Use of a large triaxial cell for testing conditioned soil for EPBS tunnelling

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Abstract

Laboratory testing of soil conditioning for EPB tunnelling is a common procedure to assess the suitability of the conditioning itself in different tunnel projects, but normally the stress influence is not taken into account. This work describes the behaviour of two different conditioned masses in different stress conditions through a large diameter triaxial cell, which allows to reproduce different stress scenarios. The results obtained show the influence of the stress on the shear strength of the conditioned material and the different attitude of behaving as a fluid testing a granular material and a more heterogeneous one. Also the two material behaved differently as the presence of a more relevant fine part in the conditioned mass allows the material to maintain its fluidity also at higher pressures.

Keywords: EPB, Soil Conditioning, Triaxial Testing, Shear Strength

1. Introduction

The use of EPB shield technology for the construction of tunnels in urban areas, is more and more taking a relevant role among the excavation methods in such conditions. This is due to the fact that it allows to proceed safely and effectively in several challenging conditions, such as heavily heterogenous geologies, low overburdens in densily populated areas and relevant water table levels. Moreover EPB shields are not requiring large spaces at the tunnel entrance such in the case of slurry shields, which need complex and extended infrastructures (Herrenknecht, 1994; Maidl and Hintz, 2003; Lovat, 2006; Peila, 2009; Thewes, 2014). In addition, the improvement of this technology throughout the ages allowed the extension of the range of applicability of EPB shields almost to any excavation medium, from clay to rock masses (Mair et al., 2003; Merritt et al., 2003; Milligan, 2000; Thewes, 2007; Vinai et al., 2007; Thewes et al., 2010; Zumsteg et al., 2013a,b; Peila, 2014; Martinelli et al., 2015b; Peila et al., 2016; Martinelli et al., 2015a), and its use with higher counterpressures that today reach values over 6 bars. This is also due to the intense development of the agents used for the conditioning process, such as foams, polymers and fillers. This paper is specifically focused on cohesionless soils.

One important issue regarding the study of the conditioned soil is to understand its mechanical behaviour when the mass is stressed by an external pressure. This aspect is crucial to assess the suitability of a conditioned mass during an excavation. The mass has to be fluid enough to flow into the excavating chamber through the cutterhead openings and to apply effectively the counterpressure to the front, but maintaining a workability pulpy enough to be extracted through the screw conveyor. The second aspect can be efficaciously studied by mean of tests such as slump test, which can give good indications on the workability of the conditioned mass (Bezuijen et al., 2005; Vinai et al., 2008; Peila et al., 2009; Budach and Thewes, 2010; Thewes et al., 2012; Galli and Thewes, 2016). On the contrary the first aspect is a bit more difficult to be assessed with standard tests, as no clear indications on the pressure transmissivity can be studied. This is a key aspect for the present work, and this new testing approach is an attempt to investigate it. An important study on this issue has been already carried out by Mori et al. (2015), Mooney et al. (2016) and Mori et al. (2018): their researches illustrate how pressure influences conditioned soil behaviour and how atmospheric test results must be viewed in the context of expected chamber pressures taking into account, through digital image analysis, the influence of pressure on bubble-soil interaction (including with time). The study is aimed to assess the compressibility, shear strength, and abrasivity of conditioned soil under pressure explained in terms of density, soil and air compressibility and porosity. Similar approach has been preliminarily investigated by Psomas (2001) by characterizing the coupling foam/sand mixture under different stress conditions and by Yang et al. (2018) who has considered also the chemical influence of polymers.

In order to proceed with this study, it is necessary to imagine a model of the problem to be studied. In an EPB tunnelling project in soil, the material is first excavated, mixed with a conditioning agent (usually water and foam) and then strained with an external stress. In the excavating chamber this stress is represented by the compression of the conditioned material with other material up to the needed counterpressure. The stress should be ideally hydrostatic, that is the reason why the conditioning has to bring to the mass sufficient fluidity.

The best way to represent in laboratory such a situation is to apply a confinement to the conditioned mass, in order to reproduce the excavating chamber as a cylindrical pressurized tank with one of the bases which represent the cutterhead and thus which can be able to move and virtually apply a distributed pressure. Of course the most suitable material to apply the pressure in this condition is a fluid like the water, because by definition when a pressure is applied on this, it is transmitted immediately in all the directions hydrostatically. On the contrary a soil is not able to transmit the pressure in such a way, for example in a natural deposit close to the surface the vertical stress is given usually by the weight of the soil itself, but the horizontal resulting stress is usually lower and is function of the friction angle φ. Considering a normally consolidated granular deposit, the at rest lateral earth pressure coefficient K_0, linking the vertical and horizontal in-situ stress, is equal to (Jaky, 1948):

$$K_0 = 1 - \sin \varphi' \tag{1}$$

As clearly achievable from the Equation 1, in order to obtain the hydrostatic condition and therefore a K_0 equal to 1, the effective angle of friction must be equal to 0°. This drop of friction angle can be obtained by mixing conditioning agents with the cohesionless mass.

In order to establish the true mechanical behaviour of the soil after conditioning, it is crucial to maintain the foam and the liquid trapped inside the mass, otherwise the actual behaviour cannot be established. By applying the pressure without a confinement, for instance a piston in a tank which is not completely sealed, a substantial fluid loss (water and foaming agent) can be observed. This will cause a wrong assessment of the actual mechanical behaviour of the mass, as the intergranular voids will loose the presence of the bubbles and the trend will be to have less space between the grains.

The aim of this work is to study the behaviour of the conditioned soil under pressure with a standard common geotechnical test such as the triaxial test, even though carried out in particular conditions. For this study a large cell has been used to assess the shear strength of the material depending on the pressure conditions.

2. Importance of pressure on soil conditioning

In order to avoid this fluid loss in the conditioned mass to keep the material as in the bulk chamber, the best solution would be to seal all the possible gaps where the liquid might flow away. For this reason, the situation that has to be studied is similar to the undrained condition usually considered in geotechnics while performing triaxial tests. In that case the water in the intergranular voids, which is produced by the external pressurization when the sample is saturated, is creating a pore pressure. In general in geotechnics the definition of undrained condition is directly linked to the pore pressure, and this condition is encountered when the rate of loading is highly relative to the soil hydraulic conductivity, so that water cannot escape from the pores during loading (Lancellotta, 2009). This condition, performing a triaxial test, indicates the circumstance in which a soil element (i.e. locally) cannot exchange water mass with the surrounding ambient. If the soil is saturated and both particles and water are assumed to be incompressibile, the above definition means that the undrained condition is a constant volume condition. Because of this constraint, an excess pore pressure develops and increments of effective and total stresses do not coincide.

Considering the above mentioned definitions, it is immediately clear that the undrained condition used for testing conditioned soils cannot strictly coincide with the geotechnical one. This is mainly due to the fact that the conditioned sample is not saturated with water: it is usually in a condition close to the saturation but most of the pores are filled with foam bubbles which can change size depending on the acting pressure. In this scenario it is thus clear that compared to a sample saturated with water, the conditioned sample is compressible, therefore the constant volume condition is not fulfilled. The saturation of the conditioned sample with water and foam is crucial in order to transmit effectively the pressure. If this is not happening, the material once compressed does not immediately transfer the pressure in all the directions, as the fluids are first absorbed by the drier mass. Thus the condition we are considering for testing the conditioned samples is just partially equal to the undrained condition used in geotechnics; in the samples studied in this research the medium is compressible and the pore pressures develop from a mixture of water, foaming agent and mostly air.

The mechanical behaviour of the conditioned material in certain pressure conditions is not fully clear: those pressures which are acting on the material are according to Terzaghi's theory. The theory states that the stress in any point of a section through a mass of soil can be computed from the total principal stresses σ_1, σ_2 and σ_3 which act at this point. The balance $\sigma_1' = \sigma_1 - u$, $\sigma_2' = \sigma_2 - u$ and $\sigma_3' = \sigma_3 - u$ (effective principal stresses) represents an excess over the neutral stress u (pore pressure) and it has its seat exclusively in the solid phase of the soil. The theory of the effective pressure in EPB tunnelling has been treated especially by Anagnostou and Kovári (1996), where a distinction is given between fluid-pressure and effective pressure in the chamber. In this case, the effective pressure can be visualized as a grain to grain contact pressure between the muck and the ground at the face. The water pressure in the chamber reduces the hydraulic head gradient in the ground and, consequently, the seepage forces acting in front of the face. Considering the front stability, the face is thus stabilized both by direct support of the pressurized muck and by the reduction of the seepage forces in the ground. The difficult point which has to be better studied, and that is object of this research work, is the influence and the contribution of the foam bubbles inside this theory.

In EPB tunnelling, the material is usually conditioned under a certain stress condition, which is not zero. Thus the study of the conditioned soil should be carried out under particular pressure conditions which are proper to the excavating chamber in operation. This issue is quite complex to be taken into account: in laboratory the addition of foam and other conditioning agents is usually conducted at room conditions, and the representation of the pressurized status is difficult to be considered.

The main aspect in this case is to verify the behaviour of the conditioned material in different pressure conditions: if in one side the slump test is generally giving a good answer and response on the quality of the conditioned soil for EPB applications, on the other hand it cannot give indications on its behaviour under particular stress conditions. This is a crucial issue, especially considering that a key parameter of the conditioning is the FER, which is representing the expansion ratio and which is strictly linked to the pressure. Considering that the conditioned soil is a multiphase medium, composed of different material with different compressibilities, its characterization is quite difficult.

In this context new testing procedures would solve this important issue. Theoretically, the application of the stress on the conditioned mass would cause a large deformation in the first phase, as the bubbles of the foam are the first to be strained due to the higher compressibility of the air; in the second phase, once the intergranular voids between the grains are small enough to allow again the contact of the soil (as it usually happens in the natural soil), the deformability is different and also the stress application behaviour of the soil itself. In this second stage it is normal to think that the deformability of the medium will decrease and the hydrostatic transmission of the pressure would be much more difficult. Figure 1 shows the mechanics of the conditioned mass when the pressure is applied: at room pressure the grains are not in contact (Figure 1a), after the application of the pressure the grains are moving closer when the bubbles are deforming much more compared to the soil (Figure 1b).

This consideration explains why this study is crucial in the future laboratory testing procedure, as the rigidity of the conditioned spoil is dependent on the stress. A material that is too stiff in the excavating chamber can cause an increase of torque and temperature, with possible faults and severe damages to the machine. This aspect, as already mentioned in the introduction, has been investigated by Mori et al. (2015), Mooney et al. (2016) and Mori et al. (2018).

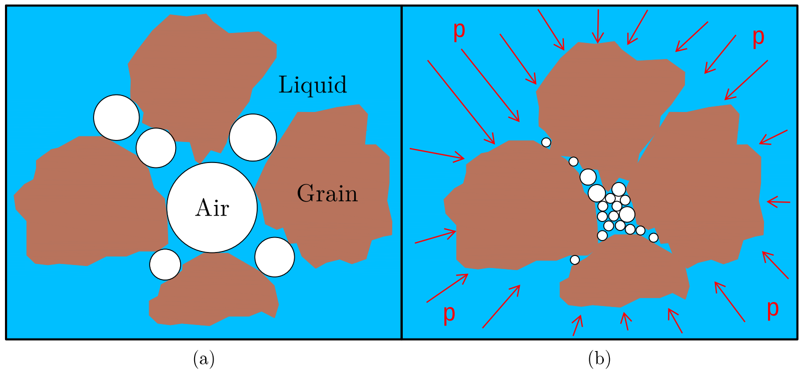


Figure 1: Conditioned mass before (a) and after (b) the pressure application (represented by the red arrows). The soil grains in this model can be considered as non-deformable compared to the air.

3. Modified large diameter triaxial test

In order to study the conditioned material and fulfilling the new approach on testing this type of material, the use of the triaxial test has been considered for assessing the behaviour of the material and for studying the apparent transition from a fluid material to a rigid one.

For this type of testing, it is essential to reduce any external disturbance and create an homogeneous sample: for this purpose, a large triaxial cell should be used. This type of equipment has also another advantage; the sample is large enough to be separately tested in a slump cone at the beginning and at the end of the triaxial test.

3.1. Apparatus

The apparatus used for this research (Figure 2) had been initially designed for testing undisturbed and disturbed samples of coarse soils, such as gravel and cobbles. The original design included the possibility of testing loose soils and cores of undisturbed samples obtained by using the freezing technique. The apparatus used has been designed by the staff of the geotechnical laboratory of the Department of Structural, Geotechnical and Building Engineering of Politecnico di Torino and the original design details have been introduced by Fiorio (2003).

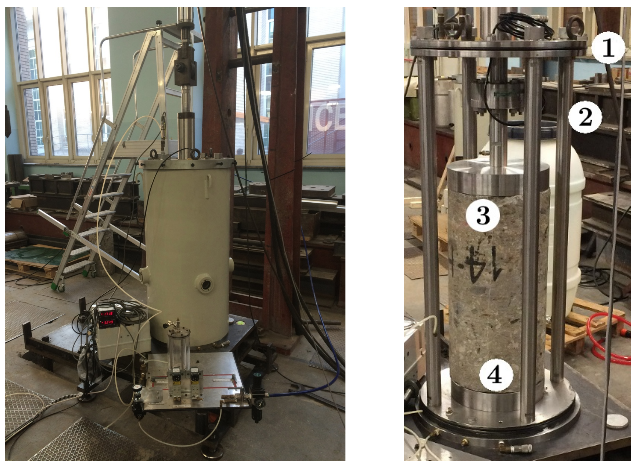


Figure 2: Large diameter triaxial cell apparatus used for the research with its main internal parts: 1) top plate, 2) steel bar, 3) top cap, 4) bottom cap (Martinelli, 2016).

The cell is composed of a bottom cap (number 4 in Figure 2) of 300 mm in diameter, which allows to accommodate samples 600 mm high. The sample is placed on the bottom stainless steel cap (number 3 in Figure 2) with the same diameter as the sample and with a thickness of 60 mm. On the upper face the cap has a deeper cross groove which collect the liquid passing through the porous stone which is inserted at the top of the bottom cap. This connection between the sample and the external part of the cell allow the possibility of drainage of water or measurement of pore pressure. For this research, the hole used for this purpose has been sealed to avoid the drainage of the foam along the tubes. In the upper part a similar plate is closing the sample, and also in this case there is a hole for the drainage. This hole has been left open both for creating the depression at the beginning which allows to close the triaxial cell, and moreover to measure the pore pressure generated by the conditioned mass strained in the cell.

This bottom cap element is fixed to a base plate made of stainless steel, with a diameter of 530 mm and 60 mm thick. This element has been designed in order to allow the passage of the drainage system, which is mostly composed of the line coming from the bottom cap and from the top cap, both connected through flexible pipes, from inside the pressure cell to the exterior; guarantee the sealing on the contact of the cell with the base itself, through a o-ring which is inserted in a groove; rigidly fasten the 4 steel bars (number 2 in Figure 2). The 4 stainless steel bars (diameter 45 mm) are 1025 mm high and they are equipped with o-rings in the upper part in order to guarantee the sealing in the top plate (number 1 in Figure 2) .

In the upper part of the cell, a similar cap (same size than the one on the bottom) which is rigidly linked to the ram is placed in contact with the sample. As already stated the drainage circuit in this case has been kept in operation. Last important element of the top part is the top plate which has the same thickness of the bottom one but a smaller diameter (489 mm) needed to allocate the pressure cell. Also in this case the design has been done to rigidly fasten the 4 steel bars and the loading ram with a pressurized airtight seal and to allow the passage, also in this case with a pressurized airtight seal, of the connecting cables for the transducers and the load cell from inside the pressure cell and the data acquisition device.

The cylindrical pressure cell, as the fluid used for pressurizing the sample is compressed air, is made of steel 1091 mm high, inner diameter of 491 mm and thickness of 16 mm. The bottom and top extremities are thicker to guarantee the tightness with the o-rings.

Even though the dimension of the apparatus is much larger than a common triaxial cell, the accuracy of the load transmission has the same importance, and thus also the loading ram needs a perfect alignment with the sample. This is especially complex due to the actuator which is providing the axial force, which is a large MTS hydraulic actuator located at the MASTR-LAB laboratory of the Department of Structural, Geotechnical and Building Engineering of Politecnico di Torino. This device, that is really precise on providing even small loads, has the problem of connecting the piston to the ram in order to have a perfectly axial load. To obtain this result, a swivel has been connected to a rigid steel frame which is holding the actuator and moreover the connection between the piston and the ram is done by using a radial spherical plain bearing, which is transmitting effectively the thrust axially to the ram. The ram is inserted in a guide (Figure 3) with two ball bearings which guarantee the perfectly straight direction on transmitting the load to the sample. Moreover, between the two bearings there is a length of 50 mm in which the ram is moving in a guide with a maximum tolerance on the diameter of 0.2 mm, guaranteeing the minimum loss of pressure which can be easily counterbalanced with the flow of air. At the top of the guide a system to lock the ram has been provided.

The loading ram, where is also located the loading cell, has a variable

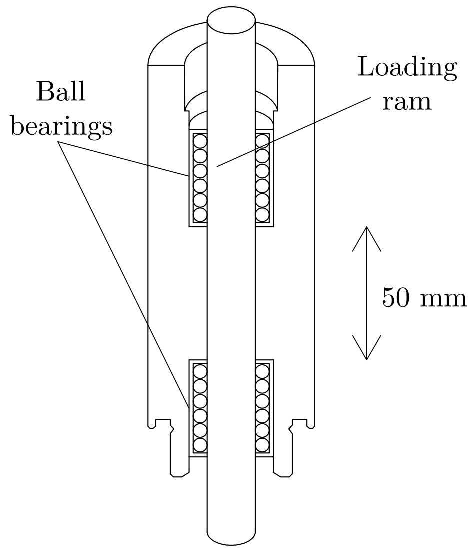


Figure 3: Guide of the loading ram.

length depending on the test needed (compression or extension). The maximum stroke of the loading ram is around 150 mm, larger than the 20% of the sample height, so more than the recommended deformation needed for the triaxial test.

With such dimensions, the estimated volume of the sample is around 42 dm^3, much larger than a slump cone (its internal volume is around 5.5 dm^3). In this way it is possible to verify the state of the conditioned soil after the testing through a slump test, which has been always performed on the soil at the top and and the bottom of the conditioned sample.

3.2. Concerns about the tests

The study of conditioned soils through undrained triaxial tests brought to a series of considerations about the applicability of methods which are mostly used in geotechnical engineering to materials which are not typical of this discipline. From the past studies of conditioned soils it is known that this material cannot really be considered neither a granular material nor a fluid (Vinai et al., 2007; Budach and Thewes, 2015; Mori et al., 2017). The aim of this study is thus to estimate the total shear strength of the soil before and after the conditioning process with similar procedure, in order to obtain parameters which are directly comparable.

Nevertheless it is important to be careful when performing a standard geotechnical test on a conditioned soil, and especially it is necessary to consider two fundamental aspects:

1. the test procedure, the positioning of the sample and the drainage condition could modify the intrinsic nature of the conditioned material. This aspect is particularly evident with the loss of liquid while carrying out a standard direct shear test (Martinelli et al., 2017), which resulted in a reduction of content and dimension of the bubbles, and thus a modification of the conditioning parameters;
2. the constitutive laws which usually are applied on evaluating the results of a triaxial test have been obtained under particular hypothesis, with assumptions regarding the variation of volume or compressibility of the different phases. These issues might not be applicable for the conditioned soil, thus it is crucial to verify for each equation which one can be eventually used.

During the testing campaign, started by using a compression loading stress path, which is regularly used in geotechnical engineering tests, the tests on the dry material brought satisfactory results. On the contrary, the use of this type of stress path on conditioned material did not allow to perform satisfactorily the test. This is mostly due to the fact that after the mold is placed to confine mechanically the sample, in order to remove the mold itself from the cell it is necessary to apply a negative pressure through the drainage pipe (usually 20–30 kPa are enough): for the dry sample (Figure 4) the process works smoothly, as the sample has no liquid; for the conditioned material it did not work due to the presence of liquid under the form of bubbles, which just partially saturated the sample with a relevant part of air trapped between the grains of soil. In this case the grains are not directly in contact, so when a depression is applied through the drainage pipe, the air trapped between the grains starts to flow outside the sample, bringing the foam with it and changing the volume and the state of the sample.

This problem brought to a necessary adjustment of the test procedure for conditioned material: in this case the most suitable method is the use of extension unloading stress path. This allows to skip the depression stage, as the mold can be left in place because the sample is reducing its width during the test and the top cap is moving upwards.

The two test configurations have different molds: the one for the compression loading tests is made of two half pipe thick steel elements, linked each other with bolts; the one for extension unloading tests is a polyvinyl chloride pipe which is less stiff. This mold is rigidly linked at the base with a lashing strap which also dovetails the membrane with the bottom cap.

The triaxial cell has been also used for a non-conventional test, taking advantage of the equipment features: this test is performed by locking the loading ram in a rigid position (no axial displacement, $\delta_a = 0$) and increasing in steps the radial pressure. This type of test would allow to study the

Figure 4: Dry sand sample with the external depression applied

behaviour of the conditioned material at different pressures, especially it is important to verify the difference between the applied confinement radial pressure σ_r and the pressure induced by the fluids trapped in the soil in the sample (pore pressure p_p), which is present when the material is still fluid with the grain separated (the air is still able to deform).

3.3. Testing procedure

The main use of the apparatus in its original configuration is the testing of granular soils with compressive stress paths, carried out under control of load or deformation, both drained or undrained.

The testing procedure has been proposed both for the dry and the conditioned material, but after the first test in the conditioned soil the procedure has been changed, as the compression loading stress path was not possible due to the difficulties on creating the necessary void needed for removing the mold. For this reason the conditioned material has been tested by using an extension unloading stress path, which would not require the removing of the mold, as the sample is reducing its width during the test.

The tests performed during this research have been of three types, depending on the material and the needs:

1. compression loading test (axial pressure σ_a and axial displacement δ_a increasing, radial pressure σ_r constant);
2. extension unloading test (axial pressure σ_a and axial displacement δ_a decreasing, radial pressure σ_r constant);
3. lateral confinement increase test (axial displacement $\delta_a = 0$, radial pressure σ_r increasing in steps);

In this research the modified triaxial test consists mainly on these operations:

1. *preparation of the sample.* The material is placed inside the rubber membrane which is rigidly linked to the mold. The dry material is inserted in layer, and as it is a non-cohesive dry material, it has been

placed in its natural state, without pressing it. Also in the conditioned material case, the material appears so fluid that it flows almost like water in the mold. The most critical part for the conditioned soil testing is the time, as the foam is naturally degrading in the time. The test was attempted to be carried out within 60–90 minutes, in any case this parameter has been always registered.

It is also well known that the behaviour of the conditioned soil is not only related to the foam half-life time (up to 20–30 minutes with high concentrations of surfactants), but especially by the life of the bubbles in the soil itself, that normally is much larger. This is even more evident while confining the samples in a closed tank and mixing it before the insertion in the mold. This aspect has been investigated while preparing the optimal conditioning of the two soils and it will be discussed in Section 4.1 (Figure 7).

The phases of preparation depend on the material to be studied and the testing type. The common operations are as follows:

(a) the bottom cap is cleaned and its lateral surface is covered with a layer of silicone greased;

(b) the porous stone and the filter paper are placed over the bottom cap;

(c) the rubber membrane is inserted in the bottom cap, in contact with the grease;

(d) the mold is placed on the bottom cap and the membrane is turned over it in the upper part;

(e) the membrane is filled with the material to be tested. The dry material is inserted in layer, and as it is a non-cohesive dry material, it was placed in its natural state, without pressing it. Also in the conditioned material case, the material appears so fluid that it flows almost like the water in the mold;

(f) once the material fills the membrane and the mold for the necessary height (600 mm), the material is levelled off in order to obtain a perfectly straight and uniform surface. Over this surface a filter paper is placed in contact with the porous stone which is embedded in the top cap;

(g) connection of the membrane with the top cap, greased in the same way of the bottom cap, and application of o-rings to fasten the membrane over the cap;

2. *assembly of the apparatus.* This phase regards all those operations concerning the assembling of all the mechanical components, the disposition and connection of all the sensors and to the configuration of the system actuator;

3. *consolidation.* This phase allows to apply any initial stress condition to the sample, in this research the initial condition applied to the sample has been always isotropic, in order to reproduce as much as it is possible the hydrostatic conditions. This phase is usually performed, as in this research, load controlled. It represents the first actual part of testing of the sample and it is performed by removing the depression and applying the radial pressure (compression loading tests) or just by applying the radial pressure (extension unloading tests). The most important issue regarding this phase is the perfect combination between radial pressure applied by the compressed air, which is flowing into

the cylindrical pressure cell, and the the axial load applied with the loading ram: these values in fact must be kept equal in order to fulfill the initial isotropic condition of the sample. Once the desired confinement pressure is reached and the axial load is balanced to obtain the isotropic condition, this state is usually kept for several minutes because, especially in clays, viscous deformation can occurs; nevertheless in the case of conditioned material the presence of bubbles which are naturally degrading this operation should be neglected in order to keep the material as much as possible in the initial state.

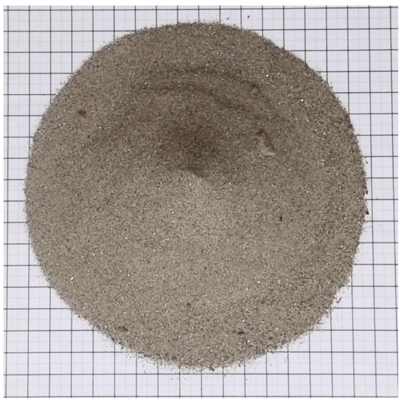
4. *test execution.* The actuator is moving the loading ram in order to apply the load. This phase is usually performed, as in this research, deformation controlled. The test is ending at the limit stroke of the piston, usually after reaching the peak strength and during the post-peak phase.

4. Testing campaign carried out

4.1. Soils tested

The apparatus has been used for testing two natural soils: Soil A and Soil B (Figure 5), characterized by grain size distributions as in Figure 6. These two soils represent possible lithologies to be encountered during an EPB excavation, and they fit the range of optimal application for this technology (Budach and Thewes, 2015).

As a preliminary stage of this research, the optimal soil conditioning through slump testing for the two materials has been assessed. The results are summarized in Figure 7 and Table 1.



(a)

(b)

Figure 5: Photos of Soil A (a) and Soil B (b). The reference square size is 1 cm x 1 cm.

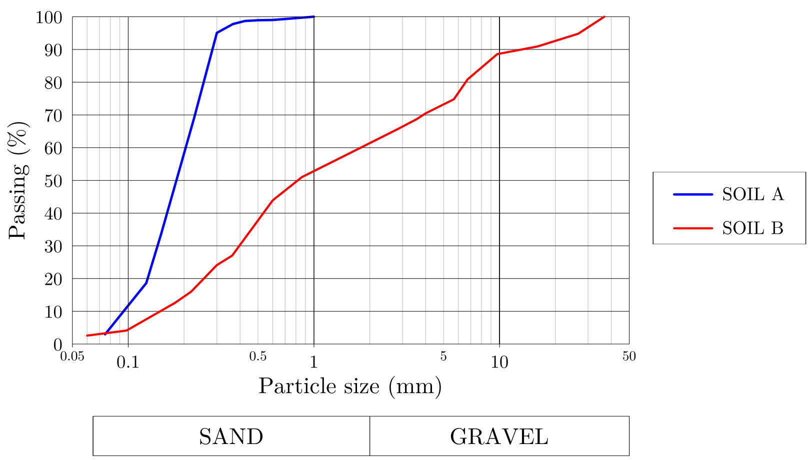


Figure 6: Grain size distributions of the two soils used for this research

Table 1: Optimal conditioning parameters for the soils studied

Parameter	Soil A	Soil B
Natural water content (in weight), w_{nat} (%)	0	0
Final water content (in weight), w_{fin} (%)	20	10
Surfactant concentration in the liquid generator, c (%)	2	2
Half-life time of the foam, t_{50} (s)	770	710
Foam Expansion Ratio, FER (-)	15	12
Foam Injection Ratio, FIR (%)	80	50
Slump (cm)	20	18

(a) (b)

Figure 7: Photos of optimal slump for Soil A (a) and Soil B (b).

The preparation of the conditioned soil samples has been always carried out by using a well established procedure consisting in (Peila et al., 2009; Martinelli et al., 2018):

- preparation of the natural sample to be tested (for filling the triaxial cell around 45–50 kg);
- mixing of the sample with the water to be added to reach the final water content w_{fin};
- generation of the required amount of foam according to a specific FER and FIR;
- mixing of the soil and the foam at room pressure in a standard concrete mixer (time around 3-5 min at 25 rpm);
- insertion of the conditioned sample into the testing mold of the triaxial apparatus.

The foam generator used is produced by Spoilmaster Ltd (UK). The system allows the control of the flow of water and the air flow rate, as well as the control of the dosage of the foaming agent. Once the operating parameters are set, except modest fluctuations, the foam with the FIR defined a priori can be produced. However, before the execution of each test, a verification of the FER is performed by weighing a pre-determined volume of foam.

4.2. Testing campaign

The first campaign of tests has been carried out on Soil A, by using the compression loading stress path. The natural dry soil did not present any particular problem during the testing, while when testing the conditioned samples it was not possible to apply the depression, as stated in Section 3.2. For this reason the testing method has been changed by using a different stress path, that is the extension unloading. In this way the problem of applying effectively the depression can be overtaken.

The campaign carried out on Sand B has been performed just by using the extension unloading stress path. First of all the dry samples have been studied, in order to get the shear strength which was not possible to assess with the shear test. Then a campaign of tests has been carried out on the conditioned samples.

Both the dry and conditioned samples have been directly inserted into the mold thanks to the absence of cohesion for the first and excellent fluidity for the second. Every 20 cm the layer of material has been regularized up to the top and the final stratum is well-groomed with an aluminium bar.

The use of two stress paths on the testing, brought of course to two different failure of the samples, by compression or by extension. A picture of the broken samples in the two cases is presented in Figure 8. The measured parameters, needed for this research, are the vertical load, the confinement pressure and the displacement of the piston.

5. Results

5.1. Soil A

The campaign on this soil has been carried out first using compression loading configuration by using 3 different confinement pressures of 150 kPa, 200 kPa and 300 kPa. Nevertheless, considering the aspects already described

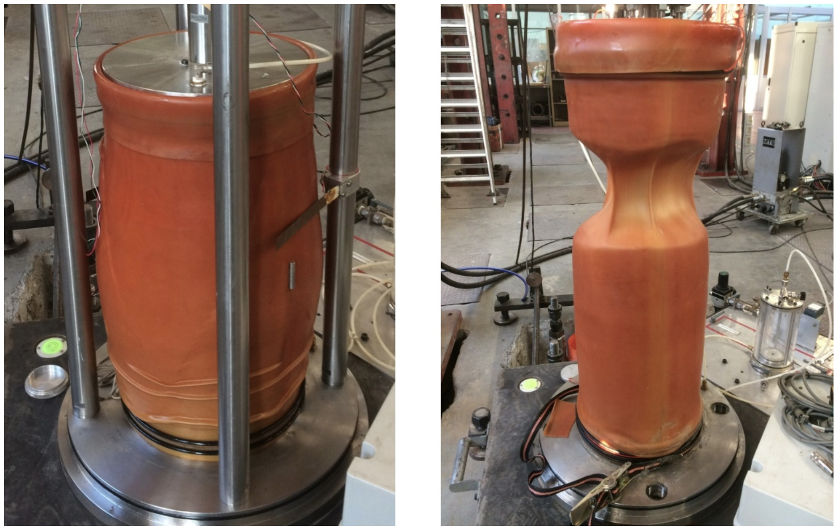


Figure 8: Samples after the failure at the end of a compression loading (left) and extension unloading (right) tests.

in 3.2, when testing the conditioned soil with the compression loading test, the depression was not guaranteed and the tests have been carried out by using extension unloading configuration. In order to better compare the results, also on dry Soil A a campaign of extension unloading triaxial tests have been performed using the same confinement pressures.

The results of the campaign obtained from the 6 tests are summarized in the plot in Figure 9. With this values, it is possible to obtain the Mohr-Coulomb failure envelope through the Mohr's circle in Figure 10.

Regarding the conditioned samples, the campaign has been carried out by using 4 different confinement pressures σ_r equal to 100 kPa, 250 kPa, 325 kPa and 400 kPa. The choice of using an additional test compared to the usual procedure is due to the results given from the test with $\sigma_r = 100$ kPa which returned a unusual graph. This might be explained by the fact that

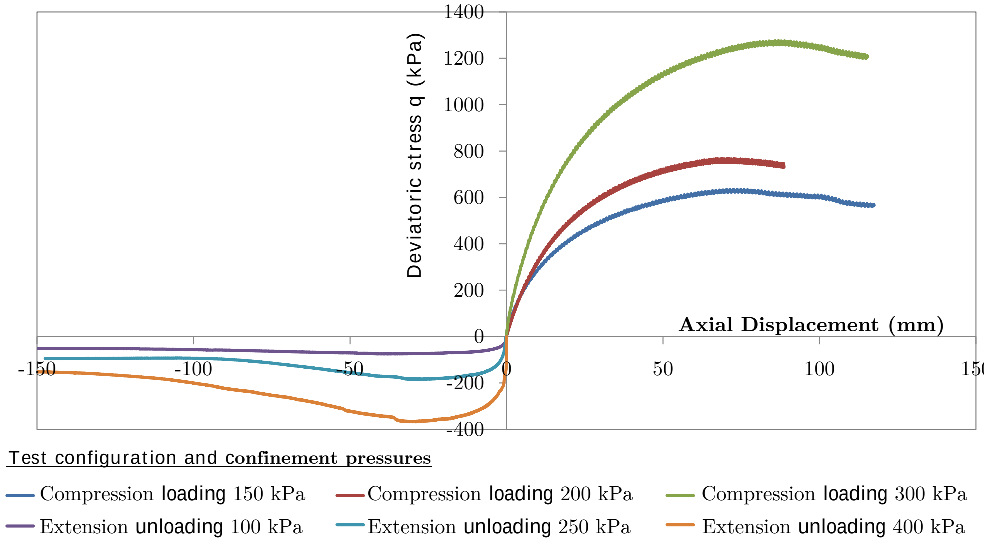


Figure 9: Outcome of the triaxial campaign on dry Soil A.

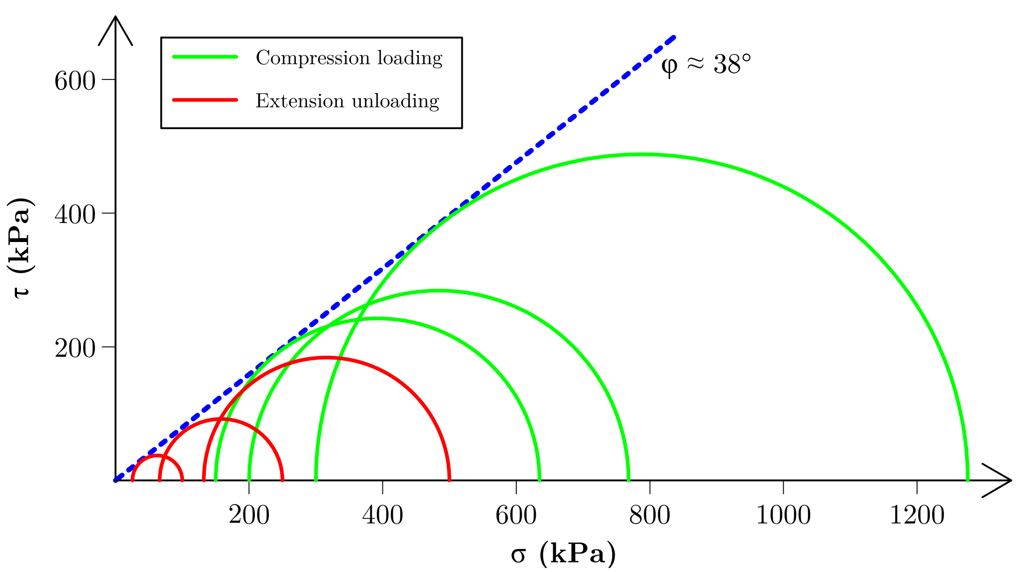


Figure 10: Failure envelope and Mohr's circles from the triaxial tests performed on the dry Soil A.

the material is acting completely as a fluid at this confinement, and does not reach a pressure able to compress the bubbles enough to guarantee the contact between the grains. In this state, at this pressure, the material can transmit effectively the pressure in a EPB shield excavating chamber. The results of the triaxial testing on conditioned Soil A are plotted in Figure 11.

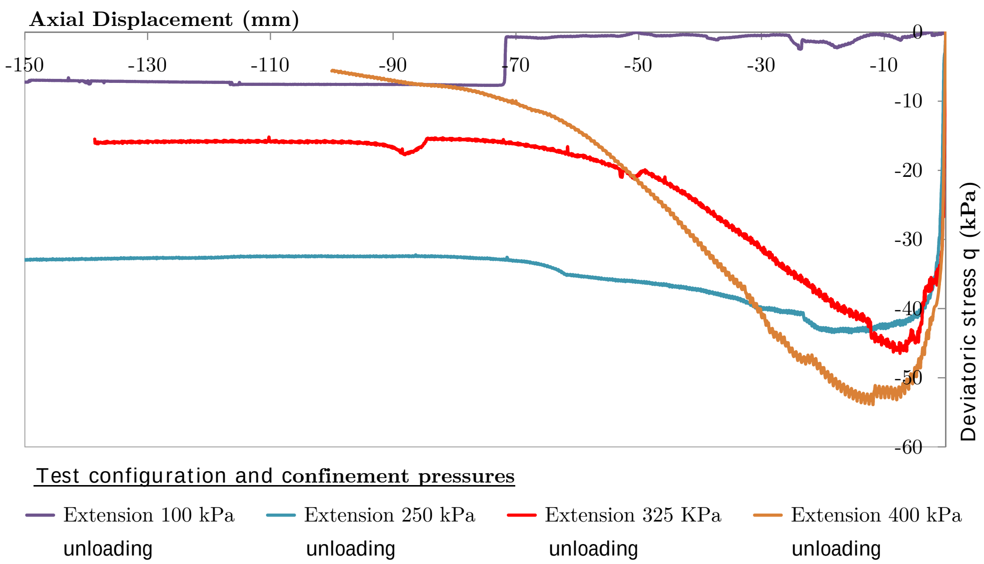


Figure 11: Outcome of the triaxial campaign on conditioned Soil A.

Another test performed on the conditioned sand, carried out in order to assess the behaviour of the mass during the application of the pressure in the cell, is the lateral confinement increase test. The maximum reached pressure has been set to 500 kPa. The test has been performed in steps of 50 kPa after the first pressure set to 150 kPa and each step has been kept some minutes (around 5-6 minutes) to stabilize the pressures. The outcome of this test is shown in Figure 12: while the radial confinement pressure σ_r is increasing, there is a direct and equal response of the pore pressure p_p up to 10–120 kPa, and then this response is stabilizing the p_p which remains almost constant while the σ_r reaches 500 kPa.

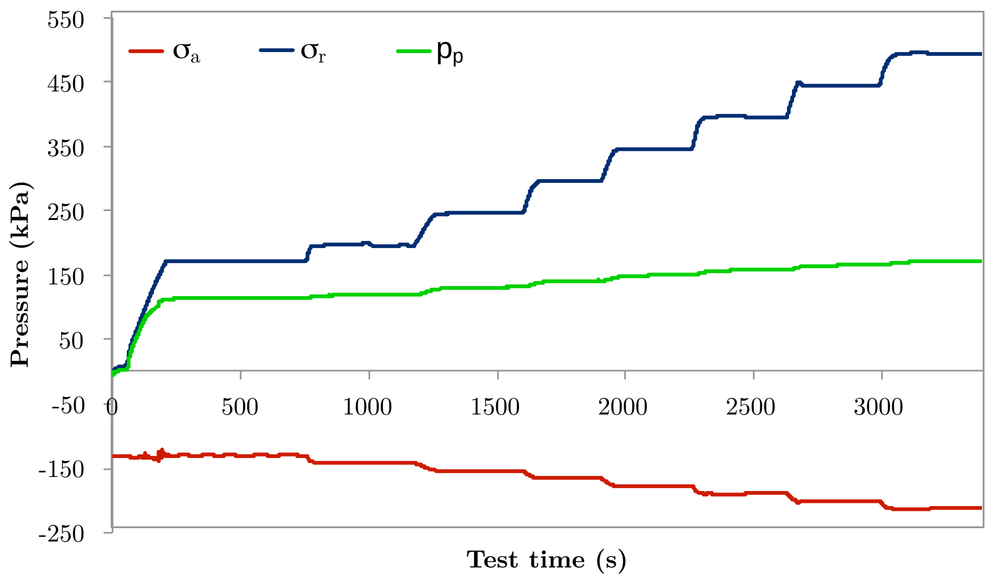


Figure 12: Triaxial lateral confinement increase test of conditioned Soil A up to $\sigma_r = 500$ kPa. σ_a is the registered induced axial pressure, σ_r is the applied radial confinement pressure and p_p is the registered pore pressure in the sample.

For better understanding the mechanical behaviour of the conditioned mass under different pressure conditions and the response of the p_p with different values of σ_r, the results obtained from the test campaign on conditioned Soil A have been plotted together in Figure 13. In this graph the outcomes of the 5 tests are represented in Y-axis with the Δ pressure, which is representing difference between the pressure applied in the cell σ_r and the pore pressure p_p, and in X-axis the σ_r itself. This graph is interesting to understand the moment in which the material is starting to become more rigid due to the contact between the grains as shown in Figure 1. The graph shows that for confinement pressures σ_r lower than 150 kPa the Δ pressure is small, confirming the fact that at 100 kPa of confinement the material is still behaving as a fluid.

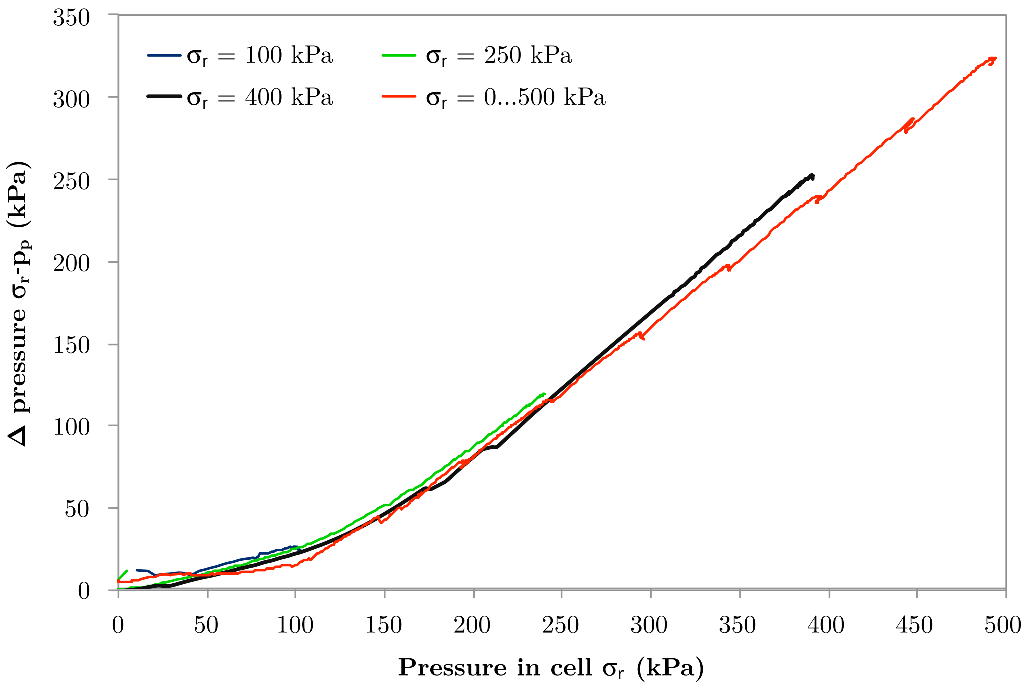


Figure 13: Δ pressure vs. pressure in the cell (σ_r) for the conditioned Soil A.

Another important result is given by an unexpected failure of the membrane which occurred during the test with $\sigma_r = 400$ kPa much after the peak. In Figure 14 this event is showed through a pressure vs. time graph which shows the axial pressure peak at around 500 s from the test starting and the failure of the membrane, indicated by the sudden rise of the pore pressure to the cell pressure. After the removal of the cell the failure was visible from the membrane, with the foam flowing out from the sample. This failure has proved to be positive, as in this way it was possible to check the behaviour of the material in drained conditions.

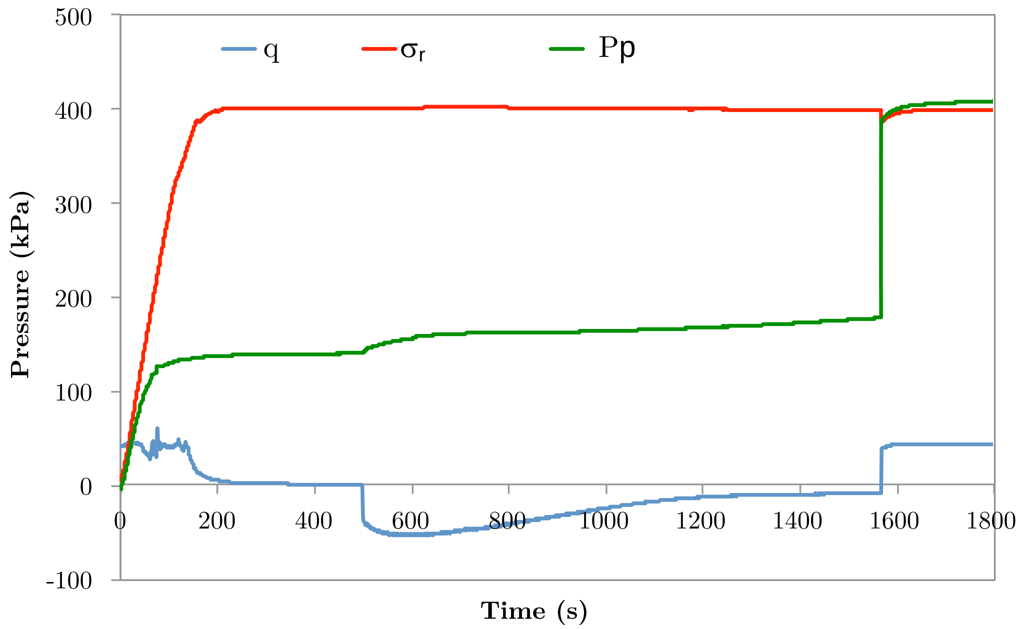


Figure 14: Graph pressure vs. time of the triaxial test on conditioned Soil A with $\sigma_r = 400$ kPa with the evidence of the membrane failure (the pore pressure p_p reaches the same value of the applied confinement pressure σ_r.

After each test on conditioned Soil A, slump test has been carried out to verify the quality of the mass after the triaxial test. Table 2 shows the results of all the tests carried out on the material at room pressure which was stored in a sealed tank during the triaxial test and on the material inside the membrane in the top and bottom part. In this way also the stability of the mass can be assessed: if the top and bottom samples are similar, it means that the foam is not flowing down because of the gravity. Also from this test it has been possible to notice the difference of behaviour of the material in drained and undrained conditions: at the row corresponding to $\sigma_r = 400$

kPa, the top slump shows a dry material due to the failure of the membrane, on the contrary the bottom slump shows that the material kept its properties due to the good stability of the conditioned mass which prevented too big loss of foam through the breach on the membrane: in this test the conditioned soil collected from the top, the part where the failure happened, appears to be much stiffer loosing completely its workability although still wet. This is caused by the loss of the foam which was able to flow through the membrane due to the applied pressure. The slump for this sample has returned a value equal to just 3 cm (result highlighted in red in Table 2).

This represents an important result, as it is clear that in most of the cases the bubbles which where strained by the increase of the lateral pressure were still visible from the material collected from the triaxial apparatus after the test and from the slump test itself, meaning that they were not broken after the triaxial loading, but just deformed (Figure 15).

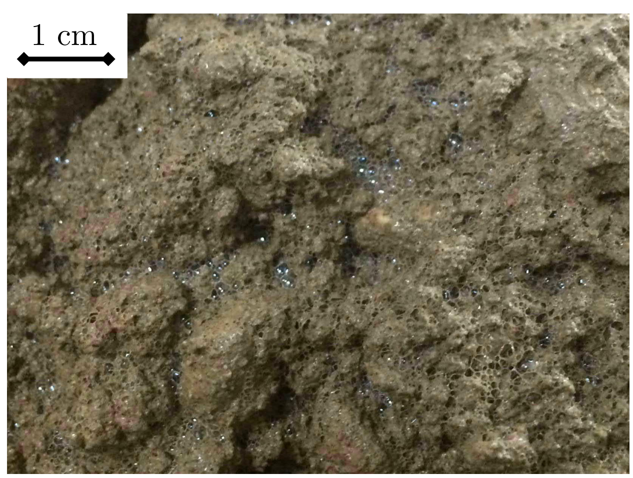
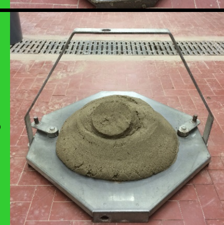
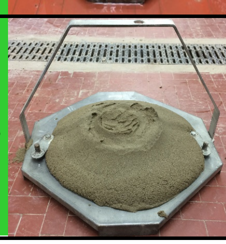


Figure 15: Conditioned sample of Soil A collected just after the triaxial testing. The material has still a good workability and foam bubbles are clearly visible.

Table 2: Slump values and pictures from the samples taken after each triaxial test. For each pressure there is a slump of the sample at room pressure (P_0), from the top and from the bottom of the cell. The colours identify a suitable (green), borderline (yellow) or unsuitable (red) slump.

σ_r (kPa)	**Time (min)**	**Slump (cm)**		
		P_0	**Top**	**Bottom**
100	160	22 	19 	17 
250	135	22 	18 	18 
325	135	21 	17 	19 
400	150	22 	3 	14 
0...500	180	23 	19 	16 

5.2. Soil B

The campaign on this soil has been carried out just using extension unloading configuration by using 3 different confinement pressures of 100 kPa, 250 kPa and 400 kPa.

The results of the campaign obtained from the 3 tests are summarized in the plot in Figure 16. With this values, it is possible to obtain the Mohr-Coulomb failure envelope through the Mohr's circle in Figure 17.

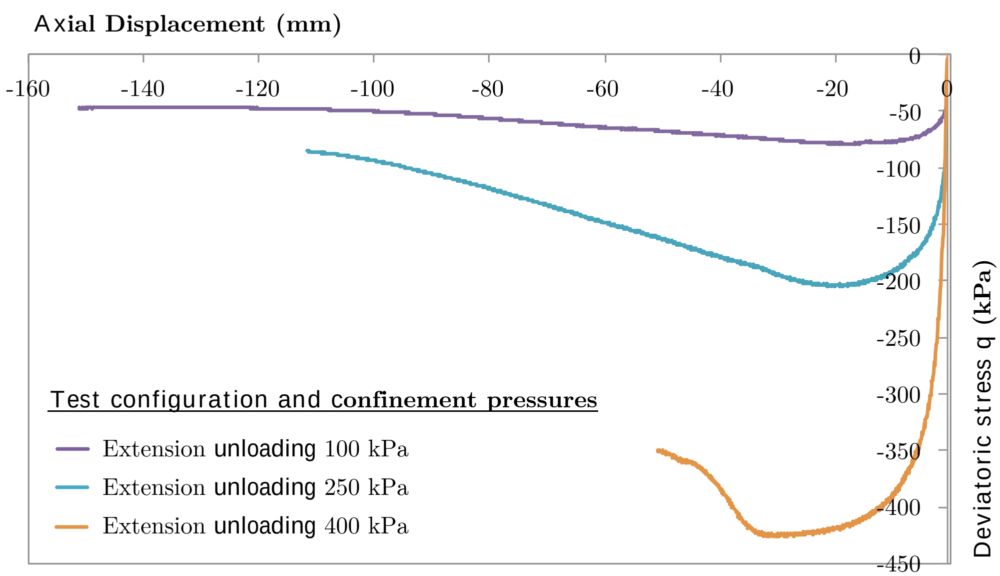


Figure 16: Outcome of the triaxial campaign on dry Soil B.

Regarding the conditioned samples, the testing has been more difficult compared to the previous material. Two tests have been performed with confinement pressures equal to 150 and 250 kPa; the test with this last σ_r has been repeated twice because the first test did not return valid results. Although the testing campaign did not return the expected results, anyhow

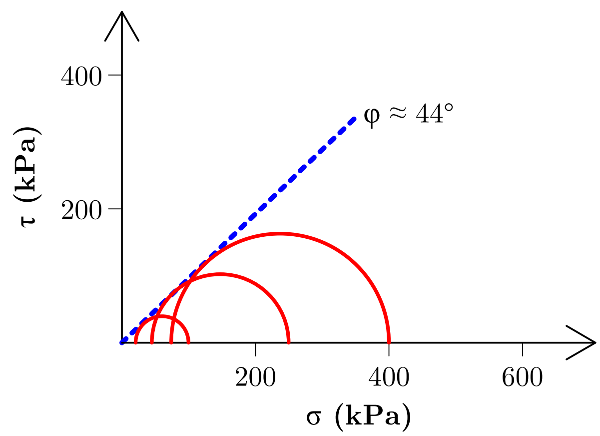


Figure 17: Failure envelope and Mohr's circles from the triaxial tests performed on the dry Soil B.

the overall behaviour of the material during the testing phases was sufficient to give useful indications. The results of these tests are shown in Figure 18.

Also for this soil the lateral confinement increase test has been carried out by increasing the cell pressure σ_r up to 500 kPa. In this case the test has been performed just after the two tests recorded in Figure 18, in order to check the behaviour of the conditioned mass through the measured pore pressure response (Figure 19).

The outcome of these two variants of the test are showing a slight different behaviour of the conditioned mass: as a matter of fact the samples are behaving effectively when the pressure is increased, probably due to the fluid behaviour of the fine part of the soil (clay and silt). In fact the clayey conditioned soils are usually transmitting the pressure much more effectively, thus

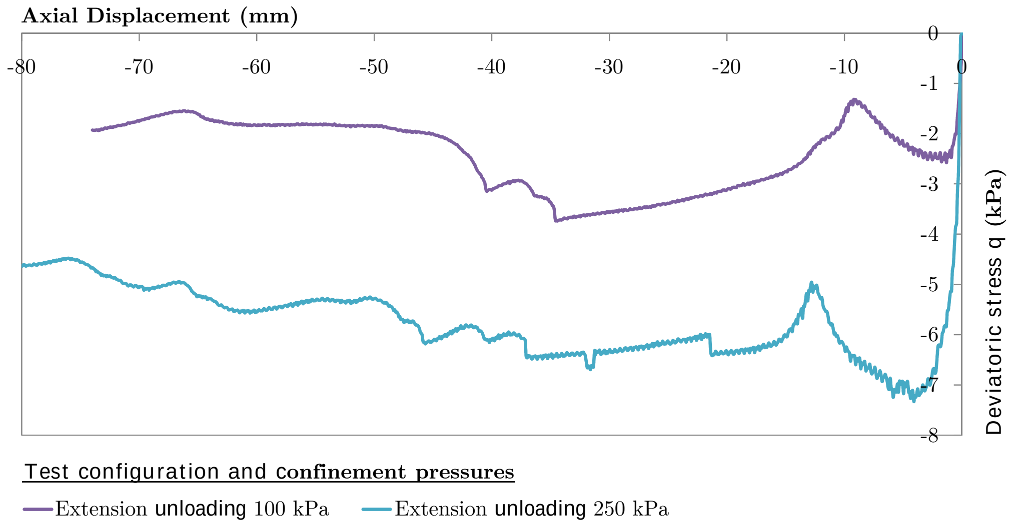


Figure 18: Outcome of the triaxial campaign on conditioned Soil B.

also in this case the finer part is helping the increase of the pore pressure.

5.3. Analysis of the results

The campaign carried out on Soil A returned interesting results regarding the comprehension of the mechanical behaviour of the conditioned masses. The method allows to easily compare the behaviour of the material in different states, by studying similar parameters proper to geotechnical engineering and especially by assessing parameters useful to mechanized tunnelling engineering. These lasts include the verification of the attitude of the material of transmitting effectively pressure during the stress increase phase and the verification after the test of the condition of the mass through for example slump testing.

The testing carried out on Soil B underlined, especially through the increasing confinement tests shown in Figure 18, the good attitude of the ma-

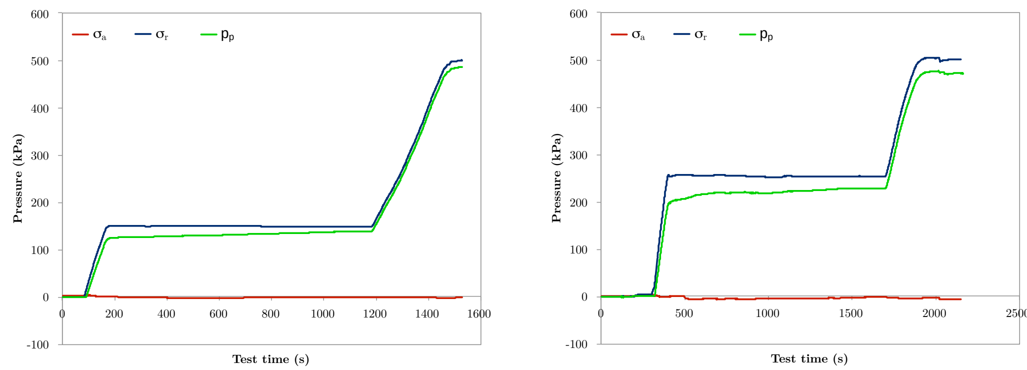


Figure 19: Plots of the radial pressure increase in the triaxial tests with initial confinement $\sigma_r = 100$ kPa (left) and $\sigma_r = 250$ kPa (right). σ_a is the registered induced axial pressure, σ_r is the applied radial confinement pressure and p_p is the registered pore pressure in the sample.

terial on behaving more like a fluid at higher pressures as well, as in this case it is not noticeable a true contact between grains as in Soil A. In fact the conditioned Soil B sample has a behaviour similar to the toothpaste, as the fine part is creating a slurry made of clay/silt, water and surfactant.

The use of extension unloading stress path allows to avoid to apply the negative pressure to a sample which is not saturated and needs to keep the air trapped inside the conditioned mass in form of foam bubbles.

6. Conclusions

The increasing number of EPB tunneling applications with high pressure in the chamber has pushed the researchers to concentrate the researches in this field to better understand the influence of this parameter in the conditioned soil behaviour. In this field remarkable laboratory researches have been carried out by Psomas (2001) and Mori et al. (2018) who using a confined compression device have demonstrated the influence of the pressure on the void index of the conditioned mass. The present research has the goal to provide further information of the behaviour of conditioned rock mass under pressure using a large size triaxial test device. The obtained results cannot be applied directly to the design of conditioning but they form one side confirm the behaviour observed by Psomas (2001) and Mori et al. (2018) and give further information on the important influence of pressure on the soil behaviour.

A campaign of large diameter triaxial tests has been conducted on two different conditioned soils, in order to study their behaviour in triaxial stress conditions. The obtained results show a clear trend of the conditioned material of behaving as a fluid a low confinement pressure, where the grains are not in contact each others and the foam is creating a floating barrier between them and reducing the shear strength; on the contrary at higher pressures the materials are becoming stiffer and the shear strength increases. The campaign underlined also the main difference between a typical granular material as Soil A and a more heterogeneous material containing also clay and silt as Soil B: in the first the contact between the grains is more evident, as by increasing the confinement pressure over 150 kPa the measured fluid pressure remains constant; in the second case the fluid pressure is increasing while increasing the confinement pressure due to the fine part that is acting like a slurry strained by the radial pressure.

Another important result has been obtained by the slump campaign on the material tested in the triaxial cell, in most of the cases the bubbles which where strained by the increase of the lateral pressure were still visible from the slump test itself, meaning that they were not broken after the triaxial testing, but just deformed and reduced in volume. The failure on one triaxial test allowed moreover to verify the state of the conditioned material after braking the membrane, reaching a drained condition: in this case the loss of foam returned the material stiffer.

The use of this cell for assessing the behaviour of the conditioned material in triaxial stress conditioned allowed to better understand the response of this material in a possible EPB application and potentially helps the suitability of the conditioning for applying an effective counterpressure to the front of a tunnel. A direct assess of the situation in the work chamber must be investigated in the future, by correlating the parameters obtained by this test with real data.

7. Author contributions and acknowledgements

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