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Hydro-mechanical characterization of Jurassic marls to study load degradation

Caractérisation hydro-mécanique de marnes du Jurassique pour étudier la dégradation résultante du chargement

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ABSTRACT

Mechanical properties of soft rocks such as marls are strongly affected by suction, directly connected with wetting and drying cycles resulting from climate actions. An extensive experimental programme was carried out in order to characterize the physical and mechanical properties of Abadia marls, used in the A10 motorway near Arruda dos Vinhos (Portugal). The experimental programme consisted of laboratory unconfined compression and Brazilian splitting tests, oedometric tests and triaxial tests, all of them performed under controlled suction.

RÉSUMÉ

Les propriétés mécaniques des roches tendres, comme les marnes, sont fortement affectées par la succion, directement associée avec les cycles de mouillage/séchage résultants des actions climatiques. Un programme d'essais en laboratoire est mené pour caractériser les propriétés physiques et mécaniques des marnes de Abadia, utilisées dans l'autoroute A10 près de Arruda dos Vinhos (Portugal). Le programme expérimental a été constitué par des essais de compression uniaxiale, essais brésiliens de traction, essais oedométriques et essais triaxiaux, exécutés dans des conditions de succion contrôlée.

Keywords: Soft rocks, marl, suction, mechanical properties, unconfined compression and triaxial tests

1 INTRODUCTION

Marls, mainly those that exhibit significant weatherability, are frequently involved in engineering design situations difficult to tackle in sound basis. Mechanical properties of this particular kind of soft rocks are strongly affected by suction and degradation, directly connected with wetting and drying cycles resulting from common climate actions. Their characterization and modelling is very difficult. To start with, just collecting and preparing samples for laboratory tests is a complex and delicate task. The need to accurately control suction of the samples and the long time required for the samples to reach equilibrium under an imposed pre-defined suction value render any test programme very time consuming. Moreover, preparing the samples for tests is extremely laborious, since water is not allowed in drilling and cutting operations. As a consequence, reliable models describing soft rock mechanical behaviour taking into account the effects of material degradation are still scarce.

An extensive experimental programme was developed in order to characterize the physical, mechanical and hydraulic properties of Abadia marls, dated from the Upper Jurassic. The experimental programme consisted of controlled suction

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laboratory tests, such as unconfined compression, Brazilian splitting, oedometric and triaxial tests. Results from this experimental programme were used to model the Abadia marls behaviour, which is presented in another paper [1].

2 ABADIA MARLS

In general, marls are classified as hard soils/soft rocks and exhibit evolutive behaviour, since their mechanical and hydraulic properties change markedly due to alternate wetting-drying cycles and to other weathering processes. Crack opening and/or loss of bonding are associated with these processes, having negative impact on the strength and compressibility of the material.

Some geotechnical challenges had to be tackled during construction of motorway A10, around 40 km North of Lisbon (Portugal). Near Arruda dos Vinhos, the motorway crossed Jurassic marly formations known as Abadia Marls.

To perform laboratory tests of marl samples a 2 m deep excavation was carried out allowing to collect five large blocks with dimensions ranging between 80 cm and 2 meters. The marls were practically saturated (in situ water content varying between 9% and 16%). Special care was taken in sample conditioning during transportation to the laboratory. Once there, the large blocks were completely wrapped with plastic film, paraffin and metallic film.

Sample preparation was a difficult task. First attempts to drill samples directly from the large blocks using standard diamond coring equipments proved to be unsuccessful. Instead, prisms were cut from the large blocks using diamond saw disks. Some prisms were used to obtain cylindrical samples, while others were directly used as samples for unconfined compression tests. Samples for unconfined compression tests were drilled out of the prisms using a drilling equipment connected to a dust removal system in order to eliminate the very fine dust produced by drilling that could clog around the bit and break the sample (Figure 1). Cylindrical 54 mm in diameter samples for triaxial tests were obtained from prisms cut from the large blocks using a lathe to shape the prisms into cylinders.

Figure 1. Drilling equipment, sample and prism after drilling.

The samples were placed in humidity controlled environments (desiccators or chamber) immediately after being cut from the large blocks. Suction was applied using vapour equilibrium technique. In some cases, standard saturated salt solutions were adopted (reference values at 25ºC - LiCl: RH=11%, s=303 MPa; NaCl: RH=75%, s=39 MPa; KCl: RH=84%, s=24 MPa). In other cases, specimens were placed in a chamber with controlled relative humidity and temperature.

3 PHYSICAL PROPERTIES

Concerning the mineralogical composition of the marls, carbonates (calcite mainly) (16-23%), clays (54-64%), and a very small percentage (0-2%) of organic matter are present. The relation between the percentages of clay and carbonates justifies the designation of the material as marl. Existing expansive minerals are chlorite (1-5%) and gypsum (traces found in some samples). The presence of these minerals may explain the degradation (mainly cracking and disaggregation) and the moderate expansive behaviour observed when these geomaterials are fully saturated. The disaggregated marl can be classified as low plasticity clay (CL), which is in accordance with the nature of the clay minerals found. Several other characterization tests were also performed [3], and other properties are presented in [1].

Water adsorption tests performed by Jeremias [2] at 95% relative humidity and 25ºC (96 hours of exposure) indicated good capacity for water absorption. This capacity increases with the degree of weathering.

A marked volume dependence on water content was registered (Figure 2), associated with micro-cracking. The water retention curve was measured for three drying-wetting cycles, in which degradation was registered by the increment of the saturated water content [3].

Finally, swelling tests were performed on marl specimens with different initial water contents and under different stresses. As expected, the dryer the material and the lower the stress, the larger the swelling deformation.

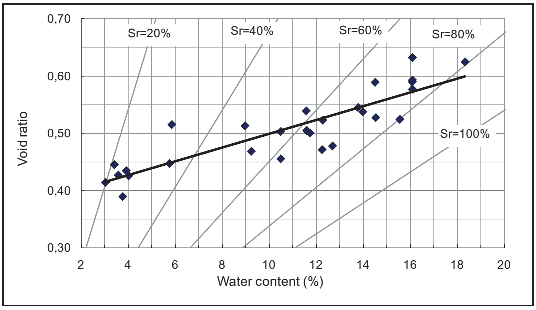


Figure 2. Void ratio dependence on water content [3].

4 UNCONFINED COMPRESSION TESTS

Unconfined compression tests with unsaturated marl samples following ASTM Standard D 7012-07 were performed. Samples kept with the in situ water content (around 9.2% corresponding to a suction of 14 MPa) were tested, along with other samples kept in the three above mentioned standard salt solutions.Standard loading and measuring equipment was used; the axial stress was measured using a load cell and the axial strains by external displacement transducers placed along the middle part of the samples. Due to the duration of the test (strain rate about 0.005%/min) the samples (around 50 mm in diameter and 125 mm in height) were loosely wrapped with a thin plastic film to maintain the water content.

During the tests, loading-unloading cycles were applied until failure occurred. Independently from suction, samples showed ductile behaviour since relatively high values for axial strain (larger than 0.5%) were reached (Figure 3). Plastic and hysteretic behaviour was also displayed, being more significant for lower suctions.

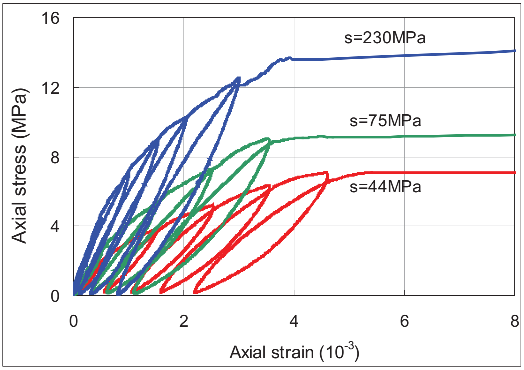


Figure 3. Examples of unconfined compression tests.

Cracking is responsible for stiffness reduction and so may be looked at as damage. Stiffness decreases progressively with increasing strains. Dryer samples exhibit higher stiffness, but also a higher relative reduction with the loading cycles. However, stiffness values for the dryer samples are always higher than those measured in the other samples.

The large variability of the results found in all the unconfined compression tests can be seen in Figure 4. The relation between the water content measured in each sample after the test and uniaxial compressive strength σ_c is shown in the figure. Water contents of pieces of the broken samples were measured revealing that samples from the same desiccators had slightly different water contents, which can be accounted for part of the variability of the results.

Uniaxial compressive strength results were averaged after considering the samples for which visual inspection before the test had shown neither relevant cracking nor heterogeneity identified by colour differences. The relation between σ_c and suction s is presented in the equation (1).

$$\sigma_c = 0.0276\,s + 6.14 \ \text{(MPa)} \qquad (1)$$

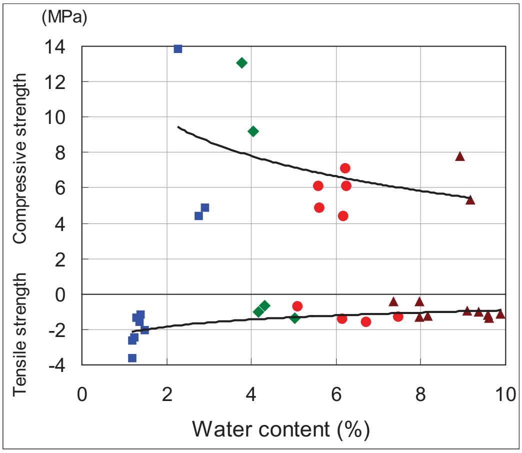


Figure 4. Results of the unconfined compression and Brazilian splitting tests.

5 BRAZILIAN SPLITTING TESTS

Splitting tensile strength tests (Brazilian splitting tests) were performed following ASTM D 3967-08. Tested samples were around 5 cm in diameter and 2.5 cm thick.

As for the stiffness and strength determined in unconfined compression, tensile strength σ_t decreases with water content (or increases with suction). Its relation with water content measured for each sample after the tests is also presented in Figure 4. In spite of the dispersion, increasing strength for the dryer samples can be observed.

Orientation of low strength strata relative to the diametral loading force, natural heterogeneity of the marl matrix in some samples revealed by colour differences, and the existence of microcracks explain the variability of the results. Considering only the results of representative samples chosen by visual inspection after the tests allowed establishing the relation between tensile strength and suction presented in equation (2).

$$\sigma_t = 0.0066\, s + 1.01 \text{ (MPa)} \tag{2}$$

6 OEDOMETRIC TESTS

Oedometric tests were performed in totally saturated and dry conditions marl samples where stress cycles were applied [3]. The specimens (3 cm in diameter and 1.8 cm thick) had an initial void ratio e of 0.29. They were initially dried in laboratory environment (RH=45%, s=124 MPa, w=3.4%). In test 1, the sample was fully saturated under a relatively low vertical stress (253 kPa), after which three unloading-reloading cycles up to 2.2, 4.4 and 7.6 MPa were applied (Figure 5). A similar test procedure was adopted in test 2 [1], but in this case the sample was kept in dry conditions.

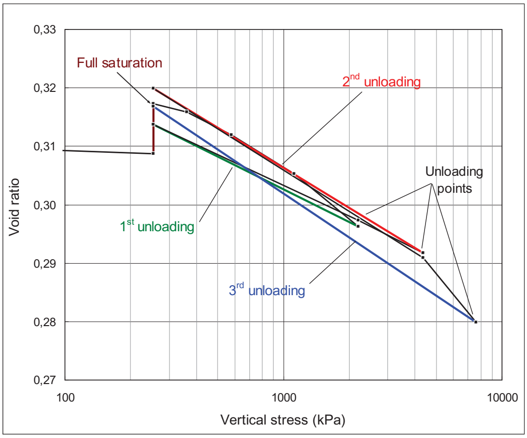


Figure 5. Oedometric test. Specimen saturated at 253 kPa.

Both tests show that under constant suction the elastic compressibility index C_s increases with the cycles (from 0.019 to 0.025 in test 1, and from 0.007 to 0.010 in test 2). Larger C_s values were measured in fully saturated conditions, showing that wetting seems to be more relevant for structure degradation than loading stresses. Tests revealed similar values for the elastoplastic compressibility index C_c: 0.042 for the dry sample and 0.046 for the wet sample.

7 TRIAXIAL TESTS

Laboratory triaxial tests are commonly performed to assess intact rock strength under axisymmetric conditions. Due to the high pressures usually required, rock triaxial cells tended to be heavy and difficult to handle, so Hoek and Franklin [4] developed a simpler cell (commonly referred to as Hoek triaxial cell) that only applies the lateral pressure, and is used with a conventional compression testing machine to apply axial force to the specimen. The main advantage is that it does not require complex and time consuming preparation for assembling and deassembling the cell between tests.

As pointed out in the introduction, the main aim of this experimental programme is to allow modelling of stress-strain behaviour of the Abadia marls, based on the accurate measurement of the volumetric and shear strains. So, the triaxial tests were performed using a triaxial cell that enables the measurement of the axial and diametral deformations of the specimens. Diametral displacements are given by two perpendicular transducers sets connected directly to the specimen through the rubber sleeve located inside the cell (Figure 6). Axial displacements, the axial force and the lateral pressure are measured by common transducers controlled by a data acquisition system, enabling fully mechanical characterization during the tests. Lateral pressures up to 70 MPa are applied inside a titanium cell.

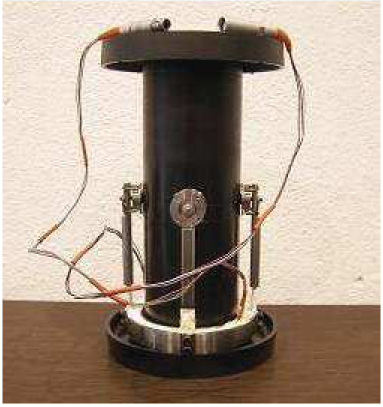


Figure 6. Internal rubber sleeve with diametral displacements transducers.

Triaxial tests using samples under constant suction were performed. Tests consisted of two stages: an isotropic phase with loading-unloading cycles, followed by a deviatoric phase with the increase of the axial stress until failure occurred. Five tests reaching confining pressures of 4 MPa (samples 3 and 4), 8 MPa (samples 6 and 8), and 12 MPa (sample 12) are reported. All samples were chamber conditioned at 75% RH and 22ºC, corresponding to *s*=39MPa and approximately *w*=5%.

Figure 7 displays the relations between net mean stress and volumetric strain during the isotropic stages of all tests. As expected, these graphs show for all samples an approximately linear behaviour during the loading and unloading-reloading cycles. The strains related to these latter cycles are almost always recovered, showing an elastic behaviour with a small hysteresis.

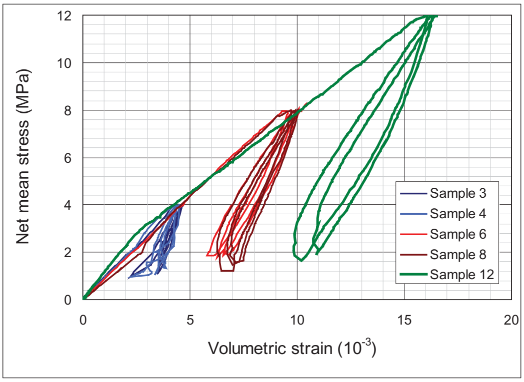


Figure 7. Results of triaxial tests. Isotropic stage (*s*=39MPa).

Considering only the first loading of each test, bulk modulus K decreases from 910 to 740 MPa with increasing isotropic stress. For the unloading-reloading paths, K_{ur} also decreases with increasing isotropic stress, ranging from 2250 to 1650 MPa.

Figure 8 presents the stress paths of the deviatoric stage of the triaxial tests, in terms of net mean stress p and deviatoric stress q, given by equation (3) as functions of the principal stresses.

$$p = (\sigma_1 + 2\sigma_3)/3$$

$$q = \sigma_1 - \sigma_3 \tag{3}$$

In the same graph, the average failure values of the unconfined compression tests and Brazilian splitting tests for the same suction conditions (*s*=39 MPa, *w*=4-5%) are also shown, revealing a curved envelope.

Figure 9 presents the deformational behaviour of the samples during the deviatoric stage of the triaxial tests in terms of the evolution of the deviatoric stress and volumetric strain ε_v with shear strain ε_s. These strains are given by (4).

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$$

$$\varepsilon_s = \frac{2}{3}\left(\varepsilon_1 - \varepsilon_3\right) \tag{4}$$

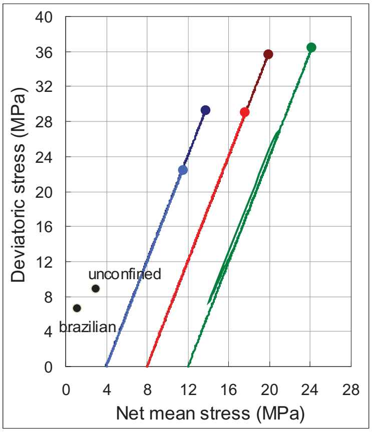
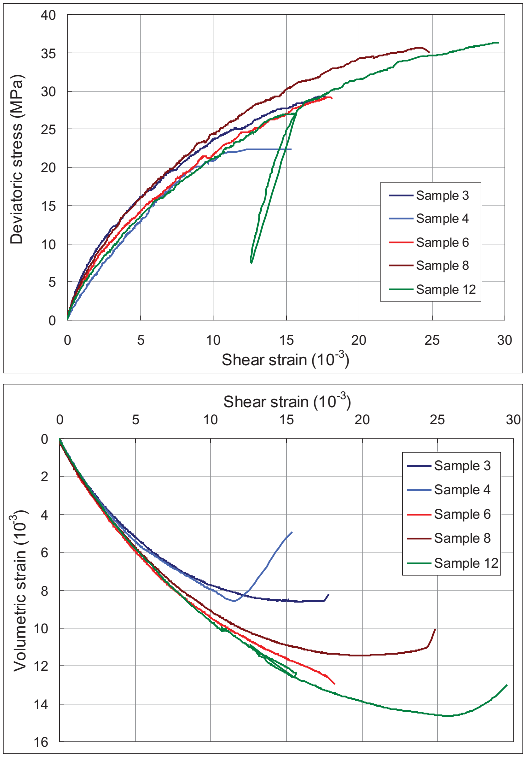


Figure 8. Results of triaxial tests. Stress paths in the deviatoric stage (s=39MPa).



.Figure 9. Results of triaxial tests. Deformational behaviour in the deviatoric stage (s=39MPa).

Both graphs show that the deformational behaviour of all samples is remarkably similar, with a stiffness decrease as the deviatoric stress increases, as usual. The unloading-reloading of sample 12 reveals that elastic recovery is only around 25% of the shear strain and points out that the stiffness decrease is a result of plastic behaviour under deviatoric stress. In some tests (samples 3, 8 and 12), close to failure, samples were deforming without volume change, attaining the critical state.

8 CONCLUDING REMARKS

Some interesting results from several types of tests performed to characterize Abadia marls were presented. The results of the tests under different load paths (uniaxial compression, brazilian splitting, isotropic compression, oedometric, and shear in triaxial compression) revealed that the Abadia marls are soft rocks with a remarkable ductile behavior.

Oedometric tests, where suction paths were also imposed, shown that it is not possible to describe adequately the mechanical behavior of the marls without taking into account their load and suction history.

Data of this experimental work will be used to calibrate suitable models, namely those where damage parameters are used. This is the case of oedometric tests where encouraging results were obtained [3]. This type of approach was also used for isotropic compression under constant suction [1].

Results displaying the influence of suction in isotropic and shear under triaxial compression are to be presented in a near future

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