Portuguese steel slags. A new geomaterial

Laitiers d'aciérie Portugaise. Un nouveau géomatériau

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ABSTRACT

The engineering properties of Portuguese processed steel slags (ISACs) are tested to evaluate the appropriateness of their use in transportation infrastructures and geotechnical works. The laboratory results are compared with values specified in the Portuguese standards for natural aggregates and with values found for natural aggregates of various geological origins. The elastic modulus is carefully evaluated in order to compare the two ISACs with two standard base coarse materials (granite aggregate 0/31.5mm and limestone aggregate 0/19mm). All laboratory results show that the national processed steel slags could be used in geotechnical works, and particularly in transportation infrastructures. The two ISACs demonstrated better mechanical properties than the standard, unbound, granular base, coarse materials.

RÉSUMÉ

Dans cet article sont présentés les résultats d'essai en laboratoire pour évaluer les propriétés des agrégats laitiers d'aciérie Portugaises (ISAC), dans le but de leur utilisation dans des infrastructures de transport et des travaux géotechniques. Les résultats sont comparés aux valeurs indiquées dans les normes portugaises pour les agrégats traditionnels et avec des valeurs trouvées pour les agrégats naturels de différentes origines géologiques. Une attention particulière est faite en termes du module élastique, comparant les deux ISACs, à deux matériaux standards de sous-couches de chaussées (agrégat 0/31.5mm de granite et agrégat 0/19mm de calcaire). Tous les résultats de laboratoire montrent que les laitiers d'aciérie Portugaises pourraient être employés dans les travaux géotechniques, et en particulier dans les infrastructures de transport. On l'a également expérimentalement observé que les deux ISACs ont de meilleures propriétés mécaniques que les matériaux non traités des sous-couches des chaussées.

Keywords: Steel slags, Young modulus, index properties, engineering properties

1 INTRODUCTION

According to the routine tests and criteria for natural materials, nontraditional materials have generally been considered unsuitable for use in geotechnical works. However, there is now an increasing pressure to re-use these materials. Therefore, it is necessary to demonstrate that the use of nontraditional materials in lieu of natural materials will assure, at a minimum, the same construction quality and long-term performance.

In this framework, a Research and Development Project is underway in Portugal to determine a re-use application in geotechnical works for the processed steel slags (actually defined as Inert Steel Aggregates for Construction – ISAC) produced by the two Portuguese Steel Companies. Details of the processing ISACs were reported by Roque et al. (2007). The two Portuguese Steel Companies (Seixal - SN of Seixal; and Maia - SN of Maia) estimate the annual production of ISACs in their electric furnaces to be about 270 000 tons; they expect to produce, within medium term, 400 000 tons. The project, named "Application of waste in transportation infrastructures and geotechnical constructions – Re-use of steel slags", is financially supported by the Portuguese Foundation for Science and Technology (FCT) and Portuguese Steel Companies (SN), and also embraced by the Portuguese Roads Administration (EP) and the Institute for Waste Affairs (APA). It involves the National Laboratory of Civil Engineering (LNEC - coordinator), the University of Minho (UM) and the Centre for Re-use of Waste (CVR). The main purpose of the project is to create a mechanistic and environmental approach intended to promote the re-use of waste, in general, and processed steel slag, in particular.

There is some common understanding that many of the engineering test methods used for natural materials may not predict true field performance when applied to non-natural materials. For this reason, this project gives priority to laboratory performance-related tests for engineering properties. It also examines environmental properties, which are relevant for non-natural materials, as well as field tests, involving monitoring to calibrate the laboratory test results. In this sense, this project follows the most relevant recommendations of the European Community projects (Courage, Alt-Mat and Samaris).

In this sense, to evaluate the re-use of processed steel slags in transportation infrastructure and geotechnical constructions, a vast experimental programme was implemented in the laboratory to study the mineralogical, chemical, geometrical, physical and mechanical properties. The aim of this preliminary study is to compare the values of these properties obtained for the processed steel slags (ISACs) with values specified in the Portuguese standards for natural aggregates that could be applied in transportation infrastructures.

Some of the geometrical, physical and mechanical properties are measured and compared with values specified in the Portuguese standards for natural aggregates and with values found for natural aggregates of different geological origins. Furthermore, the elastic modulus is specially emphasized, comparing the two ISACs with two standard base course materials (granite aggregate 0/31.5 and limestone aggregate 0/19).

The laboratory results for the chemical and environmental properties can be found in the work by Roque et al. (2007). From a leachability point of view, the ISACs are an inert waste.

All the properties presented for the Maia ISAC were determined in a sample collected from a six-month maturation pile, and those of the Seixal ISAC were determined from a sample collected from a pile with a particle-size diameter range from 0 to 40mm (maturation time unknown).

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2 INDEX PROPERTIES

To assess the index properties of ISACs, Portuguese standards/specifications were used as a replacement for the equivalent European standards since, in this transition stage, many of the known reference studies have also been performed using the Portuguese standards/specifications. Table 1 summarizes some of the results obtained for the index properties of Seixal and Maia ISACs.

Table 1.Index properties of Seixal and Maia ISACs.

Properties	Parameter	ISAC	
		Seixal	Maia
Geometrics	D_{max} (mm)	38.1	76.1
	D_{10} (mm)	0.22	1.96
	D_{30} (mm)	2.63	8.50
	D_{60} (mm)	7.30	18.89
	C_u	33.20	9.64
	C_c	4.30	1.95
	Flakiness	5	10
	Shape	6	7
Physics	SE (%)	80	100
	VBS (%)	0	0
	LL (%)	NP	NP
	PL (%)	NP	NP
	ρ_{dOPM} (10^3 kg/m^3)	2.32	2.43
	w_{OPM} (%)	5.0	3.45
	ρ_i (10^3 kg/m^3)	3.31	3.45
	ρ_s (10^3 kg/m^3)	3.05	3.25
	ρ_d (10^3 kg/m^3)	2.94	3.17
	Abs (%)	3.87	2.59
	Gs	3.07	3.29
Mechanical	LA (%)	23	28
	MDe (%)	11	11
	CBR_i	100	72
	CBR_e	51	48
	Exp_{CBR}	0	0

D: Diameter; Cu: Uniformity coefficient; Cc: Curvature coefficient; SE: Sand equivalent; VBS: Value of Blue Methylene; LL: Liquidity limit; PL: Plasticity limit; ρ_{dOPM}: Dry density referred to the modified Proctor; w_{OPM}: Water content referred to the modified Proctor; $\rho_{i;s;d}$: (i) impermeable; (s) saturated particles; (d) dry Density; Abs: Water absorption; Gs: Particles density; LA: Los Angeles; MDe: Micro-Deval; $CBR_{i;e}$: (i) Immediate; e (imbibed) California Bearing Ratio; Exp_{CBR}: Expansion determined at the CBR test; NP: Non-plastic.

Table 1 shows that the values found for the two ISACs are quite similar.

As concerns grading, the two ISACs show continuous grading size and similar Flakiness and Shape Indexes. As the physical and mechanical properties demonstrate, the ISACs are non-plastic and have high values of dry density and low water content referred to the modified Proctor. ISACs have good resistance to fragmentation and abrasion, with values of Los Angeles of 25% and micro-Deval of 11%. The values found for the CBR are substantially higher than the values specified into the Specification of the Portuguese Roads Administration for traditional materials. The imbibed CBR test showed that ISACs do not swell (expansion value of 0%).

3 ISACS ELASTIC YOUNG´S MODULI

The state conditions of the studied ISACs samples are shown in Table 2. The same table also presents the results for two standard base course materials (granite aggregate 0/31.5; 0/19 and limestone aggregate 0/19), which will be used for modulus comparison purposes.

The triaxial ISAC specimens were 150mm in diameter and 300mm in length. They were compacted in six layers by vibrating hammer.

Table 2. Compacted specimen state conditions.

Material	ρ_d (x10^3 kg/m^3)	w (%)
Seixal ISAC (0/19)	2.31	5.8
Maia ISAC (0/19)	2.43	3.5
Granite aggregate (0/31.5)	2.19	3.9
Limestone aggregate (0/19)	2.13	3.9

The ISACs' moduli were evaluated by precision triaxial test with the equipment available at the Civil Engineering Laboratory (Geotechnics) of the University of Minho. Axial strains were locally measured using three vertical LDTs (Local Deformation Transducer - Goto et al. 1991). The interstitial air in the material specimen is assumed to be at the atmospheric pressure through the drainage system.

The test procedure to obtain the material elastic modulus uses several stresses following a test protocol presented by Gomes Correia et al. (2005). For each confining pressure (100, 200 and 300 kPa), after consolidation, the test begins with a deviatoric loading applied up to around 1x10^{-3} of axial strain, to obtain the decay curve of secant Young's modulus with vertical strain. The strain rate of the test is approximately 0.03 mm/min. During the unloading process, very small unloading/reloading cycles of vertical stress were performed at different steps (at approximately the maximum value of deviatoric stress (q_{max}) applied to the specimen, at $q_{max}/2$, and at q = 0 kPa). For each step, five unloading/reloading cycles of small vertical stress amplitude were applied. The amplitude was controlled to ensure that the cycles were closed and linear, in order to evaluate the elastic modulus.

Based on previous findings (e.g., Hoque & Tatsuoka 1998, Gomes Correia et al. 2001) the very small strain vertical Young's modulus (E_v) is fitted by a power law with the vertical stress σ_v. The results have been analysed in total stresses and the values normalised for a stress p_a, of value 100 kPa. The power law to describe such behaviour is given by Equation 1.

The test results, for a strain level of 4x10^{-5}, are shown in Figure 1.

$$E_v = C\left(\frac{\sigma_v}{p_a}\right)^n \qquad (1)$$

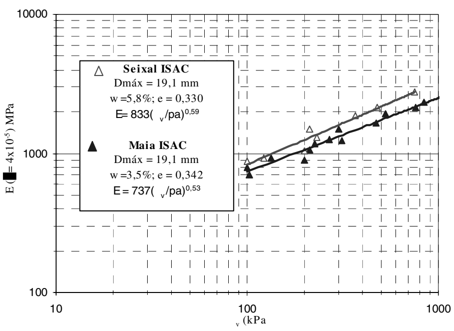

Figure 1. Young's modulus evolution of national ISACs with total stresses.

As can be seen, the total stress analysis leads to a power (n) equal to 0.59 and 0.53 for Seixal and Maia ISACs, respectively. These power values are similar to the usual values found for natural traditional materials, which normally are around 0.5. Figure 1 also shows that the values found for the elastic modulus are too high, around 1GPa for a vertical stress of around 150 kPa. This reveals the excellent mechanical behaviour (stiffness) of the national ISACs.

4 TECHNICAL VIABILITY OF USING ASICs INTO PAVEMENTS STRUCTURAL LAYERS

4.1 *Comparison of Index Properties between ISACs and Natural Aggregates*

Table 3 compares the values found for the index properties for ISACs and for natural traditional aggregates of different geologic origins. The natural aggregates were studied in a European project named Courage.

Table 3.Index properties of ISACs and natural aggregates.

Parameter	ISAC		Aggregate		
	Seixal	Maia	Gneiss	Granite	Limestone
LL	NP	NP	29	NP	16
PL	NP	NP	20	NP	NP
Shape Index	6	7	30	7	17
Gs	3.07	3.29	2.62	2.75	2.71
LA	23	28	16	28	19.4
MDe	11	11	9.8	-	12.2
ρ_{dOPM} (10^3 kg/m^3)	2.32	2.43	2.19	2.29	2.21
w_{OPM} (%)	5.0	3.45	6.25	5.4	4
CBR (%)	100	72	270	140	-

Table 3 reveals that the values found for shape index for ISACs and granite aggregate are similar and the Los Angeles values of Maia ISACs and granite aggregate are equal. The values of CBR found for the ISACs are very different, about 50% lower when compared with the granite aggregate. However, these CBR values are given by an empirical test and should be accepted cautiously. In a recent EC 4th Framework-funded project (Alt-Mat, 1999), some waste showed better mechanical performance in the field than what would be expected from the results of empirical tests. Consequently, the design should be based on performance-related tests. This reveals the need to change the principles of material characterisation, strengthening the rational bases (mechanistic approach), and relying less on the more empirical ones.

Figure 2 shows the unbound aggregates (ISACs and natural aggregates) classified by mechanical index tests according to French classification (NF P18 – 101 (1983)).

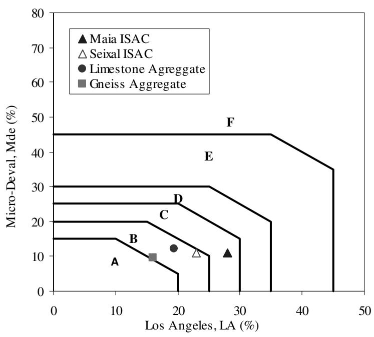

Figure 2. Unbound aggregate classification by mechanical index test.

Figure 2 reveals that Maia ISAC belongs to class C and Seixal ISAC belongs to class B, similar to the gneiss and limestone aggregates.

According to EN 13242 (2002), Seixal and Maia ISACs are both an Mde20 and, respectively, a LA25 or LA30. Natural material (limestone and gneiss aggregates) are Mde20, like the ISACs. According to the LA values, the limestone and gneiss aggregates are LA20 and the granite aggregate is LA30. These classifications imply that natural aggregates have better mechanical index properties than Maia ISAC. However, this evaluation must be considered carefully, as Section 4.3 will demonstrate.

4.2 *Comparison between ISACs Properties and Specification of the Portuguese Roads Administration for Natural Aggregates*

The Specification of the Portuguese Roads Administration establishes that the natural, raw, crushed materials to be applied in base and sub-base layers should be non-plastic and that the same materials, when applied in capping layers, should present a liquidity limit less than or equal to 25% and a plasticity index less than or equal to 6%. The specification also establishes a minimum value of 30%, 45% and 50% for the sand equivalent at capping, sub-base and base layer, respectively. For Los Angeles, established values are 40% for capping and base layers and 45% for the sub-base layer. These requirements are completely satisfied by the ISACs.

Figure 3 shows the particle-size distribution curves of ISACs and the particle-size distribution ranges defined in the Specification of the Portuguese Roads Administration for crushed natural raw materials for these applications. The curves of the ISACs do not fit completely in the specified ranges. Although correction grading would be feasible, embankment trials have shown a good performance during compaction and have demonstrated good mechanical behaviour, both for Maia and Seixal ISACs existing gradings (Gomes Correia et al. 2008).

In conclusion, the results obtained with the tested ISACs demonstrate that these materials do fulfill the requirements of the Portuguese Roads Administration.

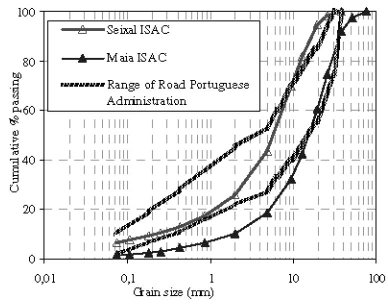

Figure 3. Particle size distributions of Maia and Seixal ISACs and their comparison with particle size distribution ranges specified by the Portuguese Road Administration.

4.3 *Comparison between ISACs and natural aggregates moduli and index properties*

The results obtained for the elastic modulus as a function of total stress are shown in Figure 4 for the ISACS and two standard base course materials (granite aggregate 0/31.5 and limestone aggregate 0/19) after void-ratio normalization (e = 0.3). Details of grain-size distribution curves and void-ratio normalization are described in Gomes Correia et al. (2009).

Figure 4 demonstrates that the moduli values found for ISACs are much higher than for natural aggregates. This reveals that national ISACs have much better mechanical properties (stiffness) than a standard base course material. These results, alongside those reported by Gomes Correia et al. (2005, 2006, 2008) and Roque et al. (2007), emphasize that the national ISACs could be used in geotechnical works, and particularly in transportation infrastructures.

Upon comparing the results obtained from the mechanical index test and the values found for the Young's modulus for the ISACs and natural aggregates, the ISACs demonstrate better mechanical performance than would be expected based on the mechanical index test results (CBR tests, MDe and LA). This reveals the need to change the principles of material characterisation, strengthening the rational bases (mechanistic approach) and lessening the focus on the more empirical ones, especially in case of nontraditional materials.

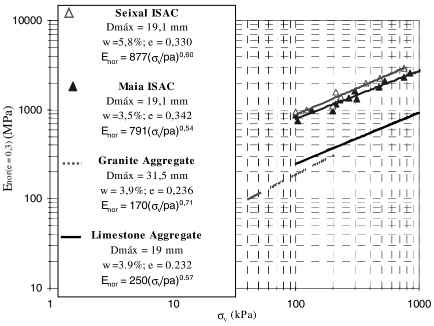

Figure 4. Comparison of moduli for ISACs and standard base course materials (Gomes Correia et al. 2009).

5 CONCLUSIONS

This research seeks to promote the re-use of processed steel slags as a substitute for natural aggregates or traditional materials used in transportation infrastructures and geotechnical works. It contributes technically and scientifically to the application of the principles of sustainable development to construction, specifically to geotechnical works. It also contributes to the preservation of natural resources (natural materials) and reduction of waste volume to be deposited in landfills.

Based on the empirical test results obtained with the tested ISACs, these materials do meet the specifications of the Portuguese Roads Administration. The laboratory performance-related tests show that these materials have better mechanical properties (stiffness) than standard base course materials. These results emphasize that the Portuguese processed steel slags, named ISACs, could be used in geotechnical works, and particularly in transportation infrastructures (embankments, capping layers and base courses).

This study additionally revealed that the empirical test, when applied to nontraditional materials, must be critically considered. The principles of material characterisation should possibly be changed to focus more on the rational bases and less on the more empirical ones, at least in case of nontraditional materials.

A full-scale road section has been built and field test results during construction (data not presented here because lack of space) confirm these laboratory findings. Furthermore, field tests are being performed to evaluate long-term mechanical and environmental property behaviours.

As concerns the environmental aspects of this material, the ISACs are an inert waste in terms of leacheability.

Based on the experiences of other countries, as well as the technical data already collected in the framework of this national research project, the Portuguese processed steel slags should be considered as a construction material and, consequently, should be used in competition with natural aggregates for construction of transportation infrastructures and other geotechnical works.

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