MECHANICAL AND ENVIRONMENTAL BEHAVIOR OF GRANULAR MATERIALS. APPLICATION TO NATIONAL STEEL SLAG

Sandra M. Reis Ferreira and António Gomes Correia
University of Minho, Department of Civil Engineering, Guimarães, Portugal
E-mail: sandraferreira@civil.uminho.pt

António J. Roque
National Laboratory of Civil Engineering, Lisbon, Portugal

António M. Cavalheiro
Portuguese Iron Steel Company, Seixal, Portugal

KEYWORDS
ISAC, exploitation, performance laboratory tests, empirical tests

ABSTRACT

Nowadays, there is strong pressure to use industrial by-products and waste in construction of transport infrastructures and geotechnical works. The possibility of recycling of these materials benefits environmental issues, resulting in reduction of deposits and the preservation of raw materials. This paper presents the geotechnical and geoenvironmental results obtained in the processed Portuguese electrical arc furnace steel slag that are studied during the PhD research. These test results were in a first step compared with those based in the empirical tests used in the national specifications for the embankments and structural layers of transport infrastructures. It was concluded that performance laboratory test results show a much better material performance than the results based in empirical tests (Los Angeles and micro-Deval). In addition, this material, when compared with results of mechanical tests of natural unbound granular materials used in road construction, has showed better mechanical performance. Additionally, leaching test results show that this by-product is inert and became titled “Inert Steel Aggregates for Construction (ISAC)”. These laboratory conclusions were validated in a full-scale trial by end performance testing, where were applied raw materials and ISAC.

1 INTRODUCTION

The two Portuguese Iron Steel Companies - ISC (one is located at Seixal - ISC Seixal, and the other at Maia - ISC Maia) estimate the annual production of processed steel slag in their facilities at about 270,000tons per year (t/y) and are expecting to produce, within medium term, 400,000(t/y). The management of this large volume of material, in accordance with the applicable legal framework, represents a significant source of concern for the Companies and for the country.

According to the routine tests and criteria for natural materials, steel slag materials have generally been considered, in the past, as unsuitable for use in geotechnical works, as many other non-traditional materials.

Therefore, the waste management strategy should favor the exploitation of its potential, namely through re-use solutions. In this context it is desirable to apply to these materials the principles of sustainable development: (i) reducing the quantities of waste that is disposed of in landfill; (ii) creating a new and important national market; and (iii) preserving natural raw materials. It is, therefore, necessary to demonstrate that the use of non-traditional materials, instead of natural ones, will assure, at least, the same construction quality and long term performance. On this basis, a Research and Development Project (R&D) is undertaken in Portugal, which is intended to study the re-use processed steel slag, actually named Inert Steel Aggregate for Construction (ISAC), produced in the Portuguese Iron Steel Companies. The project, named “Application of waste in transportation infrastructures and geotechnical constructions – Re-use of steel slag”, is financially supported by the Portuguese Foundation for Science and Technology (FCT) and ISC, and also embraced by the Portuguese Roads Administration (EP) and the Portuguese Environment Agency (APA). It includes the National Laboratory of Civil Engineering (LNEC - coordinator), the University of Minho (UM) and the Centre for Re-use of Waste (CVR). Its main purpose is to contribute to the creation of 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 slag in transportation infrastructure and geotechnical constructions, a vast experimental programme was implemented in the laboratory to study the mineralogical, chemical, environmental, geometrical, physical and mechanical properties.

This paper presents the geotechnical and geoenvironmental results obtained in the processed Portuguese electrical arc furnace steel slag that are studied during the PhD research. These test results were in a first step compared with those based in the empirical tests used in the national specifications for the embankments and structural layers of transport infrastructures. In addition, this material is compared with results of mechanical tests of natural unbound granular materials used in Portuguese road construction.

2 FROM STEEL SLAG TO ISAC

Steel slag is initially separated from liquid steel and emptied in a steel slag pit. It is afterwards subject to one appropriate processing so as to be recycling as ISAC (see Figure 1) in the transportation infrastructures and geotechnical works. The three phases of that processing are described below (Roque et al., 2007).

Phase A: Flow and cooling of steel slag
A.1: Transferring steel slag from the pit to an impervious zone, cooling with water, and transport to the storage/treatment zone; A.2: Cooling to air at the storage/processing zone (may be accelerated by water). The resulting material is designated as non-processed steel slag.

Phase B: Recycling of the metallic component
B.1: Breaking up of larger steel slag plates and recovering the larger metallic components; B.2: Separating the metallic parts from the non-metallic parts using magnetic drums. The metallic parts are to be recycling in steel production. Only a small quantity of minor metallic scraps is present in the remaining steel slag.

Phase C: Recycling of the non-metallic component
C.1: Sieving/grading in various grain-size ranges; C.2: New mechanical breaking up, with possible grinding, to produce finer grain-sizes; C.3: Elimination of smaller metallic scraps, not eliminated in the previous phase, by passage with magnetic plate and/or re-processing, by passing again the material in the magnetic roller; C.4: Storage and maturation by hydration to air, for the time necessary to neutralise the remaining lime.

Figure 1. Portuguese processed steel slag (ISAC).

3 CHEMICAL MINERALOGICAL AND ENVIRONMENTAL PROPERTIES

To study the chemical and mineralogical properties of the global fraction of ISAC, 5 samples were collected from a pile with a 3-month maturation and 5 samples were collected from a pile with a 6 month maturation at the storage facilities of ISC Maia and ISC Seixal. The other properties of ISAC from ISC Maia were studied on a sample collected from a pile with a 6-month maturation, and of ISAC from ISC Seixal were studied on a sample collected from a pile with a grain-size in the range of 0-40 mm diameter (the maturation time was unknown at the ISC).

The contents of the chemical species were obtained by X-ray fluorescence spectrometry, for a basis of 100% in weight. The three chemical species with the highest percentages are iron oxide (Fe_2O_3), calcium oxide (CaO) and silicon oxide (SiO_2), which from the set of all chemical analyses, range, respectively, from 30.40 to 48.23%, 23.80 to 35.21%, and from 11.96 to 15.72%. As a whole, these elements represent a percentage of 81.33 to 84.44% of the chemical composition of steel slag.

The chemical compositions obtained for the ISAC from the two ISC demonstrate that the variation in the intra-ISC composition is less, for the majority of the chemical species, than the variation in the inter-ISC composition.

The mineralogical analysis was performed by X-ray diffraction and complemented by electron scanning microscopy. At ISC Maia, the following minerals were identified: wustite ($Fe_{0.965}O$), hematite (Fe_2O_3), kirschsteinite ($Ca(FeO_{0.69}MgO_{0.31})SiO_4$) and akermanite ($Ca_2Mg(Si_2O_7)$) and at ISC Seixal: wustite, calcium silicate (Ca_2SiO_4) and ghelenite ($Ca_2Al(AlSiO_7)$).

The leachability potential of ISAC was only studied on samples collected from ISC Maia. The values presented at Table 1 correspond to the leachability potential of a single sample, collected from the pile with a 3-month maturation. In the period when the tests were performed, the applicable Portuguese legislation in force was the Decree-law nr. 152/2002, 23 May, and, therefore, the German standard DIN 38414-S4 was adopted rather than the European Standard EN 12457-Part 2 or Part 4, defined in the Portuguese legislation that is presently in force (Decree-law nr. 183/2009, 10 August).

Table 1: Chemical composition and classification of the ISAC leachate

Parameter	Leachate composition	Inert waste(*)	Classification
pH	10.3	5.5<x <12	Inert
Elec. Cond. (mS/cm)	0.117	6<y<50	Inert
Ammonium (mg N/l)	< 0.13	5	Inert
AOX (mg Cl/l)	< 0.010	0.3	Inert
Arsenic (mg/l)	< 0.0018	0.1	Inert
Cadmium (mg/l)	0.01	0.1	Inert
Lead (mg/l)	< 0.06	0.5	Inert
Cyanide (mg/l)	< 0.05	0.1	Inert
Chloride (mg/l)	< 3	500	Inert
Copper (mg/l)	< 0.025	2	Inert
COT (mg C/l)	3.8	40	Inert
Chromium VI (mg/l)	< 0.05	0.1	Inert
Total chromium (mg/l)	< 0.05	0.5	Inert
Phenol (mg/l)	< 0.01	1	Inert
Fluoride (mg/l)	0.04	5	Inert
Mercury (mg/l)	< 0.002	0.02	Inert
Nickel (mg/l)	< 0.04	0.5	Inert
Nitrite (mg/l)	< 0.04	3	Inert
Sulphate (mg/l)	< 10	500	Inert
Zinc (mg/l)	< 0.008	2	Inert

COT - Carbon Organic Total; AOX - Adsorbable Organic Halogens; *Maximum admissible values established in the Portuguese legislation (Decree-Law n.º152/2002).

Comparing the leaching values obtained with the leaching limit values established in Decree-law nr. 152/2002 for waste admissible in inert waste landfills, it is observed that all elements present lower values, sometimes significantly lower, than the leaching limit values required. Hence, ISAC is, from a leachability point of view, and in accordance with the requirements established in the mentioned legislation, a waste admissible for inert waste landfills.

4 INDEX AND MECHANICAL EMPIRICAL PROPERTIES

For assessing the index properties of ISAC, a decision was made to use Portuguese standards/specifications as a replacement for the equivalent European Standards, because, in this transition stage, many of the known reference studies have also been performed using the Portuguese standards/specifications.

Table 2 summarizes the values found for index properties of Seixal and Maia ISAC.

Table 2: Index properties of Seixal and Maia ISAC

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
	Cu	33.20	9.64
	Cc	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} (10^3kg/m^3)	2.32	2.43
	w_{OPM} (%)	5.0	3.45
	ρ_i (10^3kg/m^3)	3.31	3.45
	ρ_s (10^3kg/m^3)	3.05	3.25
	ρ_d (10^3kg/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.

The particle size distributions were done in accordance with the Portuguese Specification E 196 and the

Atterberg limits with the Portuguese Standard NP 143. Considering the particle size classification used by Soil Mechanics to describe natural soils, the ISAC from the ISC Maia, of which the percentage of fines (∅ ≤0.075mm) is about 1.5%, consists of about 8.5% of material belonging to the sand fraction (0.06mm<∅ ≤2mm), 78.5% to the gravel fraction (2mm<∅ ≤ 60mm) and 1.5% to the fine blocks fraction (60mm <∅ ≤200mm). The Seixal ISAC consists of about 19.5% of material belonging to the sand fractions and 74% to the gravel fraction, the fine percentage being about 6.5%. In terms of maximum diameter, Dmax, and particle size indices (effective diameter D10 and uniformity and curvature coefficients, Cu and Cc, respectively), the values obtained for the Maia ISAC and for Seixal ISAC were, respectively: Dmax (mm) = 76.1 and 38.1; D10 (mm) = 1.96 and 0.22; Cu = 9.64 and 33.20; and Cc = 1.95 and 4.30. The two aggregates are well graded materials. Based in the Atterberg limits results, both materials are non-plastic.

Seixal ISAC and Maia ISAC show 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 Road Administration for natural materials. The imbibed CBR test showed that ISACs do not swell (expansion value of 0%).

Analyzing Table 2 it is showed that the values found for the Seixal ISAC and Maia ISAC are quite similar.

5 ISAC ELASTIC YOUNG'S MODULI

The preparation procedure of the ISAC specimens, to study the Young's modulus, is the same for all the tests: the ISAC are sieved to remove the coarse grains greater than 19.1mm, as the triaxial specimen sizes were only 150mm diameter and 300mm height, then the ISAC is mixed up with the right quantity of water to obtain the desired water content. After that, it is placed in a sealed plastic bag for 24 hours to allow the hydric equilibrium to be established. The specimens were compacted in 6 layers by vibrating hammer with a static weight of around 7kg and a plate of 146mm. The time of vibration was that necessary to achieve, approximately, the same dry density found by the modified Proctor curves. The decision to compact the samples to a very dense state is because this is representative of typical compacted pavement layers. The state conditions of studied samples are shown in Table 3. In the same table are also presented the results for two standard base course materials (granite aggregate 0/31.5 and limestone aggregate 0/19), which will be used for moduli comparison purposes.

Table 3: Modified Proctor test results and state sample conditions

Material	ρ_d (10^3kg/m^3)	w (%)
Seixal ISAC	2.31	5.8
Maia ISAC	2.43	3.5
Granite aggregate (0/31.5)	2.19	3.9
Limestone aggregate (0/31.5)	2.13	3.9

The ISAC moduli were evaluated by precision triaxial tests with the equipment available at the Civil Engineering Laboratory of the University of Minho. Axial and radial strains were locally measured using 3 vertical LDT (Local Deformation Transducer - Goto et al., 1991) and 1 horizontal LDT. All the LDT's were manufactured at University of Minho. A standard pressure transducer and a sensitive load cell located inside the triaxial cell are used to measure the boundary stresses (cell and deviatoric stresses). The interstitial air in the specimen is at the atmospheric pressure through the drainage system. Figure 2 shows a detail of the LDT's used during the tests.

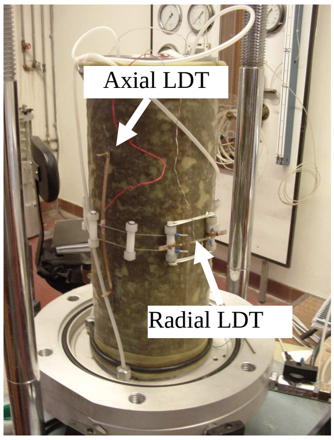

Figure 2: On specimen local deformation transducers of triaxial cell at University of Minho.

The test procedure to obtain the material Young's modulus uses several stresses following a test protocol presented by Gomes Correia et al. (2005). For each confining pressure (100, 200 e 300 kPa), after consolidation, the test starts with a deviatoric loading applied up to around 1×10^{-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 around 0.03mm/min. During the unloading process, very small unloading/reloading cycles of vertical stress were performed at different steps (approximately at the maximum value of deviatoric stress (q_{max}) applied to the sample, at $q_{max}/2$ and q = 0 kPa). For each step was applied five unloading/reloading cycles of small vertical stress amplitude. The amplitude was controlled to ensure that the cycles were closed and linear, in order to evaluate the elastic Young's modulus. An example of one of these cycles is presented in Figure 3.

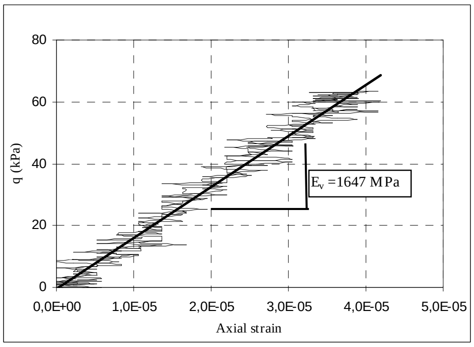

Figure 3: Example of stress-strain relationship of one small amplitude loading/unloading cycle.

Based on previous findings (e.g., Hoque and Tatsuoka, 1998 and 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 4.

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

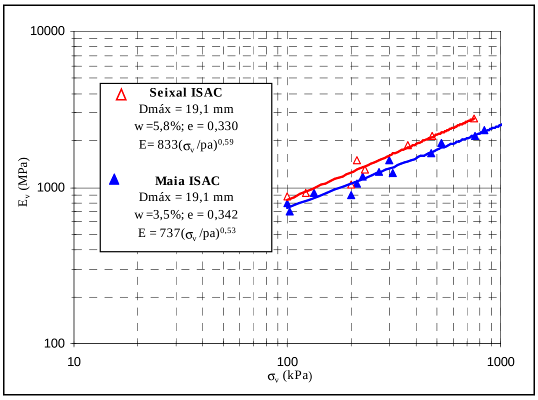

Figure 4: Young's modulus evolution of national ISAC with total stresses.

As can be seen, the total stress analysis leads to a power (n) equal to 0.59 and 0.53 for Seixal and Maia ISAC, respectively. These power values are similar to the usual values found for natural materials, which normally are around 0.5. Figure 4 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 ISAC.

6 TECHNICAL VIABILITY OF USING ISAC INTO PAVEMENTS STRUCTURAL LAYERS

6.1 Comparison of index properties between ISAC and natural aggregates and this classification

Table 4 compares the values found for the index properties for ISAC and for natural aggregates of different geologic origins. The natural aggregates were studied in a European project named Courage.

Table 4 reveals that the values found for shape index for ISAC and granite aggregate are similar and the Los Angeles values of Maia ISAC and granite aggregate are equal. The values of CBR found for the ISAC 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.

Table 4: Index properties of ISAC and natural aggregates

Parameter	ISAC		Aggregate		
	Seixal	Maia	Gneiss	Granite	Limest.
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} (10^3kg/m^3)	2.32	2.43	2.19	2.29	2.21
w_{OPM} (%)	5.00	3.45	6.25	5.40	4.00
CBR (%)	100	72	270	140	-

Figure 5 shows the unbound granular materials (ISAC and natural aggregates) classified by mechanical index tests (empirical tests) according to French classification (NF P 18-321, 1982). Figure 5 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 ISAC and Maia ISACs are both an MDe20 and, respectively, a LA25 or L30. Natural materials (limestone and gneiss aggregates) are MDe20, like the ISAC. According to the LA values, the limestone and gneiss aggregates are LA20 and the granite aggregate is LA30. It is necessary to point out that the results presented are obtained from the national standarsds/specifications and not with the Europeen standards, so these European classifications could suffer a slightly change. These classifications imply that natural aggregates have better mechanical index properties than Maia ISAC.

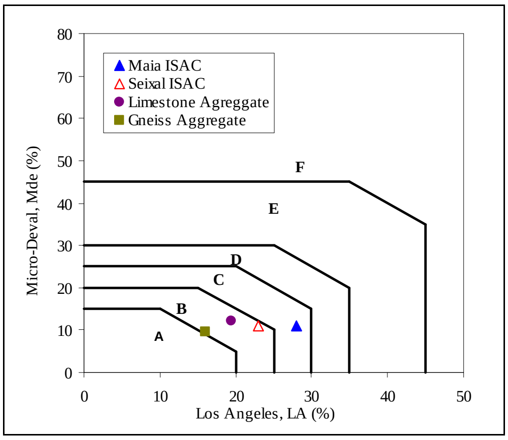

Figure 5: Unbound aggregate classification by mechanical index test.

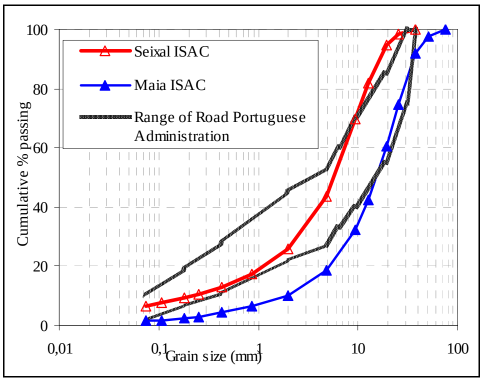

Figure 6: Particle size distributions of Maia and Seixal ISAC and their comparison with particle-size distribution ranges specified by the Portuguese Road Administration.

6.2 Comparison between ISAC properties and specification of the Portuguese Road Administration for natural aggregates

The Specification of the Portuguese Road Administration establishes that the crushed natural raw 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 fulfill by the ISAC.

Figure 6 shows the particle-size distribution curves of ISAC and the particle-size distribution ranges defined in the Specification of the Portuguese Road Administration for crushed natural raw materials for these applications. The curves of the ISAC 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 ISAC existing gradings (Gomes Correia et al., 2008).

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

6.3 Comparison between ISAC and natural aggregates moduli

The moduli results of ISAC materials are compared with two standard base course materials (granite aggregate 0/31.5 and limestone aggregate 0/19). The particle-size distribution curves, of all studied materials, are shown in Figure 7 and the state material specimen conditions are shown in Table 3.

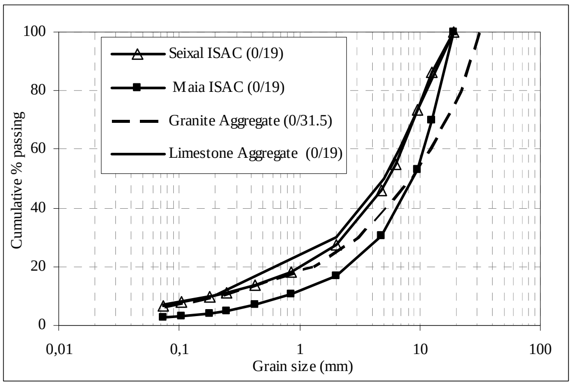

Figure 7. Studied grain size distribution curves.

The results presented for the granite aggregate were obtained by Gomes Correia et al. (2001). These authors studied the modulus of the natural material by means of a relatively large triaxial apparatus with square prismatic specimen (580mm height and 230mm diameter). Axial and lateral strains were also measured with LDT's. The results presented for the limestone aggregate were obtained by Coronado (2005). This author studied the modulus of the natural material by means of a triaxial apparatus with a specimen 150mm diameter and 300mm height. Axial and lateral strains were also measured with LDT's.

To proceed with the comparison, the test results of the four materials were all normalized for the same void ratio value of e = 0.3. Equation 2 was used, where *f(e)* is the void ratio function and *E** being the values measured on specimens.

$$E = E * \frac{f(0.3)}{f(e)} \quad (2)$$

The void ratio function used was proposed by Iwasaki et al. (1978) and represented by Equation 3.

$$f(e) = \frac{(2{,}17 - e)^2}{1 + e} \quad (3)$$

Figure 8 shows the results obtained for the elastic modulus as a function of total stress, after void ratio normalization. The values found for ISAC are around four times higher than for granite aggregate (0/31.5). This reveals that the national ISAC have much better mechanical properties than a standard base course material. These results, when considered alongside the results reported by Gomes Correia et al. (2005), Gomes Correia et al. (2006), Roque et al. (2007), Gomes Correia et al. (2008 and 2009) emphasize that the national ISAC could be used in geotechnical works, and particularly in transportation infrastructures (embankments, capping layers and base courses).

It should be mentioned that a full scale road section was built and field test results during construction confirm these laboratory findings (Gomes Correia et al. 2008). Furthermore, field tests are being performed periodically during time in order to evaluate long term behaviour in terms of mechanical and environmental properties.

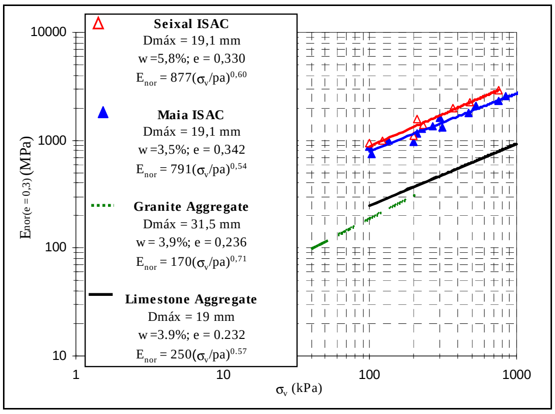

Figure 8: Comparison of moduli for ISAC and standard base course materials (Gomes Correia et al., 2009).

7 VALIDATION OF RESULTS IN THE FIELD

Figure 9 compares the mechanical performance of different natural aggregates and alternative materials when using empirical tests (LA and MDE) and the performance-related tests. Figure 9a) shows the classification of several natural aggregates (results presented by Paute et al., 1994) and Maia and Seixal ISAC, based on the results of empirical tests (standard NF P 18-321, 1982). Figure 9b) shows the Young's modulus correspondent to a strain level of approximately to $4x10^{-5}$, depending on the vertical stress and corrected to a void ratio value equal to 0.30, for three natural materials used in base layers (granitic aggregate 0/31.5 and 0/19 and limestone aggregate 0/19) and national ISAC.

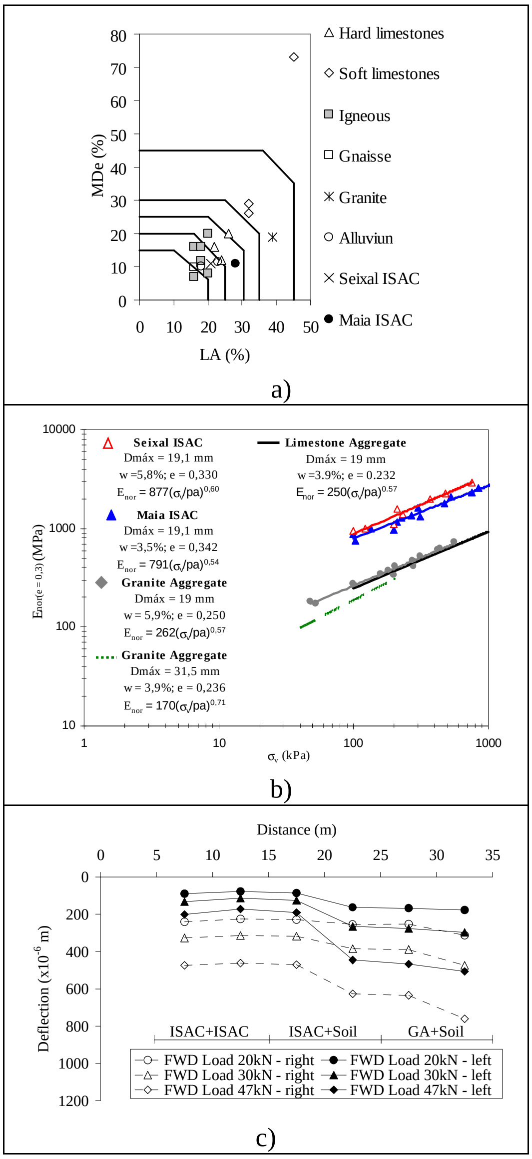

Figure 9: (a, b, c) Discussion of empirical tests versus performance based tests and better performance of ISAC in laboratory and in field, compared with natural materials (soil and granite aggregate: GA).

Analysing the Figure 9a) it appears that the Maia ISAC have a mechanical behaviour worse than some natural aggregates, including aggregates obtained from igneous rocks, alluvium and hard limestone rocks.

Figure 9b) demonstrates that the moduli values found for ISAC are much higher than for natural aggregates. This reveals that national ISAC have much better mechanical properties (stiffness) than a standard base course material.

Upon comparing the results obtained from the mechanical index test and the values found for the Young's modulus for the ISAC and natural aggregates, the ISAC demonstrate better mechanical performance than would be expected based on the mechanical index test results (CBR, MDe and LA tests). 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 non-traditional materials.

The results presented in Figure 9c), relative to the maximum deflection as a function of applied load during Falling Weight Deflectometer test (FWD), in one monitoring campaign carried out in the full-scale trial, show the better performance of ISAC than natural materials (soil and granite aggregate (0/31.5)).

Also in a recent European project (Alt-Mat, 1999) some waste showed a better mechanical performance on the field than expected by the results of empirical testing. These findings, better field performance than expected by empirical tests have been observed for natural materials, either to by-products (Paute et al., 1994, Reid, 2001, Gomes Correia and Lacasse, 2005). This shows the need to change the principles of characterization of materials, giving greater emphasis to rational basis (mechanistic approach) rather than empirical testing. Consequently, the design of materials should be based on performance-related tests.

The performance-related tests are much more realistic because it uses mechanical parameters refer to the mechanical behaviour of integral materials, with grading and state conditions (dry density and moisture content) and not to a characterization of particle properties, which may not be representative of the overall behaviour of the material. Thus, should be use the rankings based on performance-related tests in order to better rationalize the use of natural aggregates and especially when using alternative materials.

8 CONCLUSIONS

This research seeks to promote the re-use of processed steel slag as a substitute for natural materials or traditional aggregates 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 ISAC, these materials do meet the specifications of the Portuguese Road 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 slag, named ISAC, 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 non-traditional 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 non-traditional materials.

A full-scale trial was built and field test results during construction and field tests performed to evaluate long-term mechanical and environmental property behaviours (data not presented here because lack of space) confirm the laboratory findings.

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

The technical data collected in the framework of this national research project shows that the Portuguese processed steel slag can be considered as a new construction material and, consequently, could be used in competition with natural aggregates for construction of transportation infrastructures and other geotechnical works.

It is important to point out that the study methodology and the consequent results allowed the use of ISAC in the works of major construction Companies and accepted by public bodies such as the Portuguese Road Administration (EP) and Refer and the development of the marketing conditions of the ISAC. According to data supplied by Portuguese Iron Steel Company, the accumulated Maia ISAC has already sold and at this time there is lack of material for delivery to permanently stock to zero. The same is expected to the Seixal ISAC where the stock is falling constantly. This year sales of ISAC already have a significant economic value, of a few hundred thousand Euros.

ACKNOWLEDGMENTS

The authors would like to thank FCT for the financial support given to this Project (PPCDT/ECM/56952/2004), by the program POCI 2010 and cohesion found FEDER and the doctoral grant within company SFRH/BDE/15661/2007.

REFERENCES

Alt-Mat 1998/1999. *Alternative materials in road construction*, Project Funded by the European Commission under the Transport RTD Programme of the 4th Framework Programme.

Coronado O. 2005. *Study of mechanical behaviour of unbound granular materials compacted at non saturated state under cyclic loading*. Phd Thesis. Ecole Centrale Paris (in French).

Courage 1999. *Construction with unbound road aggregates in Europe*. Final report: 123.

Gomes Correia A., Anhdan L. Q., Koseki J. and Tatsuoka F. 2001. Small strain stiffness under different isotropic and anisotropic stress conditions of two granular granite materials. In Shibuya, Tatsuoka, & Kuwano (eds), *Advanced Laboratory Stress-Strain Testing of Geomaterials*: 209-215. Balkema, Swets & Zeitlinger.

Gomes Correia, A. and Lacasse, S. 2005. *Technical session 2e: marine & transportation geotechnical engineering*. Proceedings of 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan, pp. 1707-1710.

Gomes Correia A., Reis Ferreira S., Araújo N., Castro F., Trigo L., Roque A., Pardo de Santayana F. and Fortunato E. 2005. *Viability study of Inert Steel Aggregates for Construction (ASIC) for base, sub-base, capping layers and embankments.* Internal CVR Report 257/2005: 87. (in Portuguese)

Gomes Correia A., Reis Ferreira S., Castro F., Trigo L., Roque A., Pardo de Santayana F. and Fortunato E. 2006. *Viability study of Inert Steel Aggregates for Construction (ASIC) from Seixal Steel Company for base, sub-base, capping layers and embankments. Comparison with Maia ISAC.* Internal CVR Report 24/2006: 47. (in Portuguese)

Gomes Correia A., Martins J. P., Reis Ferreira S., Roque A. and Fortunato E. 2008. *Trial road section in EN311 Fafe/Várzea Cova. Construction and quality control.* Internal CVR Report 2/2008: 20 (in Portuguese)

Gomes Correia A., Reis Ferreira S., Roque A. and Cavalheiro A. 2009. Processed Portuguese steel slags. A new geomaterial. *Proceedings of the Eighth International Conference on the Bearing Capacity of Roads, Railways, and Airfields,* Champaign, Illinois, USA June 29–July 2, 2009.

Goto S., Tatsuoka F., Shibuya S., Kim Y-S. and Sato T. 1991. A simple gauge for local small strain measurements in the laboratory. *Soils and Foundations* 31(1): 169-180.

Hoque E. and Tatsuoka F. 1998. Anisotropy in the elastic deformation of materials. *Soils and Foundations* 38 (1): 163-179.

Iwasaki T., Tatsuoka F. and Takagi Y. 1978. Shear moduli of sands under cyclic torsional shear loading. *Soils and Foundations* 18(1): 39-50.

Paute, J.L., Hornych, P. and Benaben, J.P. 1994. *Comportement Méchanique des Graves Non-Traitées au Triaxial à Chargement Répétés*. Bulletin de Liaison de Laboratories Central des Ponts et Chaussées, N.º 190, pp. 27-38.

Reid, J. M. 2001. *The use of alternative materials in road construction*. Avaiable at www.viastrade.it/letteratura/materiali/TRL_TO_ALT_MAT.pdf. Acessed at 14/12/2009.

Roque A., Gomes Correia A., Fortunato E., Pardo de Santayana F., Castro F., Reis Ferreira S. and Trigo L., 2007. The geotechnical re-use of Portuguese inert siderurgical aggregate. *Proceedings of the XIII Pan-American Conference on Soil Mechanics and Geotechnical Engineering,* Margarita Island, Venezuela, July 16-20, 2003.

Samaris 2002/2005. *Sustainable and advanced materials for road infrastructures*, Project Funded by the European Commission under the Transport RTD Programme of the 5th Framework Programme.

AUTHOR BIOGRAPHIES

SANDRA M. REIS FERREIRA was born in Vila Nova de Foz-Côa and went to the University of Aveiro, where she studied Physics Engineering and obtain her degree in 2000. In 2003 she obtained the master degree in Georesources by "Instituto Superior Técnico - IST". From 2003 to 2005 she worked in several Research Projects at National and International level with a grant researcher and during 2004 teaches Physics at Institute Polytechnic of Viseu. In 2005 she moves to the University of Minho (UM) as researcher in a National I&D Project and get a doctoral grant within company (2006 – 2009). E-mail address: sandraferreira@civil.uminho.pt

ANTÓNIO GOMES CORREIA: Professor in Civil Engineering at UM; Director of Centre of Territory, Environment and Construction of UM; Supervisor of the PhD thesis. E-mail address: agc@civil.uminho.pt

ANTÓNIO J. ROQUE: Research Senior Officer at National Laboratory of Civil Engineering, and Coordinator of FCT Research Project (2005-2009). E-mail address: aroque@lnec.pt

ANTÓNIO CAVALHEIRO: Administration Advisor of Portuguese Iron Steel Company, and Coordinator of doctoral grant within the Company. E-mail address: acavalheiro@seixal.snlongos.pt