevention, recycling and only landfilled filled as a final solution, and knowing beforehand that preventing the production of steel slag is not feasible, the waste management strategy should focus on its recovery, mainly through valorisation and recycling solutions.

All over the world the industry of steel making produces more than 1.5 million tonnes of crude steel every year [1]. Out of this production, proximally 13% to 18% results in waste [2], which means more than 200 million tonnes in steel slag, actually defined as Inert Steel Aggregates for Construction (ISAC), and named ASIC in Portuguese. Despite the notorious growing use of steel slag in construction and road infrastructure, 40 to 50 million tonnes of this material are still being sent for deposit every year enlarging landfills. ´

Due to this situation, there is an urgent need for management and valorisation of these wastes. The incorporation of steel slag aggregates in bituminous mixtures contributes to a sustainable development, reducing the amount of waste disposal in landfills. Simultaneously the creation of a new national market contributes to preserve the environment by reducing the natural aggregate exploitation and associated energy consumption.

Several studies have already been made, in the last two decades, in order to evaluate ISAC application as unbound granular material or on bituminous mixtures [1], [3], [4], presenting as major conclusion the possibility to be considered as construction material to be used in competition with natural aggregates for construction of transport infrastructure.

Although ISAC are recognized to be an excellent substitute for natural aggregates, in Portugal as in other countries, its use in road infrastructure is mainly in the granular layers, so the goal of the study presented in this paper is to contribute for the development and knowledge of the ISAC when applied in other types of layers, namely bituminous layers, and taking into consideration the incorporation of high percentages of ISAC.

2. STUDY OF THE INCORPORATION OF STEEL SLAG AGGREGATES IN BITUMINOUS MIXTURES

Based on the European standards for natural materials, laboratory tests were performed to characterize and classify the selected steel aggregates samples.

The definition of the laboratory tests to be carried out, as well as the selection of the most appropriate techniques have to be supported on existing experience related to natural materials but with the necessary adaptations to steel slag aggregates characteristics.

The study was developed in two stages. The first one deals with the analysis of chemical composition, geometric, physics and mechanical characteristics of ISAC. Then the bituminous mixture was formulated according to the Marshall method (EN 12697-35).

In the second stage a series of tests for assessment of the bituminous mixture performance was carried out, including the evaluation of water sensitivity and resistance to fatigue and permanent deformation for evaluated the feasibility of the studied bituminous mixture for application in bounded pavement layers of transport infrastructures.

3. CHARACTERIZATION OF THE STUDIED MATERIALS

The materials used in this study were cooled air ISAC from electric arc furnace (EAF). The ISAC are from three different fractions 0/6 mm, 6/12 mm and 12/18 mm and were collected in *Seixal* steel site after a proper maturation in order to obtain minimum levels of potential expansion according to the applicable standard and laboratory testing verification. This material was submitted to the following tests and analysis.

3.1 Chemical Characterization

Chemical composition of ISAC was assessed by alkaline fusion with lithium tetraborate followed by acid digestion of the melt. The concentrations of Al, Ba, Ca, Cr, Cu, Fe, Mg, Mn, P, Ti and Zn were evaluated by inductively coupled plasma–optical emission spectroscopy (ICP–OES); the quantification of Si was performed according to polyethylene oxide method of European Standard EN 196-2; the sodium and potassium were determined by flame emission spectroscopy (FES); the concentration of chloride and sulphate was evaluated by titration and gravimetry, respectively.

The results expressed as oxides in percentage on a dry basis (Table 1) are, in general, in good agreement with reported data typically verified in Portugal [1], [6], [7] and also referenced the SAMARIS project, [8]. The reproducibility of replicate analyses was better than 5%.

In what regards to the potential expansion of the studied material registers low values for CaO and MgO.

Table 1: Chemical composition of ISAC compared with reference values

Parameter	Obtained Values (%)	Reference Values (%)	
		[1], [6] and [7]	[8]
Al_2O_3	9.02	3.63 – 6.15	< 10
CaO	21.82	23.80 – 35.21	30 – 40
SiO_2	15.00	11.96 – 15.72	10 a 20
Na_2O	0.14	0.07 – 0.16	-
MgO	4.44	2.72 – 4.44	< 10
K_2O	0.03	0.02 – 0.08	-
Fe_2O_3	41.58	30.40 – 48.23	15 – 35
TiO_2	0.67	0.71 – 0.76	0
Cl	0.02	-	-
SO_3	0.05	0.29 – 1.09	-
Cr_2O_3	2.11	1.50 – 1.97	< 2
MnO	3.57	3.62 – 3.92	< 10
P_2O_5	0.57	0.62 – 1.23	< 2
CuO	0.01	0.02 – 0.04	-
ZnO	0.02	0.01 – 0.07	-
BaO	0.14	0.11 – 0.15	-

3.2 Geometric, Physic and Mechanical Characterization

The same three ISAC fractions were evaluated for their geometry, physic and mechanical characteristics in accordance with the European Standards. The tests and results are presented in Table 2.

Table 2: Geometric, physic and mechanical characterization results

Characterization	Test	Standard	Results or classification (according to EN 13043)	
Geometric	Particle size distribution, Sieving method	EN 933-1	see Table 3	
	Flakiness index	EN 933-3	*FI*10	
	Shape index	EN 933-4	*SI*15	
Physic and Mechanic	Methylene blue test	EN 933-9	MB_F10	
	Sand equivalent test (%)	EN 933-8	87	
	Particle density (Mg/m^3)	EN 1097-6	3.672 (0/4mm) 3.600 (4/12mm) 3.569 (>14mm)	
	Water absorption (%)		$WA_{24}1$	0.5 (0/4mm)
				0.9 (4/12mm)
				0.8 (>14mm)
	Los Angeles test	EN 1097-2	LA_{15}	
	micro-Deval test	EN 1097-1	$M_{DE}10$	
	Affinity between aggregate and bitumen (%)	EN 12697-11	After	6h – 80
				24h – 70
				48h - 60

From these tests results it can be conclude that the ISAC meets all the Portuguese requirements [9] and the studied material presents a very high density, an excellent cubic shape and a clean composition, a very good fragmentation and wear resistance, a reduced water absorption, and a suitable binder-aggregate affinity but a low percentages of fine particles under 0.063 mm.

3.3 Formulation of the Bituminous Mixture

The selected bituminous mixture is a AC20 (MB) type for use in base courses in road infrastructures. This mixture has 92% of ISAC and 8% of commercial limestone filler. It was also used an unmodified bitumen of 50/70 penetration (EN 1426) with a softening point between 46ºC and 54ºC (EN 1427), a Fraass temperature up to -8ºC (EN 12593) and a temperature between 150ºC to 160ºC for the mixture procedure and 145ºC to 155ºC for its compaction.
The particle size distribution of the different ISAC fractions is presented in Table 3. The distribution considers 32% from fraction 0/6 mm, 22% from fraction 6/12 mm and 38% from fraction 12/18 mm, in a total of 92% of SSA. In the same table is also represented the size distribution particles obtained for the final adopted curve, considering the composition of the fractions.

Table 3: Particle size distribution for ISAC and adopted curve

Sieves (mm)	% of accumulated passing material			
	0/6fraction	6/12 fraction	12/18 fraction	Final curve
31.5	-	-	100	100
20	-	-	96	98
16	100	-	61	85
14	99	-	34	75
12.5	99	100	12	66
10	99	76	2	57
8	99	54	1	52
6.3	99	33	1	47
4	87	12	0	39
2	57	7	0	28
1	30	5	0	19
0.5	14	4	0	13
0.250	7	3	0	11
0.125	4	2	0	9
0.063	2.2	1.3	0.2	6.8

To determine the optimal bitumen content (OBC) the Marshall method (EN 12697-34) was used, which gives the stability (MS), flow (MF) and the Marshall Quotient (MQ) and the volumetric values as air voids (V), voids in mineral aggregate (VMA) and void filled with bitumen (VFB).
Each specimen mold has a diameter of 101.6 mm and a height between 61 and 66 mm (EN 12697-30). To guarantee this volume and due to the high percentage incorporation of the Steel Aggregates and its high bulk density, each specimen needs about 1600 g material, well up the normally used quantities for traditional mixtures with natural aggregates.
The preparation of the specimens was made according to the EN 12697-35 with the impact compactor, by applying 75 blows (usually associated with heavy traffic (EN 12697-34) and also because of the hardness of the ISAC) per specimen base. Five different bitumen percentages in mass specimens were prepared, 4%, 4.5%, 5%, 5.3% and 5.5%, in quadruplicate. Table 4 presents the Marshall test results.

Table 4: Marshall test results

Bitumen (%)	Bulk density (Mg/m^3)	Stability (kN)	Flow (mm)	BMT (Mg/m^3)	Voids (%)	VMA (%)	VFB (%)	Q. Marshall (kN/mm)
4.0%	3.20	19.97	4.83	3.526	9.23	21.66	57.40	4.131
4.5%	3.19	19.07	4.87	3.334	4.46	18.38	75.73	3.918
5.0%	3.17	17.90	4.80	3.409	6.96	22.36	68.87	3.729
5.3%	3.17	14.43	4.73	3.390	6.53	22.83	71.41	3.049
5.5%	3.14	14.97	5.17	3.339	5.98	22.74	73.71	2.897

The bulk density, stability and Marshall quotient obtained were higher than those usually observed for conventional mixtures denoting a mixture with good quality, [4]. The values recorded for the deformation, for the porosity and for the VMA, are higher than the normal values for natural aggregates. However it was considered that should be evaluated the mechanical behavior of the formulated bituminous mixture, since it is a bituminous mix with a high ISAC incorporation rate.
According with the Portuguese specifications the OBC achieved was 5.1 % in mass.

4. ANALYSIS OF THE MECHANICAL BEHAVIOUR

To evaluate the mechanical behaviour of the studied bituminous mixture, the tests presented in Table 5 were performed.

Table 5: Tests to evaluate the mechanical behaviour of the bituminous mixture

Test	Reference
Determination of the water sensitivity of bituminous specimens	EN 12697-12
Determination of the indirect tensile strength of bituminous specimens	EN 12697-23
Resistance to fatigue	EN 12697-24
Wheel tracking test	EN 12697-22

4.1 Sensitivity to Water and Indirect Tension Resistance Assessment

To evaluate the rutting susceptibility of the bituminous mixture under water conditions, the indirect tensile strength test was performed in accordance to EN 12697-12 (method A).
The test consists in preparing six specimens according to the Marshall method as previously mentioned (EN 12697-30) considering that three of these specimens are kept on a dry ambient at a controlled temperature (20ºC), while the second group of samples are saturated in a 20ºC distilled or demineralized water. This saturation is done by vacuum and gradually until a pressure of 6.7 kPa, more or less 3 kPa on a period of 10 minutes. Afterword's the samples are immersed on water at 40ºC for a period of 68 to 72 hours. After saturation both groups were kept at a temperature of 15ºC by water immersion, always keeping the first group dry. Then, both groups are subjected to the Marshall compression machine according to EN 12697-34 standard and submitted to a perpendicular charge to the diametral plan resulting on a traction tension until rupture. The relation between the resulting average indirect tension for each group results on ITSR. The obtained results are presented in Table 6.

Table 6: Water sensitivity test results

Parameters	Units	Dry specimens	Wet specimens
Volume	cm^3	499.5	506.6
Bulk density	kg/m^3	3169	3253
Max. Resistance	kN	15.467	14.575
ITS*i*	kPa	1570	1450
ITSR	**%**	**92.4**	

The resulting ITSR value (92.4% > 80%, value specified in Portuguese specifications [9]) reveals an excellent behaviour to water sensitivity which shows a good performance of the ISAC to asphalt adhesiveness due to its high superficial porosity and roughness.

4.2 Fatigue Resistance

The fatigue resistance was determined according to the EN 12697-24 standard procedure, by the four-point bending test (4PBT). Each sample is subjected to controlled and uninterrupted forces, taking them to a consecutive degradation and a subsequent reduction of its hardness module. This degradation is defined by the irreversible accumulation of successive extensions and plastic deformations that leads to shrinkage of the resistant area.
The tested beams were cut from a slab of 305×400×50 mm compressed by a rolling compressor according to the EN 12697-33 standard and considering that each sample had the dimension of 400×50×50 mm.
Table 7 presents the properties for each specimen and the respective applied extension. The result number of cycles before the fatigue analysis is also represented in Figure 1.

Table 7: Specimens properties and testing conditions for the fatigue test

Specimen identification	Stiffness (MPa)	Bulk density (kg/m^3)	Mass (kg/m^3)	Extension (µm)	N.º cycles
5	3231	3218	3166.3	250	2959700
8	3628	3194	3047.9	250	2444310
1	2543	3197	3088.8	350	860000
2	2837	3183	3042.9	350	587500
6	2957	3185	3015.4	350	728000
7	2685	3190	3018.6	500	209600
9	2628	3182	3007.2	500	204120

The conditions stablish for the 4PB test were the following:

- ✓ 10 Hz frequency;
- ✓ Strain levels: 250, 350 and 500 microns of extension;
- ✓ Rupture at 50% of the initial stiffness module;
- ✓ Testing temperature: 20ºC.

The first 100 bending cycles establish the initial stiffness module for each specimen.
At the absence of a reference mixture made of traditional pavement materials, the obtained results were compared to [9] and [10] proposed equations presented at Table 8.
The equation presented in [9] admits values of 3.0×10^{-3} to 3.5×10^{-3} and -0.20 for "a" and "b" parameters, respectively, which rely on the composition and properties of the mixture. It was considered the most conditioning value for the parameter "a" (3×10^{-3}).
For the [10] equation, the resulting Vb values obtained from the present mix (15.81%) and a typical hardness module of 5000×10^{6} Pa were considered.
Table 8 shows the used values for each equation, giving the results shown in Figure 1.

Table 8 – Equations for fatigue law referred at [9] and [10]

[9]	[10]
$\varepsilon t = a\times N^{b}$	$\varepsilon t = (0.856\times Vb + 1.08)\times Em^{-0.368}\times N^{-0.2}$
a = 0.003; b = -0.2	Vb = 15.81%; Em = 5.000 x 10^{6}Pa
$\boldsymbol{\varepsilon t = 0.0030\times N^{-0.2}}$	$\boldsymbol{\varepsilon t = 0.0039\times N^{-0.2}}$

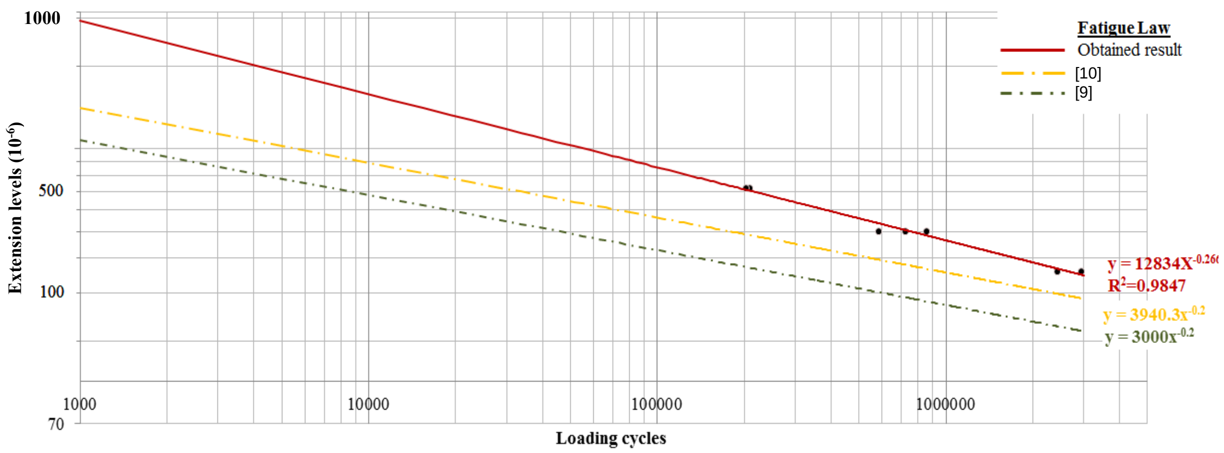

Figure 1: Graphic representation for fatigue behavior

The obtained results present a good homogeneity and consistence, which R^2 from the regression returns the excellent value of 0.985. The behaviour of this mixture presents a very good stability and fatigue resistance when compared with the results of [9] and [10] methods. This result enhances also a good affinity between ISAC aggregate and bitumen.

4.3 Resistance to Permanent Deformation

The mix assessment regarding the permanent deformations was performed according the NP EN 12697-22 standard. This test, known as the Wheel Tracking test, looks forward to assess the liability of the asphalt mix deformation when subjected to a controlled force of a standardized rubber test wheel, of which the velocity and route extension are also controlled. The total number of cycles is 10000 on an air conditioning chamber at 60ºC.
Despite the bituminous mix formulated to be applied in base layer it was considered important to assess their behavior to permanent deformation, although this parameter is not a condition for its approval.
Two small slabs, identified as 1 and 2, with 305x305x50 mm were molded with the rolling compactor (EN 12697-33) and submitted to this test as presented in Figure 2.
After the test run is considered the depth of the deformation and the data to be collected for evaluation are as follows:

- ✓ WTS_{AIR}, Wheel Tracking Slope in air;
- ✓ PRD_{AIR}, Mean Proportional Rut Depth in air;
- ✓ RD_{AIR}, Mean Rut Depth in air.

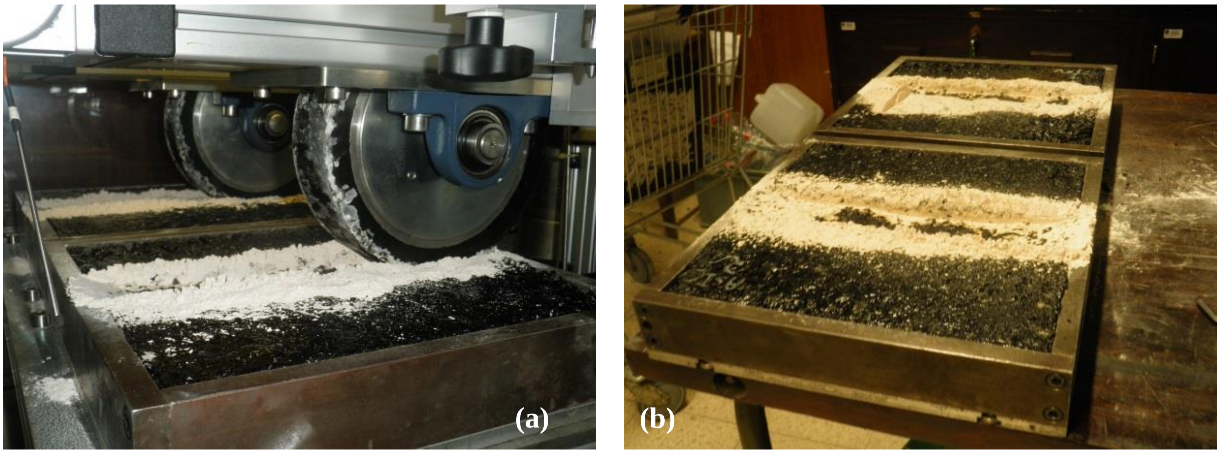

Figure 2: Two specimens during the test (a) and the final result (b)

Table 9 presents the obtained results and Figure 3 represents the variation of the deformation in function of the loading cycles.

Table 9: Wheel tracking test results

Specimens	Parameters	Units	Results
1	Max. deformation Depth deformation at 10000 cycles	mm	6.97
2			9.52
Average depth deformation at 10000 cycles			**8.2**
1	Deformation rate between 5000 and 10000 cycles	$mm/10^3$ cycles	0.18
2			0.26
Average deformation rate for *WTS_{AIR}*			**0.22**
1	Depth deformation at 10000 cycles	%	13.94
2			19.00
Average depth deformation for *PRD_{AIR}*			**16.5**

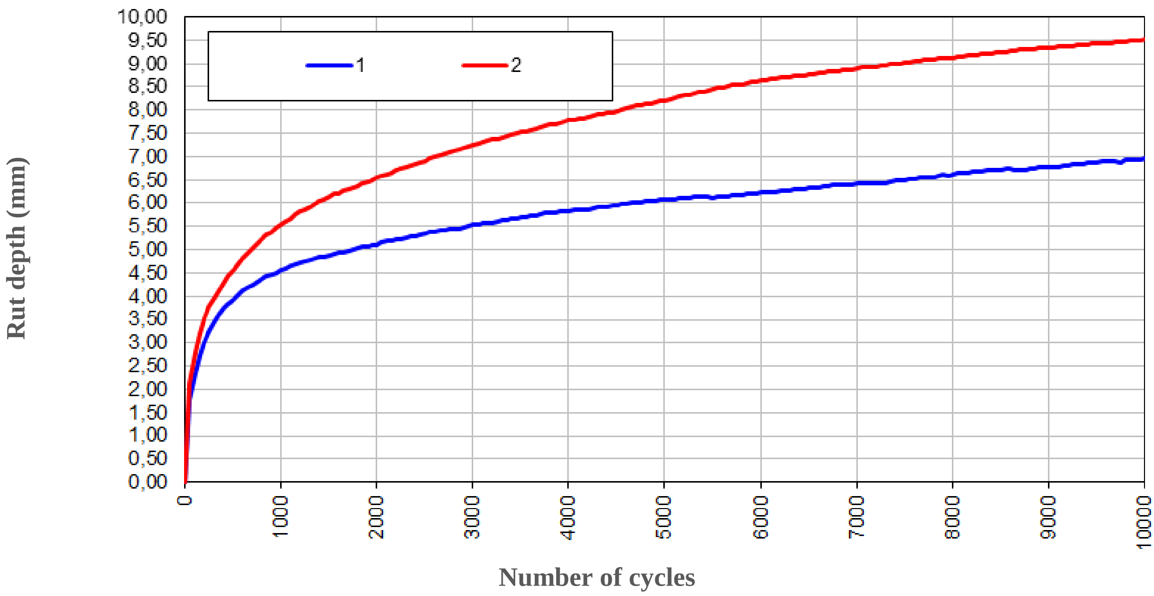

Figure 3: Rut depth evolution from Wheel Tracking test

The obtained data reveals some divergence between the two tested samples (1 and 2), from which result some low average values.

Despite not being prepared a reference mix with the same features from the one presented in this study, for a counterweigh, it's noticeable that the observed deformation is low, but considering the examples before, they seem to point out that use of steel slag aggregates mixed with natural aggregates increases the resistance to permanent deformation.

Considering that we are dealing with a bituminous mixture formulated to be applied on as base course, this behaviour isn't a condition to its application.

5. CONCLUSIONS

The present paper evaluates the feasibility and mechanical behaviour of a bituminous mixture (type AC20) with a high percentage of EAF steel slag aggregates (92%), to be used in base layers of road infrastructures. From this research the following conclusions can be obtained:

- The studied steel slag aggregates respects all geometric, physical and mechanical requirements established for natural aggregates traditionally used in road constructions, presenting also better results than those;
- The chemical results indicates that the production process followed by a proper maturation of the steel slag aggregates are adequate for chemical stabilizations, preventing ambient impacts and public health safety and reducing the expansibility potential;
- The incorporations of steel slag aggregates, increase significantly the stability and the bulk density of the mixtures by Marshall method (EN 12697-35:2004+A1:2007);
- The incorporation of ISAC also increase the voids content, mostly within the upper limits required (6%) and the flow values slightly above the maximum (4 mm).The last situation was confirm by the wheel tracking test (EN 12697-22:2003+A1:2007), which presents results that should not be neglected, but are not conditioned for the studied application, as base course;
- The bituminous mixture presented a suitable affinity (EN 12697-11:2012) between bituminous binder and steel slag aggregate without any additives;
- Excellent results in the ITSR test (EN 12697-23:2003) denote a very good resistance and low water sensibility (EN 12697-12:2008);
- In the fatigue test (EN 12697-24:2012) the studied mixture presents better and promising results comparing with the [9] and [10] fatigue equations.

In summary, the present paper allows us to conclude that steel slag aggregates demonstrate an enormous potential as a substitute for natural aggregates extending its use to bituminous mixtures, acknowledge and expanding this new market and reinforce the management and recovery of this wastes, preserving so the natural resources and the environment.

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