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Strength of Non-Traditional Granular Materials Assessed from Drained Multistage Triaxial Tests

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Abstract

When granular materials are applied in geotechnical works, like embankments and road pavement layers, one of the most relevant engineering properties in stability analysis is ultimate shear strength. In geotechnical engineering, the triaxial test is one of the most reliable methods available for determining ultimate shear strength. In this test, a soil specimen, compacted in laboratory or collected from exploratory soil borings, is generally used. In order to determine the strength parameters, at least 3 identical specimens are required in this test. Having 3 identical specimens, a single stage triaxial test procedure is used. If not, multistage triaxial test procedure is used to eliminate the effects of soil variability in the results. In this case, several confining pressures are applied to the same specimen. Although multistage triaxial tests have been used for soils for a long time, there is still a lack of test results for unbound granular non-traditional materials. This paper presents triaxial test results obtained from a Portuguese unbound granular non-traditional material (named as Inert Steel Aggregate for Construction - ISAC). The triaxial tests were carried out using multistage and single stage techniques. As the results are quite well comparable, it is concluded that it is possible to determine shear strength parameters with just one specimen. Consequently, the research conducted has validated the use of multistage triaxial tests as a reliable and cost-effective alternative to the conventional single stage triaxial test in the mechanical characterization of unbound granular materials.

Keywords: Multistage Triaxial Test; Single Stage Triaxial Test; Ultimate Shear Strenght; Monotonic Triaxial Test; Unbound Granular Non-Traditional Material; ISAC

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1 Introduction

Environmental policies have strongly limited the extraction of natural materials and have encouraged at the same time the use of materials obtained from waste. Considering that natural granular materials are the third most used natural resource in the world and also that the iron and steel industry is a large generator of waste (slag) with potential to become aggregates, the study of these non-traditional materials is crucial.

In Portugal, there are two iron steel companies (ISC). These companies are currently operating with electric arc furnaces. One is located at Paio Pires, Seixal (Seixal ISC), and the other at S. Pedro de Fins, Maia (Maia ISC). In 2010, these two Portuguese ISC produced about 1 500 000 tons of steel, resulting in 270 000 tons of black steel slag. After the unfused metal scrap to be removed for recycling, 250 000 tons of nonmetallic components remain. Within a medium term, both ISC expect to produce about 400 000 tons/year of black steel slag. This material is subsequently processed to become an inert non-traditional aggregate. Presently, the processed steel slags are commercialized under the designation of Inert Steel Aggregate for Construction (ISAC).

For the characterization of non-traditional materials, apart from giving priority to laboratory tests concerning environmental aspects, to consider the pollutant potential for environment and public health, it is also necessary to pay attention to engineering properties. It is crucial to demonstrate that the use of non-traditional materials, instead of natural ones, will ensure identical construction quality and long term performance.

When granular materials are applied in geotechnical works, one of the most relevant engineering properties to evaluate the stability of foundations, retaining walls, slopes or embankments is ultimate shear strength. The most widely used laboratory equipment for investigating ultimate shear strength and deformation behavior of unbound granular materials is the triaxial apparatus. In traditional tests, each specimen undergoes a phase of consolidation and triaxial monotonic loading, which means different confining pressure levels and new specimens for each one (so called single-stage test procedure). A series of three or more specimens, consolidated at several pressure levels, supplies an ensemble of stress data allowing identification of a failure envelope and thus ultimate shear strength parameters. It is frequently impossible to have a set of homogeneous or identical compacted specimens, and it is especially difficult in case of unbound granular materials. In fact, it is very difficult to replicate compacted specimens of unbound granular materials in laboratory with the same structure and initial state conditions (density and water content). To overcome this problem, the multistage triaxial test procedure is used, involving different confining pressure levels for the same specimen and allowing to determine ultimate strength parameters with just one specimen.

In fact, the multistage triaxial tests have been used for soils for a long time to reduce the variability resulting from the use of multiple specimens in single stage tests [1, 2]. However, despite the multistage triaxial tests procedure being frequently used to determine shear strength parameters, there is still a lack of test results carried out on the drain condition of testing especially when applied to unbound granular aggregates and, particularly, in non-traditional materials.

In this paper, a series of single and multistage testing is performed using triaxial apparatus under drained condition to investigate the ultimate shear strength parameters of ISAC material which is being produced by Maia ISC. A comparative study of test results obtained from both triaxial test procedure is made and the Mohr-Coulomb failure criteria is used to determine the ultimate shear strength parameters.

2 Test Materials

The tested material is an unbound granular non-traditional material obtained at ISC in S. Pedro de Fins, Maia, currently named by Maia ISAC. The steel slags to become an aggregate are initially separated from liquid steel and emptied in a steel slag pit. They are afterwards subjected to an appropriate processing to be recycled as ISAC (Figure 1a) in transportation infrastructures and geotechnical works. Details of the processing can be found at [3].

Two different grain-size distribution curves are tested (Figure 1b): Maia ISAC and a Trial Road ISAC. The Trial Road ISAC was used in the construction of a full-scale field trial located at National Road EN 311, connecting Fafe to Cabeceiras de Basto, in the north of Oporto (<100 km). Considering the grain-size classification used by Soil Mechanics to describe natural soils, the Maia ISAC consisted of about 1.5% of fines ($\varnothing \leq 0.075$mm), 8.5% of sand (0.06mm$<\varnothing \leq$2mm), 78.5% of gravel (2mm $<\varnothing \leq$ 60mm) and 1.5% of fine blocks (60mm $<\varnothing \leq$ 200mm). In terms of maximum diameter, D_{max}, and grain-size indices (effective diameter, D_{10}, and uniformity and curvature coefficients, Cu and Cc, respectively), the values obtained were: D_{max} (mm) = 76.1; D_{10} (mm) = 1.96; Cu = 9.64; and Cc = 1.95.

The Trial Road ISAC consists of about 15.5% of sand, 83.5% gravel and 1.0% of fines. In terms of maximum diameter and grain-size indices, the values obtained for the Trial Road ISAC were: D_{max} (mm) = 50.8; D_{10} (mm) = 0.9; Cu = 13.3; and Cc = 2.1.

Both aggregates are well graded materials, non-plastics, and present a specific gravity (Gs) of 3.26. Comparing to natural aggregates, ISAC materials have high values of maximum dry density (ρ_{dmax} = 2.43x10^3 kg/m^3 for Maia ISAC and ρ_{dmax} = 2.39x10^3 kg/m^3 for Trial Road ISAC) and low optimum water content (w = 3.45 % for Maia ISAC and w = 4,8 % for Trial Road ISAC) referred to the modified Proctor test.

a

b

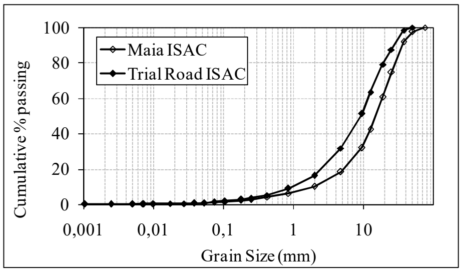

Figure.1: a) Portuguese processed steel slag (ISAC); b) Grain-size distribution curves for Maia ISAC and Trial Road ISAC.

3 Test Procedure

In this study, special care was given to specimens preparation and, in the beginning, several procedures were performed; the most appropriate used for all the tested specimens is described here. More details on the several specimens' preparation procedure tests can be found at [4]. The specimen preparation for this study is the same for all tests: after the material has been separated and placed in an oven at 105ºC for a period long enough for it to be dried, blended percentages of the different size fractions of the material were mixed according to the gradation curve. It is then mixed up with the right quantity of water. After that, it was placed in a sealed plastic bag for 24 hours to achieve uniform moisture conditions. The compaction of each specimen was performed in six layers using a vibrating hammer, the vibration time being regulated by the desired void ratio for each specimen. In this study, all specimens were compacted in a dense state. To study the ultimate shear strength, monotonic triaxial tests were carried out at drained conditions on large specimens (150mm in diameter and 300mm in height). Given the size of the selected triaxial cell, only a fraction of the materials was tested and the maximum grain-size diameter was 19.1mm.

Table 1 summarizes the state conditions of the compacted specimens (water content, w, dry density, ρ_d, and initial void ratio, e_0), as well as the applied confining pressure and triaxial test procedure.

Material	Specimen Ref.	w (%)	ρ_d (kg/m^3)	e_0	Confining pressure (kPa)			Test procedure
Maia ISAC	MT1	3,6	2,45x10^3	0,314	100	200	300	Multistage
	MT2	3,5	2,43x10^3	0,339	200	300	400	Multistage
	MT3	3,5	2,44x10^3	0,338	300	-	-	Single stage
Trial Road ISAC	TT1	5,0	2,37x10^3	0,377	100	200	300	Multistage
	TT2	5,3	2,38x10^3	0,372	200	300	400	Multistage
	TT3	5,3	2,38x10^3	0,372	300	-	-	Single stage

Table 1: Confining pressure and state conditions of specimens to study the ultimate shear strength

As already mentioned, two different grain-sizes of ISAC and three specimens for each grain- size distribution curve were tested. All triaxial tests were carried out in consolidated drained conditions. Two specimens, for each grain- size distribution curve, were subjected to a multistage triaxial test procedure. To the first one (MT1 for Maia ISAC and TT1 for Trial Road ISAC) a confining pressure of 100 kPa until consolidation of material was applied. After consolidation, triaxial compression loading in drained conditions was applied until the maximum deviatoric stress was reached and then proceeds to unloading of specimen. This test procedure was repeated for two additional confining pressures (200 kPa and 300 kPa). In the second stage of the test procedure, the saturation of the specimen was completed and then a triaxial compression loading was applied until failure occurred. The loading speed in all tests was kept constant and equal to 0.028 mm/min.

A second specimen (MT2 for Maia ISAC and TT2 for Trial Road ISAC) was subject to the same test procedure but the first stage of the confining pressure was 200 kPa and the latter was 400kPa.

The third specimen was submitted to single stage triaxial test procedure (MT3 for Maia ISAC and TT3 for Trial Road ISAC). In the first stage, the specimens were submitted to a confining pressure of 300 kPa until consolidation. After that the specimens were simply subject to a cycle of load/unload. Once again, the stopping criterion of the triaxial compression loading in drained conditions was the achievement of the peak value for the deviatoric stress.

This test procedure was attempted, on the one hand, to verify whether the multistage triaxial test procedure leads to values of ultimate strength parameters equal to those obtained with the usual triaxial test procedure, i.e. application of a single stage, for each confining stress (single stage). On the other hand, with the saturation of the specimens (MT1, MT2, TT1 and TT2) in the last stage of confining pressure, the procedure was attempted to verify the influence of water in the characteristics of strength of the material.

4 Test Results

Figure 2 and Figure 3 show the stress/strain curves (q, ε_1) obtained for multistage triaxial test procedure for Maia ISAC and Trial Road ISAC specimens, respectively. Figure 4 shows the stress/strain curves obtained for the specimens submitted to single stage triaxial test procedure (MT3 or TT3) and the first cycle of load/unload of specimens submitted to multistage triaxial test procedure, for both studied grain-size distribution curves.

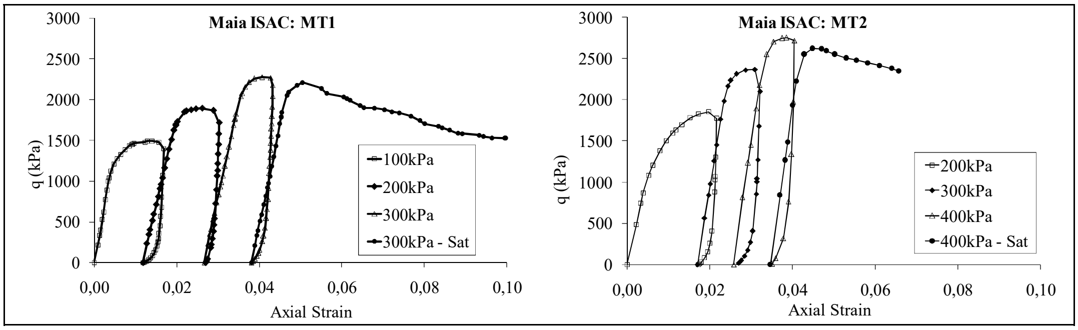

Figure. 2: Stress/Strain curves for Maia ISAC specimens submitted to multistage test procedure

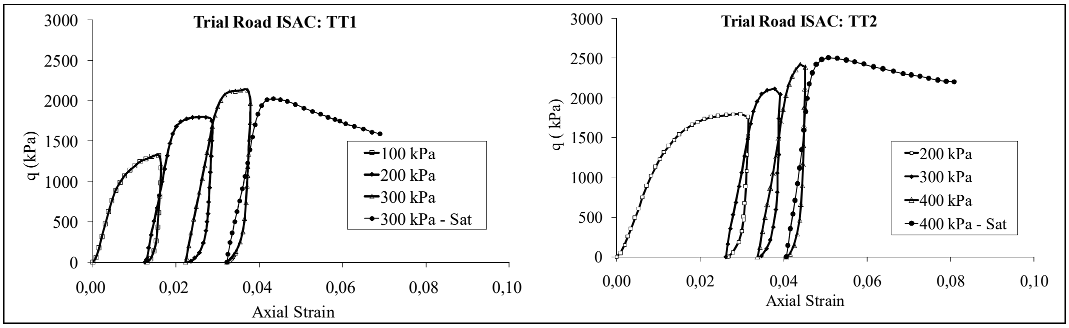

Figure. 3: Stress/Strain curves for Trial Road ISAC specimens submitted to multistage test procedure

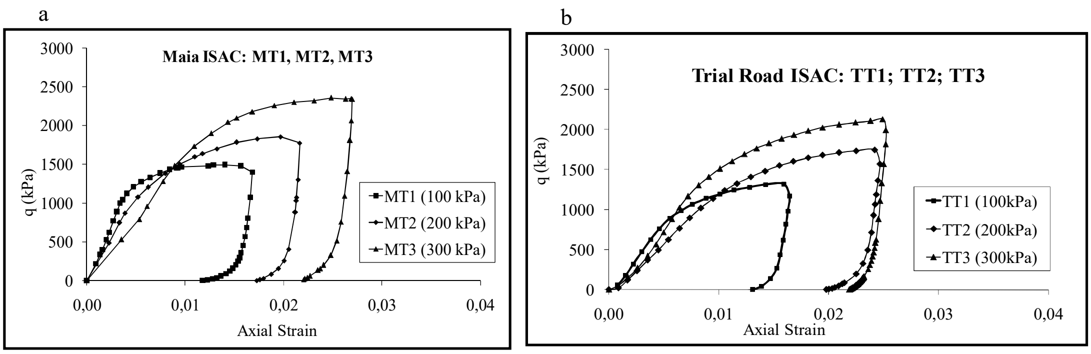

Figure 4: Stress/Strain curves for single stage test procedure: a) Maia ISAC; b) Trial Road ISAC

The test results of Figure 2, Figure 3 and Figure 4 show that stress/strain behavior of ISAC is not linear and the unloading seems quite abrupt, leaving a significant portion of unrecoverable deformation. From Figure 2 and Figure 3 it is also observed that the specimens show a behavior of a material in dense state and, as the confining pressure (σ_3) increases, the maximum value of q (peak value) also increases. In addition, saturated or unsaturated specimens lead to similar peak values of deviatoric stress and saturation of the material appears to have little influence on the stress/strain behavior of material, as expected, since the percentage of fines is too small (less than 2%).

To determine the ultimate strength parameters of both grain-size distribution curve of ISAC the Mohr-Coulomb failure criteria in diagram (s, t) were applied, where s is the average of maximum axial stress (σ_1) and confining pressure (σ_3) and t is the average of difference of (σ_1) and (σ_3). The strength parameters, cohesion (c) and internal peak friction angle (ϕ_p) of the Mohr-Coulomb failure criteria, for peak values, are deducted from equation (1) by means of equation (2) and (3), respectively.

$$t_p = a + s_p \tan\alpha \quad (1)$$

$$c = \frac{a}{\cos\phi} \quad (2)$$

$$\sin\phi_p = \tan\alpha \quad (3)$$

Figure 5 and Figure 6 show the envelope failure obtained for each one of the specimens submitted to multistage triaxial test procedure for Maia ISAC and Trial Road ISAC, respectively.

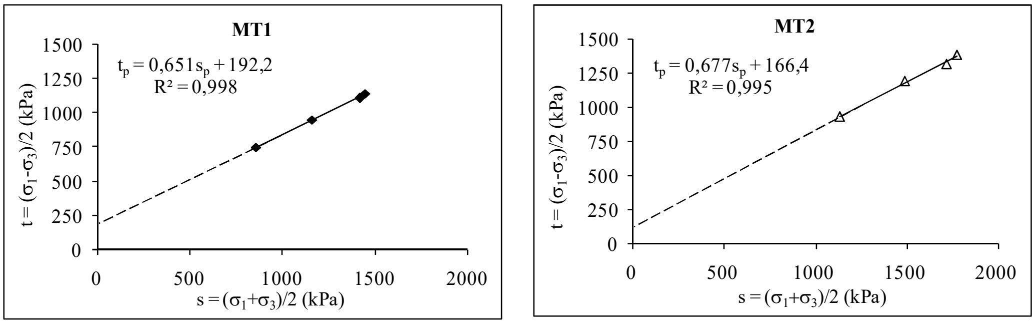

Figure 5:. Failure envelope for Maia ISAC

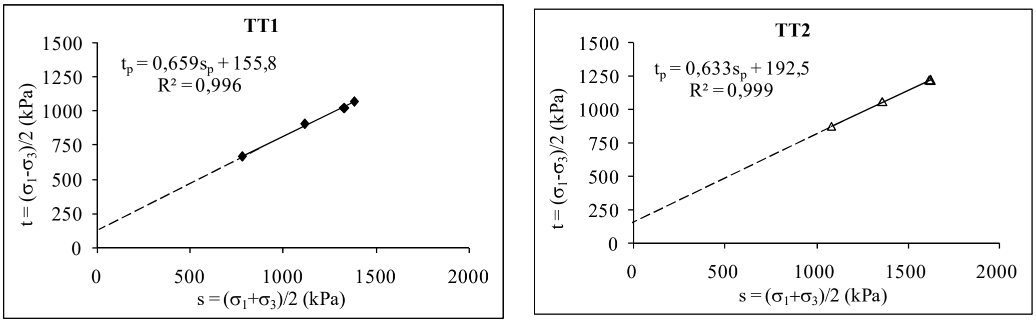

Figure 6: Failure envelope for Trial Road ISAC

To determine the failure envelope for the single stage triaxial test procedure, at least three test results from three different specimens are required. Once just one specimen, by grain-size distribution curve, was submitted to the single stage test procedure (MT3 and TT3) the pair of values of stresses (s, t) for the first cycle of each one of specimen submitted to the multistage (virgin curves) was plotted together with the test results obtained for the specimen submitted to single stage (Figure 7). Figure 7 shows the failure envelope for virgin curves (single stage) and for all test results (multistage).

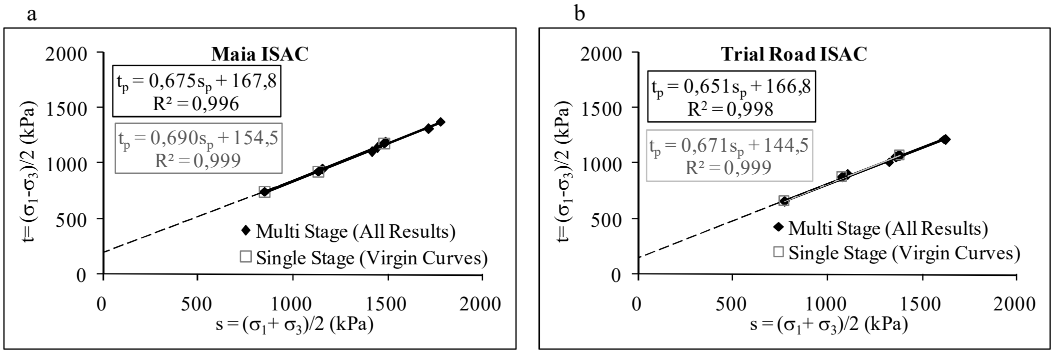

Figure 7: Comparison of failure envelope for multistage and single stage triaxial test procedure: a) Maia ISAC; b) Trial Road ISAC

Table 2 summarizes the ultimate shear strength parameters obtained for both grain-size distribution tested curves of ISAC. The cohesion is not studied as ISAC is an unbound granular material and the values in the Mohr-Coulomb criteria have only mathematical meaning.

Material	Ref. Specimen	Test procedure	tgα	ϕ_p (º)
Maia ISAC	MT1	Multistage	0,651	40,6
	MT2	Multistage	0,677	42,6
	MT1/MT2/MT3 (Virgin Curves)	Single stage	0,690	43,6
	MT1/MT2/MT3 (All Test Results)	Multi/Single stage	0,675	42,5
Trial Road ISAC	TT1	Multistage	0,659	41,2
	TT2	Multistage	0,633	39,3
	TT1/TT2/TT3 (Virgin Curves)	Single stage	0,671	42,1
	TT1/TT2/TT3 (All Test Results)	Multi/Single stage	0,651	40,6

Table 2: Comparison of multistage and single stage triaxial test procedure results.

The test results presented in Figure 5, Figure 6, Figure 7 and Table 2 show that the values of internal friction peak angle found for Maia ISAC and Trial Road ISAC are similar and high (about 41º). These values are consistent with literature where it was found that the aggregate of processed steel slag has internal friction angle in this order of values (typically showing values above 40° [5]). Comparing the values of internal friction angle for Maia ISAC and Trial Road ISAC, it seems that the difference of the grain-size distribution curves has little influence on ultimate shear strength behavior of ISAC, since the difference of ϕ_p in all specimens is less than 10%.

Comparing the test results obtained with multistage and single stage triaxial tests procedures, it is observed that the difference found for ϕ_p values in all the specimens is less than 10%. This means that in terms of ultimate shear strength multistage triaxial test procedure leads to identical values to those obtained in a single stage, as in the case of soils. This finding leads to a simplification and time savings in mechanical characterization in terms of ultimate shear strength in future studies, since just one specimen is necessary instead of at least three as in single stage test procedure. Another major advantage of multistage triaxial test procedure is that tests are performed on the same specimen which reduces the variability resulting from the use of multiple specimens.

5 Conclusions

Despite multistage triaxial tests have been used for a long time to reduce the variability coming from the use of multiple specimens in single stage tests, their usage was questioned when applied to unbound granular materials and specially in non-traditional materials. The objective of this paper was to validate this test procedure for unbound granular non-traditional materials, especially for ISAC, by comparing the failure envelope obtained by two types of different test procedures (multistage and single-stage). The peak shear strength parameters were determined using the Mohr-Coulomb failure criteria. The test results showed that the multistage test procedure led to values of internal friction peak angle identical to those obtained in the single stage test procedure. These findings lead to simplification and time consumption savings in the mechanical characterization in terms of shear strength, consequently providing a cost-effective alternative to the conventional single stage triaxial test procedure.

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