The geotechnical re-use of Portuguese inert siderurgical aggregate

La reutilización en geotecnia de agregados siderúrgicos inertes producidos en Portugal

A. J. Roque & Eduardo Fortunato, *National Laboratory for Civil Engineering, Lisbon, Portugal*
A. Gomes Correia & S. M. Sandra Ferreira, *University of Minho, Guimarães, Portugal*
Fernando Pardo de Santayana, *CEDEX, Madrid, Spain*
Fernando Castro & Luísa Trigo, *Center for Re-use of Waste, Guimarães, Portugal*

ABSTRACT

The management strategy for waste, in which the prevention of its production is not yet feasible, should privilege the valorization measurements, namely through re-use solutions. In this framework, a Research and Development Project (R&D) is under way in Portugal, which is intended to re-use steel slag produced in the two Portuguese Iron and Steel Companies. The project is joint-subsidized by the Portuguese Foundation for Science and Technology and the main entities involved are the *Laboratório Nacional de Engenharia Civil* (supervising body), the University of Minho and the Centre for Re-use of Waste. The main purpose of the research program is to contribute to create a mechanistic and environmental approach intended to promote the re-use of waste, in general, and of steel slag, in particular, through their application in the construction of transport infrastructures and geotechnical works. Following the most relevant recommendations of various European Community projects, this research program favors the laboratory tests related with mechanical and environmental properties. In order to calibrate the laboratory results and to assess the performance of steel slag when placed in situ, a trial road section will be performed with various cross-sections, on which natural raw materials and steel slag are to be placed, at the level of the sub-base and the base layers, and of the embankment.

RESUMEN

La estrategia de gestión para los residuos en que aún no es practicable la prevención de su producción, debe privilegiar las operaciones de valorización, por ejemplo a través de soluciones de reutilización. Es en este contexto, que está en curso en Portugal un Proyecto de Investigación y Desenvolvimiento para la valorización de las escorias de acería producidas en las dos Siderurgias portuguesas. Participan en el proyecto, cofinanciado por la Fundación Portuguesa por la Ciencia y la Tecnología, el *Laboratório Nacional de Engenharia Civil*, que coordina, la Universidad del Minho y el Centro para la Valorización de Residuos. Se pretende contribuir para la creación de una metodología mecanicista y ambiental que promueva la reutilización de los residuos, en general, y de las escorias de acería, en particular, a través de su aplicación en la construcción de infraestructuras de transporte y de obras geotécnicas. Considerando las recomendaciones más relevantes de varios proyectos de la Comunidad Europea, este programa de investigación privilegia los ensayos de laboratorio relacionados con las propiedades mecánicas y ambientales. De modo a calibrar los resultados de laboratorio y a valorar el desempeño de las escorias de acería cuando son colocadas en obra, se realizará un trecho experimental con diversas secciones transversales, en las cuales se aplicarán materiales naturales y escorias de acería en el relleno, y en la base y la sub-base del pavimiento.

Keywords: steel slag, re-use, inert waste, siderurgical aggregate, geotechnical works

1 INTRODUCTION

In Portugal, and also at international level, preventing the production of a significant number of different types of waste is still unfeasible. Therefore, the waste management strategy should favor its valorization, namely through re-use solutions. For instance, in the construction of transport infrastructures and geotechnical works. The adoption of this practice will make it possible to subject that type of works to the principles of sustainable development: reducing the quantities of waste that is disposed of in landfill; creating a new and important national market; and preserving natural raw materials.

In this framework, the *Laboratório Nacional de Engenharia Civil* is supervising, with the participation of the University of Minho and the Centre for Re-use of Waste, a Research and Development Project (R&D), titled: Application of waste in transport infrastructures and geotechnical works – Re-use of steel slag. Its main purpose is to contribute to create a mechanistic and environmental approach intended to promote the re-use of waste, in general, and steel slag, in particular. The Project is to take place during the 2005-2008 period, being joint-subsidized by the Portuguese Foundation for Science and Technology and being supported by the Portuguese Iron and Steel Companies, the Portuguese Roads Administration and the Institute for Waste Affairs.

On the basis of results obtained in laboratory and field tests, two output documents will be prepared: i) a technical specifications for using siderurgical aggregate obtained from steel slag in transport infrastructures and geotechnical works; ii) a national guide with the methodology of study to be followed for the re-use of waste in that type of works.

This work presents the chemical compositions of the siderurgical aggregate total mass and of siderurgical aggregate eluate, and their index properties (particle size distribution and Atterberg limits). These simple, quick and low cost tests were intended to assess, in a preliminary stage, the technical feasibility of using siderurgical aggregate in transport infrastructures and geotechnical works.

2 PORTUGUESE PLAN TO RE-USE SIDERURGICAL AGGREGATE

Steel slag produced in electric arc furnaces of the two Portuguese Iron and Steel Companies will be reused as inert siderurgical aggregate in transport infrastructures and geotechnical works, provided that economic benefits are found, that the material fulfils the expected values in environmental and engineering specifications, and that the in situ performance is equivalent or higher to natural raw materials. After knowing the experience of other countries, as well as the technical data already collected within the framework of the Project (CORREIA et al, 2005; CORREIA et al, 2006), which are partly presented in this work, there are a few reasons to expect these requirements to be fulfilled by the studied material.

Following the most relevant recommendations of various European Community projects, namely ALTMAT (1999) and SAMARIS (2005), this research Project is to favor the laboratory tests related with structural engineering properties (gyratory compaction and cyclic loading triaxial test) and with environmental properties (pollutant leaching), which may be relevant in this type of materials. With a view to calibrate the results, to assess the performance of aggregates obtained from steel slag when placed on works, and to compare them with natural raw materials, a trial road section is to be constructed with various cross-sections. A few sections will be built with raw materials (reference sections) and others with siderurgical aggregate. The various materials are applied in the sub-base and the base layers, and in the embankment. Measurement of deformations and displacements will be performed at different levels of the cross-sections, with a view to assess the mechanical performance of materials. Its environmental performance will be assessed too.

Throughout the three-year duration of the Project, the following tasks are to be performed:

Task 1 (3 months): completion of the state-of-the-art on valorization of steel slag in transport infrastructures and geotechnical works; definition of the sampling methodology of siderurgical aggregates and collection of samples.

Task 2 (9 months): laboratory tests on siderurgical aggregate samples, with a view to study the environmental, mineralogical, geometrical, physical and mechanical properties and to analyze their performance.

Task 3 (15 months): construction of the trial road section, with control of its execution and installation of observation equipment; collection of samples of materials used for laboratory characterization; execution of field tests; periodical reading of observation equipment; comparative assessment of the structural and environmental performance of sections built with natural raw materials and with siderurgical aggregates.

Task 4 (9 months): overall analysis of the performance of the material and of its potential re-use, with preparation of technical documentation.

The technical documentation that is to be prepared concerns the technical specifications regarding the re-use of siderurgical aggregate in transport infrastructures and geotechnical works and a national guide with the methodology of study to be followed for the re-use of waste in that type of works.

3 STEEL SLAG PRODUCTION IN PORTUGAL

In Portugal, there are two Iron and Steel Companies. These Companies are currently operating with electric arc furnaces: one is located at Paio Pires, Seixal (Seixal Company), and the other at S. Pedro de Fins, Maia (Maia Company) (Figure 1).

In the Iron and Steel Companies with electric arc furnaces, the steel production process comprises two phases: the fusion phase and the refining phase. The main raw material used in the fusion phase is the ferrous scrap-iron. The components which are to produce black steel slag, mainly lime, are also added in this phase. The refining phase comprises three stages: the first corresponds to the oxidation period, during which the black steel slag is produced; the second corresponds to the reduction period, which produces the black steel slag; and the last one corresponds to the final adjustment period of the composition.

In 2005, the Portuguese Iron and Steel Companies together produced about 1,500 000 tones of steel, to which about 270,000 tones of black steel slag corresponded. After removing the metallic component for recycling, 250,000 tones of non-metallic components remained, which were subsequently transformed into inert aggregates. In accordance with data provided by the Portuguese Companies, within medium term, about 400,000 tones of black steel slag are expected to be annually produced.

Figure 1 - Location of the two Portuguese Iron and Steel Companies.

4 BLACK STEEL SLAG PROCESSING

Black slag, which is separated from liquid steel at the end of the oxidation phase and emptied in a steel slag pit (Figure 2), is then submitted to one adequate processing to be re-used as siderurgical aggregate in the public works.

Figure 2 - Emptying of steel slag at the end of the oxidation phase.

The three phases of that processing are described below.

Phase A: Flow and cooling of steel slag

a. Transferring steel slag from the pit to an impervious zone, where its cooling with water will be first done (Figure 3), and then transport to the storage/treatment zone;
b. The cooling to air is completed at the storage/processing zone (Figure 4), which may be accelerated by water. The resulting material is designated as non-processed steel slag.

Figures 3 e 4 - Cooling of steel slag with water (3) and to air (4).

Phase B: Valorization of the metallic component

a. Breaking up of larger steel slag plates (Figure 5), by simultaneously recovering the larger metallic components;
b. Feeding the hopper with the resulting steel slag and separation of the metallic parts from the non-metallic parts using magnetic drums. The metallic parts are re-used in steel production (Figure 6). Only a small quantity of minor metallic scraps is present in the remaining steel slag.

Figures 5 e 6 –Breaking up equipment of steel slag (5) and metallic parts recovered during the processing (6).

Phase C: Valorization of the non-metallic component

a. Sieving/grading in particle-size ranges (Figure 7);
b. New mechanical breaking up, with possible grinding, to produce finer particles-size;
c. Eliminating smaller metallic scraps, which have not been eliminated in the previous phase, by passage with magnetic plate and/or re-processing, by passing again the material in the magnetic roller;
d. Storage and maturation by hydration to air, for the time necessary to neutralize the remaining lime (Figure 8).

Figures 7 e 8 – Classification of the material (7) and maturation phase (8).

5 INDEX PROPERTIES AND POLLUTANT POTENTIAL OF THE SIDERURGICAL AGGREGATE

The chemical compositions of the siderurgical aggregate total mass and of siderurgical aggregate eluate were determined on 10 samples collected from the storage areas of SN of Maia and SN of Seixal: 5 belonged to the 3-month maturation piles and the others to the 6-month maturation piles.

The chemical analyses to determine the composition of siderurgical aggregates were done by X-ray fluorescence spectrometry. The results obtained, expressed for a 100% weight base, are presented in Table 1.

It is observed that there are greater differences between the chemical compositions of aggregates of the two Portuguese Iron and Steel Companies, particularly as regards the major elements, than between the maturation phases of each company.

The leacheability of siderurgical aggregates was only studied on samples collected at the SN of Maia. The leachates analyzed were obtained in tests performed in laboratory according to DIN 38414-S4. The European Standard EN 12457 was not used because it only became into force in a date after the execution of the leachate test. All the parameters established in the Portuguese legislation (Decree-Law nr. 152/2002, 23 May, Annex III) were only determined on one of the leachates collected from the leachate tests carried out on the samples with 3-month maturation (Table 2).

The particle size distribution and the Atterberg limits of siderurgical aggregates from the SN of Maia were studied on a sample collected from a 6-month maturation pile, and those of SN of Seixal were studied on a sample collected from a pile with a particle size diameter range from 0 to 40mm (the maturation time was not known).

For assessing the index properties of siderurgical aggregates, 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.

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 siderurgical aggregate from the SN of Maia, of which the percentage of fines ($\varnothing \leq 0.075$ mm) is about 1.5%, consists of about 8.5% of material belonging to the sand fraction (0.06 mm $< \varnothing \leq$ 2 mm), 78.5% to the gravel fraction (2 mm $< \varnothing \leq$ 60 mm) and 1.5% to the fine blocks fraction (60 mm $< \varnothing \leq$ 200 mm). The siderurgical aggregate from the SN of Seixal 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 D_{max} and particle size indices (effective diameter D_{10} and uniformity and curvature coefficients, C_u and C_c, respectively), the values obtained for the siderurgical aggregates from the SN of Maia and from the SN of Seixal were, respectively: D_{max} (mm) = 76.1 and 38.1; D_{10} (mm) = 1.96 and 0.22; C_u = 9.64 and 33.20; and C_c = 1.95 and 4.30. The two aggregates are well graded material of continuous particle size distribution.

Table 1 : Chemical composition of the siderurgical aggregate

Classes	Chemical specie	Siderurgical aggregate of SN Maia (5 samples)				Siderurgical aggregate of SN Seixal (5 samples)			
		3 months of maturation		6 months of maturation		3 months of maturation		6 months of maturation	
		Average (%)	Standard deviation	Average (%)	Standard deviation	Average (%)	Standard deviation	Average (%)	Standard deviation
Major elements	Fe_2O_3	48.23	0.89	48.43	1.07	30.40	0.70	34.22	1.69
	CaO	24.19	0.79	23.47	0.84	35.21	1.14	33.99	1.01
	SiO_2	11.96	0.10	12.55	0.11	15.72	0.26	14.92	0.52
Minor elements	Al_2O_3	4.20	1.00	3.59	0.06	5.77	0.15	6.15	0.27
	Mn	3.89	0.14	3.92	0.02	3.92	0.29	3.62	0.17
	MgO	2.72	0.06	3.30	0.33	4.44	0.40	2.97	0.29
	Cr	1.97	0.09	1.96	0.08	1.50	0.04	1.59	0.16
	P_2O_5	1.23	0.03	1.04	0.29	0.68	0.04	0.76	0.05
	SO_3	0.31	0.01	0.04	0.02	1.09	0.29	0.66	0.13

Other elements (Na_2O, K_2O, TiO_2, V, Cu, Zn, Sr, ZrO_2, Ba) with percentage less than or much less than 1%.

The Atterberg limits obtained for the two aggregates show that this is a non-plastic material.

Table 2 : Chemical composition and classification of the siderurgical aggregate leachate

Parameter	Leachate composition	Inert waste(*)	Category
pH	10.3	5.5<x<12	Inert
Electrical conductivity (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

*Maximum admissible values established in the Portuguese legislation (Decree-Law n.º 152/2002).
AOX - Adsorbable Organic Halogens.
COT - Carbon Organic Total.

6 TECHNICAL FEASIBILITY PERSPECTIVES OF SIDERURGICAL AGGREGATE RE-USE

Considering that the application of alternative materials in the construction of transport infrastructures and in geotechnical works is recent, the existing technical specifications, which are mostly of an empirical nature, continue to be strongly associated with the properties obtained with natural raw materials. In these cases, the alternative materials that replace the natural raw materials in the previously mentioned applications are to fulfill the same requirements as the natural raw materials. Nevertheless, it has been observed that such practice is not appropriate. In fact, the alternative materials should not be studied through empirical tests and through co-relations established for natural raw materials, which do not predict correctly the performance of those materials when placed in situ.

At an international level, there are a few examples of modifications in specifications developed from the perspective of application of natural raw materials, so as to be able to include the limit values for alternative materials. Thus, the legislation becomes more adequate for integrating those materials in the construction of transport infrastructures and in geotechnical works.

In this section, the index properties (grading and plasticity) of siderurgical aggregate from the SN of Maia and from the SN of Seixal are compared with the minimum requirements for those properties predicted in the Specification of the Portuguese Roads Administration for natural crushed materials to be applied in base and sub-base layers, and in capping layer. Furthermore, those index properties are compared with the minimum requirements predicted in the Spanish *Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes* (PG-3), which, as from the 2004 revision, began to include the use of steel slag in granular layers of road pavements.

Figure 9 compares the particle size distribution curves of siderurgical aggregate with the particle size distribution ranges defined in the Specification of the Portuguese Roads Administration for crushed natural raw materials to be applied in the base, sub-base and capping layers, and in the Spanish PG-3 for artificial aggregates, in which steel slag is included, of the type A25 and A20 (the designation of the type of aggregate is done in accordance with the maximum nominal size that is defined as the opening of the first sieve retaining more than 10% in mass).

It is observed that the particle size distribution curves of the siderurgical aggregates are not between the particle size distribution curves defined in the Specification of the Portuguese Roads Administration and in the PG-3. Nevertheless, it is considered that its correction would be feasible, provided that a few adjustments in slag processing are performed, which until the moment, has not taken into account the need to produce an aggregate with a specific particle size. The exception is the particle size distribution curve of the siderurgical aggregate from the SN of Seixal, which is between the particle size distribution curves of the PG-3 for the aggregates of the type A20.

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 Spanish PG-3 establishes that the artificial aggregates should be non-plastic. In view of results obtained with the tested siderurgical aggregates, it is concluded that these materials fulfill the requirements of the Specification of the Portuguese Roads Administration and of the PG-3.

As regards the environmental aspects, a comparison is established between the leacheability of the siderurgical aggregate from the SN of Maia with 3-month maturation and with the maximum admissible values predicted in Portuguese legislation (Decree-

Law nr. 152/2002, Annex III-Table 3) for leachates from inert waste (Table 2).

From among the twenty dosed parameters, it is observed that all of them present less values, sometimes significantly less than the maximum admissible values predicted for inert waste. In these circumstances, the tested aggregates obtained from steel slag are, from a leacheability point of view, an inert waste.

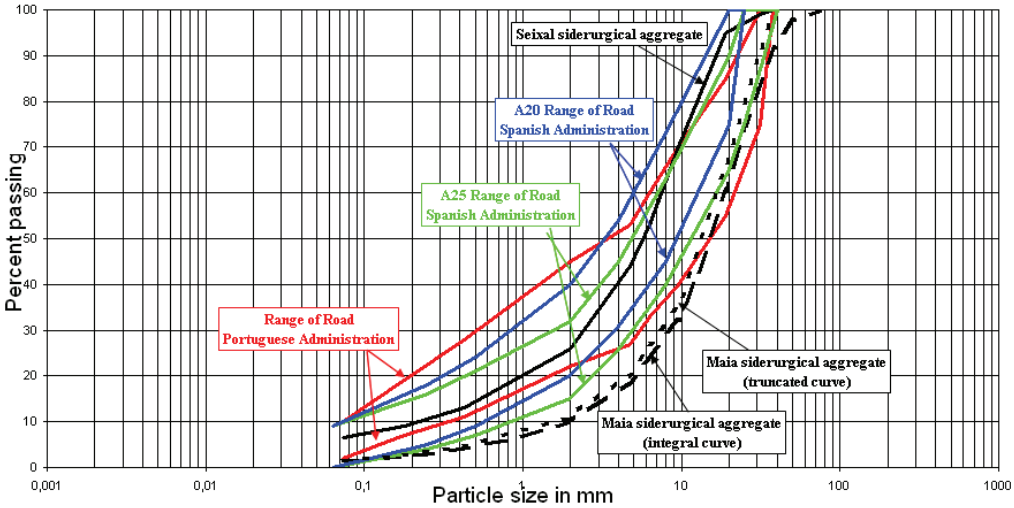

Figure 9 – Particle size distributions of Maia and Seixal siderurgical aggregates and their comparison with particle size distribution ranges specified by Portuguese and Spanish Road Administrations.

7 CONCLUDING REMARKS

The two Portuguese Iron and Steel Companies are expecting to produce, within medium term, 400,000 tones of steel slag. Within the framework of the current integrated waste management policies, which favor the waste re-use and penalize the waste disposal, a study is under way, which is intended to assess, from an engineering and environmental viewpoint, the technical feasibility of re-using the inert aggregates obtained from steel slag in transport infrastructures and in geotechnical works. The results obtained, some of which have already been presented in this work, seem to indicate that the siderurgical aggregate produced in Portugal is likely to present, similarly to aggregates obtained from steel slag produced in other countries, the characteristics adequate to their use in this type of works, without loss of construction quality, without negative effects for the public health and for the environment and by making it possible to preserve the natural resources, namely by reducing the use of natural raw aggregates.

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