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THE CYCLIC TRIAXIAL TEST AS TOOL TO QUANTIFY COARSE NON-CONVENTIONAL MATERIALS RESPONSE

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ABSTRACT
Sustainable waste management requires efficient dealing to protect landfill and reduce waste deposits. For that it becomes necessary to improve material characterization, using performance based tests, to estimate waste reuse as construction material. Several mechanical tests exist which make possible to use numerical tools to estimate reversible and irreversible behaviour of non-conventional coarse material, as industrial waste. From the available tests, the large-scale cyclic triaxial test is commonly used since it is the simple one to implement and allows the study of the irreversible behaviour, an import factor for materials to be used in roadway and railway infrastructures. The large-scale cyclic triaxial test is an equipment that exists on several important laboratories, in Europe, USA and Asia. This paper describes a large cyclic triaxial test facility developed at Centre for Waste Valorisation (Campus of University of Minho), able to study coarse aggregates/waste materials with grain size particles up to 50 mm.

Keywords: laboratory testing, large-scale cyclic triaxial test, mechanical characterization

INTRODUCTION
Attending that waste minimization and effective and sustainable waste management are basic principles of the European Environmental Legislation and Strategy [1], and also that construction industry is the major solid waste generator in the world, the stream of construction and demolition waste must be dealt attending the available landfill space for disposal and the dangerous substances contained in it. These wastes, as those of several other industries (e.g., the steel industry) can be efficiently re-use as construction material if an accurate characterization of their properties is available. As example, waste from the steel industry are proved to be suitable for use as aggregate in concrete [2], as aggregates in stone mastic asphalt mixtures [3], or as subgrade and sub-base or base course aggregate in transportation infrastructures [4].
The mechanical behaviour of these wastes, in particular those used as aggregate in transportation infrastructures, may be classified by mean of empirical tests commonly used in geomaterials. However, studies have shown that this type of classification is not reliable to predict numerical behaviour of non-conventional and also for conventional materials [5]. Since granular materials play an important role in road and railway infrastructures, laboratory procedures must be improved and used in replacement of the empirical test [6]. These procedures must be performed over the entire grain size and reproducing the stresses induced during construction and life service. The most common laboratory techniques able to correctly quantify the mechanical behaviour of non-conventional materials are: triaxial test, shear test, and hollow cylinder. Among those, the cyclic triaxial test is the most common since it can cover the small strain domain observed during live service, but also the large strain domain imposed during construction [7].

The cyclic triaxial test, together with an European standard [8], allows an accurate quantification on the elastic and plastic behaviour of the materials. Attending that non-conventional material may have particles with large dimension, a large-scale triaxial chamber is required for testing. This equipment is fundamental for the accurate mechanical characterization of non-conventional material (as well as conventional material) in order to allow its re-use as construction material.

MECHANICAL LABORATORIAL APPROACHES

The classical empiric classification of the materials is obsolete since it is fundamental to determine the mechanical parameters that control the behaviour of the materials for use in numerical design methods. This study needs to be done at a laboratory level on the selected material before they are used in construction, most especially for the case of waste materials, in which few or none experience exists.

The simulation of loading conditions is complex. For example, when simulating a road loading condition, the stress applied on a certain element comprises of two components, respectively the shear and normal stress. At beginning, with the applied load far from the study element, the horizontal shear stress is the dominant stress component, but as the wheel approaches the position above the element the horizontal shear stress lessens and the vertical and horizontal normal stresses become the dominant ones. To reproduce such complex loading conditions, the equipment must be able to attend principal stress amplitude and orientation, which can be induce by natural phenomenon (such as an earthquake), or in engineering work (such as traffic load – Fig. 1.a, or a slope – Fig. 1.b).

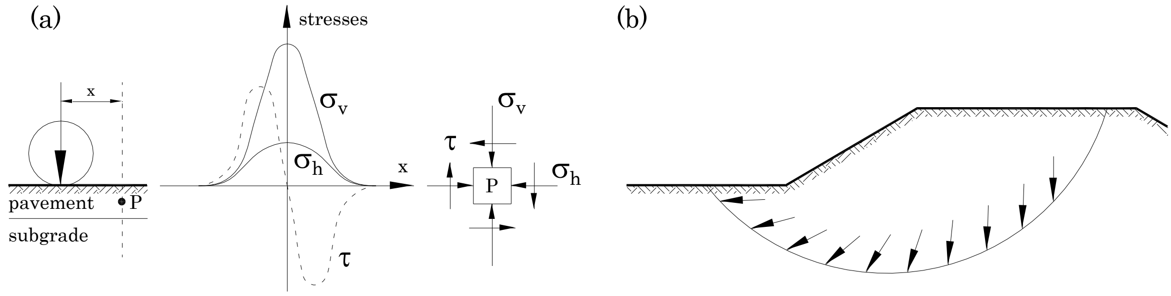
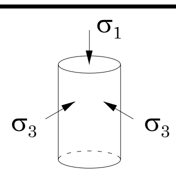
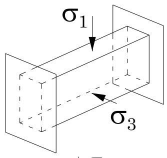
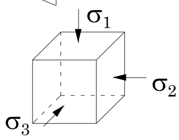
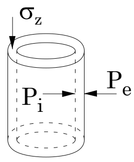
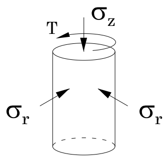
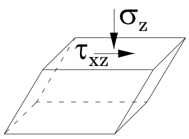
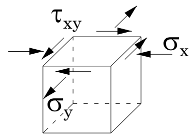
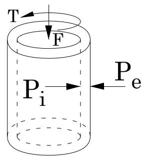


Fig. 1. Stress rotation induced by (a) traffic load or (b) a slope foundation (after [9])

The amplitude/rotation of the principal stresses can be simulated in laboratory by means of eight types of mechanical tests, respectively: triaxial tests, plane strain triaxial, true triaxial, hollow cylinder triaxial, torsional triaxial, simple shear, directional shear cell and hollow cylinder torsional. To control stress evolution, the amplitude of the three principal stresses (σ_1, σ_2 and σ_3) and their rotation (α) is required. The hollow cylinder torsional is the only equipment able to control all four parameters, since it is able to applied controlled axial load, torsion, internal pressure and external pressure. It is an apparatus that allows the rotation of the principal stresses. With the exception of the directional shear cell, all other are unable to reorient the principal stresses. The triaxial test and plane strain triaxial are only able to control the amplitude of the minimum and maximum principal stress (σ_3 and σ_1), being the true triaxial, hollow cylinder triaxial and torsional triaxial also able to control the intermediary principal stress (σ_2). The simple shear does not work with principal stresses since it induces rupture by shearing at constant stress. To resume and clarify all these tests capacities, Table 1 is given to resume controlled parameters and to illustrate the controlled actions of each one.

Table 1. Available mechanical tests and controlled parameters (after [9])

Test name	Controlled parameters	Test schema
Triaxial test	σ_1 and σ_3	

Plane strain triaxial	σ_1 and σ_3	
True triaxial	σ_1, σ_2 and σ_3	
Hollow cylinder triaxial	σ_1, σ_2 and σ_3	
Torsional triaxial	σ_1, σ_2 and σ_3	
Simple shear	σ_z and τ_{xz}	
Directional shear cell	σ_1, σ_3 and α	
Hollow cylinder torsional	σ_1, σ_2, σ_3 and α	

From all these tests, the triaxial test is the most appealing, despite being unable to control the intermediary principal stress (σ_2) and orientation. It consists on a test simple to implement than the hollow cylinder and it allow the study from the small to large stress domain. The use of cyclic loading make also possible to study irreversible behaviour. And, to allow the simulation of σ_2, it can be updated to control specimen torsion, making it possible to modify existing systems to torsional triaxial ones.

AVAILABLE LARGE-SCALE TRIAXIAL APPARATUS

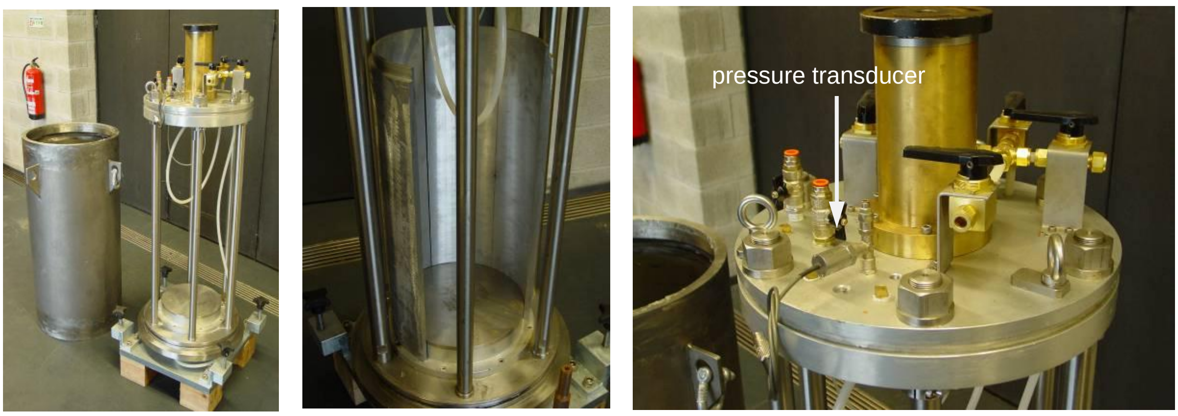
Testing of coarse aggregates or industrial wastes requires large experimental devices since the size of the sample has to be at least 6 greater than the maximum grain diameter. From the 90's, the triaxial chamber dimensions achieved considered grow. One can enumerate several of this large-scale triaxial apparatus at: the University of Cataluña (Spain) for specimen up to 300 mm diameter, the University of Tokyo (Japan) for specimen up to 1500 mm diameter, the GeoDelft (Netherlands) for specimen up to 400 mm diameter, the University of Karlsruhe (Germany) for specimen up to 800 mm diameter, the University of Berkeley (EUA) for specimen up to 915 mm diameter, the University of Nantes (France) for specimen up to 1000 mm, the Missouri Institute of Science and Technology (EUA) for specimen up to 420 mm diameter, the University of Nottingham (UK) for specimens up to 300 mm diameter, the University of Chile (Chile) for specimens up to 1000 mm diameter, the Norwegian University of Science and Technology (Norway) for specimens up to 500 mm diameter, and the “Laboratório Nacional de Engenharia Civil” (Portugal) for specimens up to 300 mm diameter.

CVR’S TRIAXIAL APPARATUS SYSTEM

The evaluation of the behaviour of geomaterials (or coarse industrial waste) in fundamental to reduce maintenance cost and to protect landfill resources. Also attending that the unique national large-scale is out-of-date, the Civil Engineering Department at University of Minho developed, in cooperation with the Centre for Waste Valorisation, a large-scale cyclic triaxial apparatus to study materials with grain size curves up to 50 mm (Fig. 2). The system was developed to allow the execution of test procedure described in [8]. The large-scale cyclic triaxial system now available at Centre for Waste Valorisation (at University of Minho), allows two testing procedures: (a) cyclic variation of the deviatoric stress with constant confining pressure, and (b) sync variation of the deviatoric and confining pressure. Two testing configurations are possible, designated in Table 2 as Conf. 1 and Conf. 2, respectively for samples with 150 mm or 300 mm diameter. The second configuration (Conf. 2) is mainly intended for the classification of materials with particles bellow 50 mm (i.e., many of the non-conventional materials).

Table 2. Main characteristics of the testing facility

Parameter	Conf. 1	Conf.2
Maximum axial load (*N*)	50 kN	200 kN
Maximum confining pressure (σ_3)	400 kPa	400 kPa
Maximum axial displacement (δ)	50 mm	100 mm
Cyclic axial load amplitude (at 1Hz)	[0.4, 10] kN	[1.7, 45] kN
Cyclic confining pressure amplitude (at 1Hz)	[25, 400] kPa	[25, 400] kPa
Cyclic axial displacement amplitude (at 1Hz)	[10, 2500] μm	[20, 5000] μm
Monotonic test velocity	[0.01, 1] mm/min	[0.01, 1] mm/min
Sample height	300 mm	600 mm
Sample diameter	150 mm	300 mm



(a) (b) (c)

(d) (e) (f)

Fig. 2. CVR's triaxial apparatus: (a) 300 mm specimen diameter triaxial chamber, (b) specimen mold, (c) top pressure transducer, (d) hydraulic group, (e) assembled chamber and (f) global large-scale triaxial system

The use of this device was susceptible to promote a steel industry waste in a new construction material, actually a commercial product [10], and its capacity to simulate stress trajectories distinct from the classical q/p=3, allows a better representation of the loading conditions. As an ongoing project, accelerometers are being used to improve specimen instrumentation. Other details regarding this new system can be found at [11].

CONCLUSION

The reuse of industrial waste protects landfill resources and can even be a profitable resource. But for that performance-based laboratorial characterization is needed to allow the use of numerical models. Several types of mechanical tests are available to replace classical empiric methods. From all them, the cyclic triaxial test is usually adopt, for its simplicity and capacity to study both reversible and irreversible behaviour. Due to the lack of this type of facility and expertise, the Department of Civil Engineering at University of Minho and the Centre for Waste Valorisation set-up a large-scale cyclic triaxial apparatus, able to apply synchronize variation of axial load and confining pressure. This equipment was presented in this study and is operational.

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