Study on short and "long term" effects of chemicals on fine grained soils for mechanized tunnelling conditioning

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ABSTRACT: This study presents the preliminary results of research activity focused on the physical and mechanical properties of soil treated with the injection of chemicals, commonly used in tunnelling performed with tunnel boring machines (TBMs) and EPB technology. For fine grained soils, the focus is to enhance the excavation process, optimizing consistency as well as reducing adhesiveness and clogging. Moreover, a study of the mechanical properties of the conditioned soil, relevant for the project of spoil disposal and reuse. Common tests and other specifically designed geotechnical tests were performed on different samples of two clayey soils. These were treated using different foams generated by the three most used foaming products. Results provide insight into the effectiveness of the chemicals tested to reduce clogging potential and on the mechanical properties of the treated soil useful for soil reuse.

1 INTRODUCTION

Tunnel boring machines (TBM) and Earth Pressure Balance (EPB) technology are a preferred option in urban tunnelling. Using this method, pressure is applied to the front face using the excavated soil mixed with water and chemicals, or rather foams, to optimize the excavation process by modifying the soil consistency.

Several hazard scenarios can occur during TBM excavation. In coarse soils unexpected consumption of the tools of the cutter-head and sudden water inflows from the excavation face into the TBM can occur. Another serious issue is the clogging effect in clayey soils where portions of soil adhere to the metallic parts of the cutter-head, thus increasing the torque and the thrust force required to perform the excavation, at times edging above the threshold available from the power installed on the TBM or over the technical limit of other mechanical components (Merritt, 2005; Langmaack and Feng, 2005). In such cases excavation has to be halted to clean the cutter-head, the working chamber, the excavation tools and the cochlea, such operations are usually dangerous for the workers involved, compromise the stability of the excavation, cause delays and additional costs as well as the risk, particularly in urban areas, of generating surface settlements.

To avoid such issues several advantages are achieved by using injected chemicals together with water at the front-face during the excavation. Specifically developed products are now commercially available, each distinguished by chemical composition, usage modes and effectiveness.

The impact of these chemicals depends on their dosage and foam production mode, as reported by Thewes *et al.* (2012) and also related to the foam-soil mixing process.

Some details regarding dosage and suggested values for the injection parameters are reported in the guidelines EFNARC (2005). Thewes and Budach. (2011) and Bezuijen (2012) proposed some empirical formulae to assess first attempt values of conditioning parameters. To further an understanding of these chemicals several experimental studies were performed by Thewes (1999), Bezuijen *et al.* (1999), Milligan (2000), Langmaack (2000), Psomas (2001), Mair *et al.*

(2003), Peila (2014), Feinendegen *et al.* (2011), Zumsteg and Puzrin (2012) and Jakobsen *et al.* (2013), among others. These reported the effects of chemical injections in different geotechnical conditions, the most effective dosage modality and the relationship between the type of soil to be excavated and the amount and type of foam required to treat it.

Several innovative laboratory test devices to measure variations in the physical and mechanical properties of the conditioned soil were also proposed. Peila et al. (2007), Sass and Burbaum (2009). Zumsteg and Puzrin (2012), Puzrin et al. (2011) and Hollmann and Thewes (2013) to name but some, introduced new devices and methodologies to further study the interaction of soil with foam and specifically tailored polymers.

Focusing on the effects of these chemicals on fine-grained soil properties, Zumsteg et al. (2012) introduced interesting insights on the use of the laboratory vane shear device and Zumsteg and Puzrin, (2012) on the use of the mixing test and new devices for the measurement of stickiness and adhesion. Thewes (1999), Thewes and Budach (2010), Feinendegen et al. (2010 and 2011) and Zumsteg et al. (2012) finally proposed useful classifications of the adherence obtained performing mixing tests and cone pull-out tests.

Short-term effects of the conditioning activity are crucial during the excavation phase, while during spoil disposal the study of the evolution of these effects on soil mechanical properties is important. In this study, short-term effects of the chemicals regard the features of the soil in the excavation chamber and based on the results of several mixing tests, cone pull out tests, laboratory vane tests and fall cone tests.

Long-term effects cover the physical and mechanical modifications induced by treatment and still noticeable before the complete biodegradation of the injected chemicals. These have been investigated by performing conventional laboratory geotechnical tests (shear box and oedometric tests).

2 SOIL SAMPLES AND CHEMICALS

2.1 *Soil samples*

The grain size distributions of the soils used are reported in Figure 1. S1 is a clayey silt with 40% clay, S2 is a silt with about 25% clay and 30% sand and S3 is a silty clay. According to Casagrande's plasticity chart in Figure 2, all the considered samples are inorganic clays; S3 can be classified as a high plasticity clay, while S1 and S2 are low plasticity clayey soils.

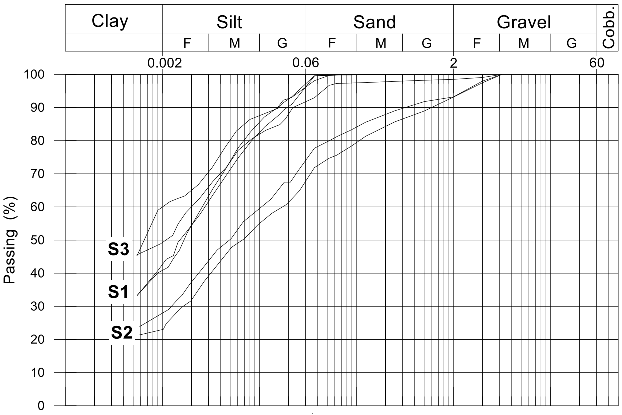

Figure 1. Grain size curves of the soils tested.

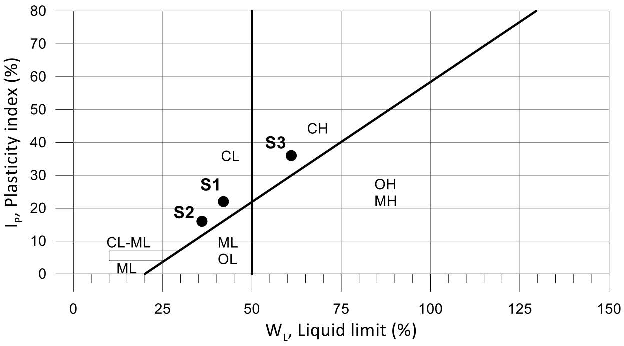

Figure 2. Plasticity properties of the tested soils (classification proposed by Casagrande)

2.2 *Chemicals*

The chemicals used, from three of the main international suppliers, are labelled FA1, FA2 and FA3. A combination of FA3 and a water retaining polymer P1, specially proposed for tunnelling in fine grained soil, was also tested.

To compare different chemicals, each test was performed for soil samples S1 and S2, first on soil mixed with only water (untreated soil) and then with the three foaming agents. Tests on S3 were performed only for untreated soil.

2.3 *Foam generation and conditioning parameters*

Foam quality plays a major role on results. Generating the foam with a *laboratory foam generation system* similar to that installed inside a TBM machine, assures that the quality of the foam will be the same each time (reproducibility) and, moreover, will be the same as that used during excavation. A scheme of the laboratory foam generation system used in this study is shown in Figure 3.

Pressure of water and air and the flux of water, air and foaming agent can be controlled manually by pressure gauges and flow-meters on the machine, and their values can be changed in real time during foam generation; all operations are controlled, monitored and recorded. Among the several typologies of foam guns available, that used here is composed of several circular filters disposed in series along the entire height of the cylinder as shown in Figure 3.

a)

b)

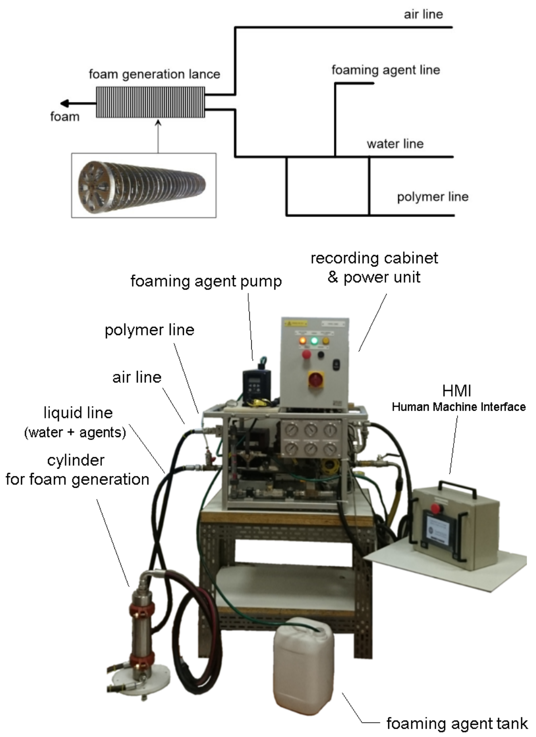

Figure 3. Laboratory foam generation system a) functional scheme, b) picture of the plant.

The Concentration Factor of the foaming solution, C_F, is defined by Equation 1 and its value is typically in the range 0.5 - 5.0%, according to the manufacturer's recommendations. This factor affects the stability of the required foam and strongly depends on the amount of water injected and on the natural water content.

$$C_F = 100 \cdot \frac{m_{f.ag.}}{m_{sol}}, \tag{1}$$

where $m_{f.ag.}$ is the mass of foaming agent used and m_{sol} is the mass of foaming solution.

The concentration of the polymer added, C_P, is defined likewise.

Foam Expansion Ratio of the foam, *FER*, defined by the Equation 2, should be in the range 5 - 30. The higher the *FER*, the drier the generated foam will be.

$$FER = \frac{V_f}{V_{sol}}, \tag{2}$$

where V_f is the volume of generated foam and V_{sol} is the volume of foaming solution.

Foam Injection Ratio, *FIR,* is defined by Equation 3 and its value is generally in the range of 20% - 100%.

$$FIR = 100 \cdot \frac{V_f}{V_s}, \tag{3}$$

where V_f is the volume of injected foam and V_s is the volume of the soil treated.

In the first phase of the research preliminary trial mixtures were created to detect for each soil sample a range of values for the conditioning parameters that guaranteed a suitable soil.

Mixtures that were too liquid provide a useful support at the front-face of the working chamber were discarded, as well as mixtures which hindered the mixer components.

For all products, Cf=2%; *FER* and *FIR* adopted are in the range 8-10 and 80%-100% respectively, while the Cp of the polymer P1 is 0.5%. For each combination of soil and chemicals 4 different mixtures were tested; the final four values of water content and the corresponding values of consistency index, Ic, are in the ranges reported in Table 1.

Table 1. Soils, chemicals, w and Ic of tested mixtures.

Soil mixture	w	Ic
	(%)	(-)
S1 + water + FA1	40 ÷ 45	0.05 ÷ -0.17
S1 + water + FA2	43 ÷ 48	-0.05 ÷ -0.29
S1 + water + FA3	41 ÷ 50	0.03 ÷ -0.38
S1 + water + FA3 + P1	56 ÷ 63	-0.02 ÷ -0.2
S2 + water + FA1	30 ÷ 39	0.36 ÷ -0.23
S2 + water + FA2	34 ÷ 40	0.13 ÷ -0.25
S2 + water + FA3	34 ÷ 39	0.11 ÷ -0.19
S2 + water + FA3 + P1	39 ÷ 46	0.25 ÷ -0.03

In Table 1 a comparison between the two tested soils shows that S 2 with a high sand content requires less water to achieve a suitable consistency.

To permit comparison of the results, dosages were combined so as to inject the same amount of foaming agent in each soil sample for each product in four different combinations of the amount of added water, *FER* and *FIR*. It was observed that the addition of the polymer required a higher amount of water to achieve the desired consistency (see Table 1).

3 TESTS, APPARATUS AND PROCEDURES

The soil samples were preliminarily dried and chopped into lumps of few millimetres in diameter. Soil, water (when planned mixed with the polymer) and foam were then added at the same time in a mixing apparatus to simulate the effects of the injection of foam during excavation.

Each test to assess the short-term effects was performed immediately after conditioning. To evaluate possible effects of the chemical on the mechanical properties, the soil was stored and dried at room temperature for about a week after treatment, according to the water content to be achieved for the geotechnical tests. Care was taken not to exceed the time necessary for the complete biodegradation of the chemicals.

3.1 *Tests for the short-term effects*

3.1.1 *Mixing test*

This test was performed following the method proposed by Zumsteg and Puzrin, (2012) to empirically quantify the clogging potential of soft soil mixtures. This measures the weight of soil sticking to the mixing tool after preparation in the mortar mixer (Fig.4).

Adherence is measured by the stickiness ratio, λ, defined in the Equation 4,

$$\lambda = \frac{G_{MT}}{G_{TOT}} \cdot 100, \quad (4)$$

where G_{MT} is the weight of soil sticking to the mixing tool and G_{TOT} is the total weight of soil involved in the mixing process, quantifying the tendency of the conditioned soil paste to remain stuck on a mixing tool after a mixing process.

Figure 4. Mixing test apparatus and test results.

3.1.2 *Fall cone test*

The fall cone test procedure measures the penetration, h_f, of a cone dropped under its own weight after being released from the standardized support (Figure 5). The resulting h_f values, together with the weight and shape of the cone, are correlated with Atterberg's limits (Wroth & Wood, 1978) and with the undrained shear strength, c_u, (Hansbo, 1957; Koumoto & Houlsby, 2001) of fine-grained soils, providing a fast, simple and accurate method to determine these parameters.

Figure 5. Fall cone test apparatus.

3.1.3 *Laboratory vane test*

The laboratory vane shear test, performed at atmospheric pressure, is a standardized investigation method to determine the undrained strength of fine-grained soils described by the ASTM standard D4648 (2000) .

3.2 *Tests for the "long-term" effects*

"Long-term" effects involve not only geotechnical but also environmental and chemical features, such as the biodegradation of the product and the interaction of the chemical agent with the soil particles. Here only some preliminary results about the effects of treatment on the mechanical properties of Soil 2 are presented and discussed, focusing on the time lapse in which the soil is out of the excavation chamber and stored before the hypothetical reuse.

On completing the above-described tests (§ 3.1), the conditioned soil was dried at room temperature to avoid an alteration of the natural degradation of chemical agents. Once a suitable water content for the preparation of the specimens was obtained, the soil was compacted (ASTM D698) to obtain samples for mechanical tests.

The range of adequate water content was estimated by performing compaction tests.

Samples for shear box and oedometer tests were obtained from the same mold. The same procedure was applied to untreated soil, prepared and tested for comparison.

4 RESULTS: DESCRIPTION, ANALYSIS AND DISCUSSION

The results of the tests performed to study the variation of Atterberg's limits of soils due to treatment show that the addition of all foaming agents tested in concentrations ranging between 1%-3% do not ensure variations in both plastic and liquid limits of all soils tested. For both soils the addition of small amounts of the polymer induces about a 30% increase in the liquid limit while the plastic limit does not change appreciably.

Figure 6 shows the c_u values obtained from the fall cone and vane tests versus the liquidity index, I_L, of all the tests carried out on the S2 samples.

The values of c_u obtained from the vane and fall cone tests overlapped. The results of the tests on the unconditioned soil samples are within the range by Mitchell (1976) for different types of soil. Results of the tests on samples treated by the addition of all the foaming agents show a reduction of the c_u. The collected values on treated soil are often below the range identified for natural untreated soils. In detail, FA2 produces the highest reduction, followed by FA1. Otherwise, the addition of the polymer P1 yield experimental data located in the upper part of the curve, often out of the range for untreated soils.

Figure 7 shows the results from the vane and fall cone tests for S1. Here, too, the values of c_u obtained from the two typologies of test coincide. All the measured values are in the range provided by Mitchell (1976); therefore, for this soil, treatment with chemicals does not cause an appreciable variation of the c_u relationship.

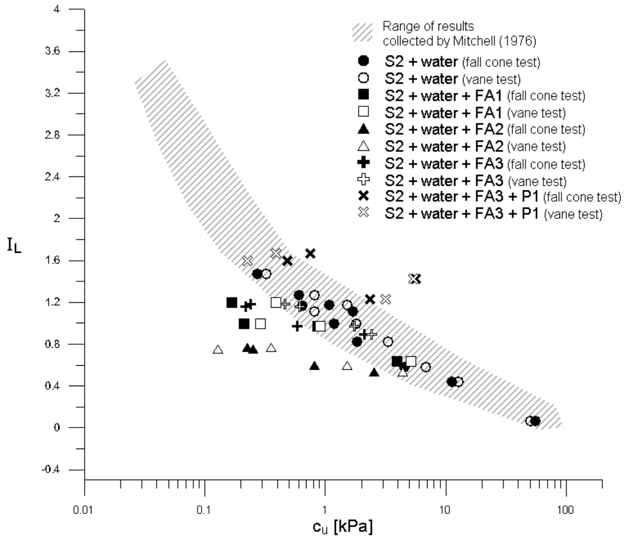

Figure 6. Results from vane and fall cone tests for S2.

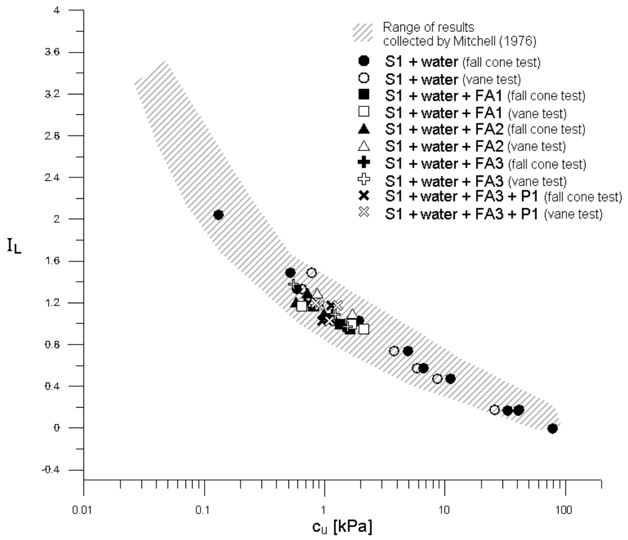

Figure 7. Results from vane and fall cone tests for S1.

Figure 8 shows that the result obtained from mixing tests on samples of the three different soils mixed only with water, follow a Gaussian curve with minimum values at either end for very high and very low values of *Ic*, and maximum of adherence for values of *Ic* between 0 and 0.7. The trends are similar for three soil samples and thus the maximum value of adherence around 70%; differences are in the values of *Ic* relative to the maximum adherence, lower for S3 and higher for S1.

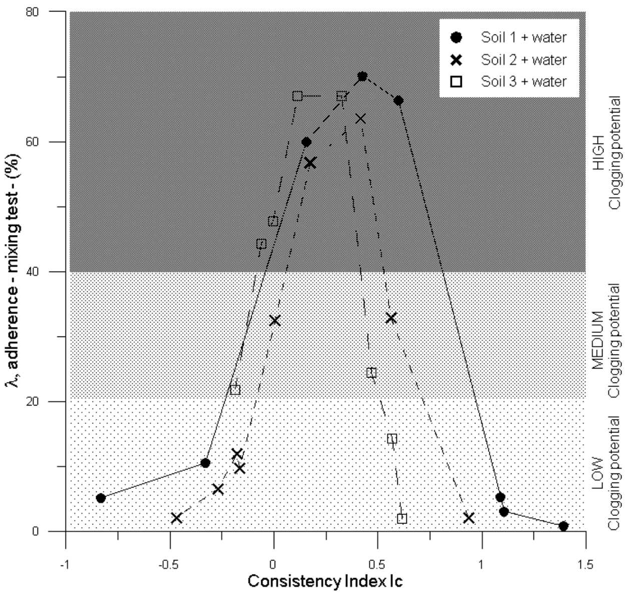

Figure 8. Relation between consistency index *Ic* and stickiness ratio λ for the three soils tested.

All the results obtained performing mixing tests on conditioned soil are reported in Figs. 9 and 10; test results obtained on untreated soils are also reported for comparison.

For S2 (Fig. 9) and for values of Ic < 0 all the points are of low clogging potential; the addition of chemicals shows no significant reduction in adherence. For higher value of *Ic*, between 0 and 0.2, FA1 ensured a more reduced adherence while FA2 and FA3 provided no apprecciable effects; the addition of the polymer P1 generates values of adherence clearly lower if compared with the values related only to FA3.

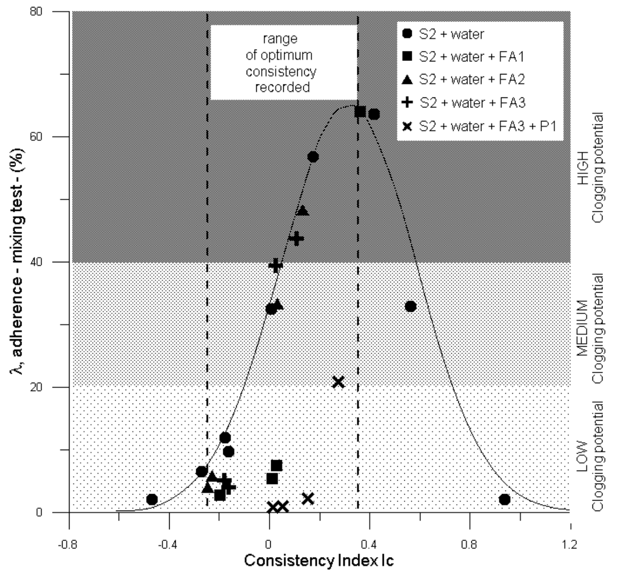

Figure 9. Results from the mixing test on treated samples of S2. Clogging potential proposed by Thewes, 1999.

For S1 the results of the mixing test (Fig. 10) show that all the points related to the conditioned samples are between values of *Ic* in the range of -0.5 – 0.1. All the tested products provide a reduction of the measured adherence, particularly FA1 and FA3; the addition of the polymer in this case lead to values of adherence very similar to those measured in the case of the soil sample treated with water only.

Considering all the recorded results on conditioned samples, for S1 all the points are of medium/low clogging potential, but none of the tested treatments achieve a stickiness ratio under 10%.

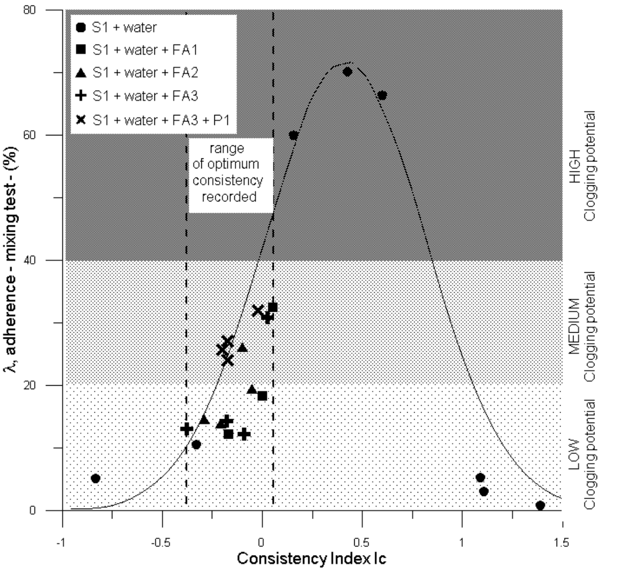

Figure 10. Results from mixed tests on treated samples of S1. Clogging potential proposed by Thewes, 1999.

Data show that conditioning generated low values of soil consistency, commonly related to low values of undrained strengths (between 0.2 and 3 kPa, according to figures 6 and 7). Spoils after the excavation process need a reduction in water content to reach suitable consistency values for the designated use.

To study the mechanical properties of the conditioned soil, the treated samples were dried at room temperature (see § 3.1).

Samples of treated soil S2+FA3 and S2+FA3+P1 were subjected to oedometer and shear box tests to determine the features of compressibility and strength of the soil skeleton (drained conditions).

Results from the direct shear test are shown in Figures 11 and 12. It can be noted that no significant effect of either FA3 or the polymer P1 is observed, so that all the data can be interpolated by a unique regression line with c'=0 kPa and φ'=23°.

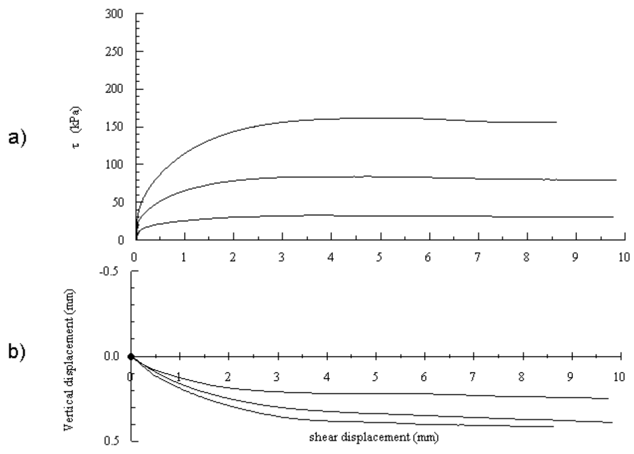

Figure 11. Results of the direct shear test: a) shear stress - horizontal displacement and b) vertical displacement - horizontal displacement curves.

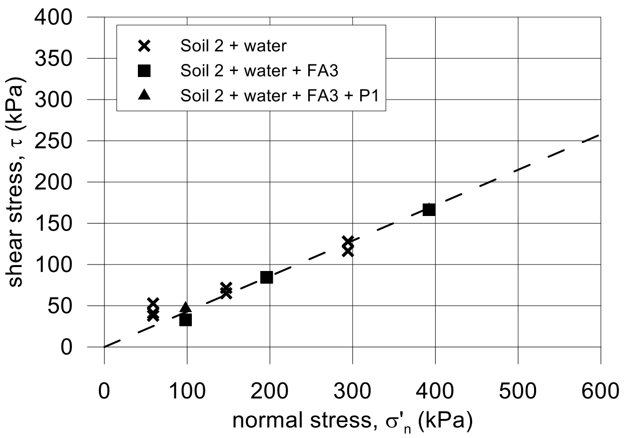

Figure 12. Results of direct shear test in the σ'_n-τ plane.

Observed stress - horizontal displacement and vertical displacement - horizontal strain curves (Fig. 11), indicate that failure occurs at high strains and pinpoints a ductile and contractive behaviour in each sample, in agreement with other studies on compacted clays (Airò Farulla and Rosone 2011, Leroueil and Hight 2013).

Compressibility of conditioned soil was studied by means of oedometer tests; results are represented in Figure 12. The addition of the foaming agent FA3 did not soil compressibility, while the addition of the polymer P1 to the mixture of soil, water and FA3 increases both compressibility parameters *Cc* and *Cs*.

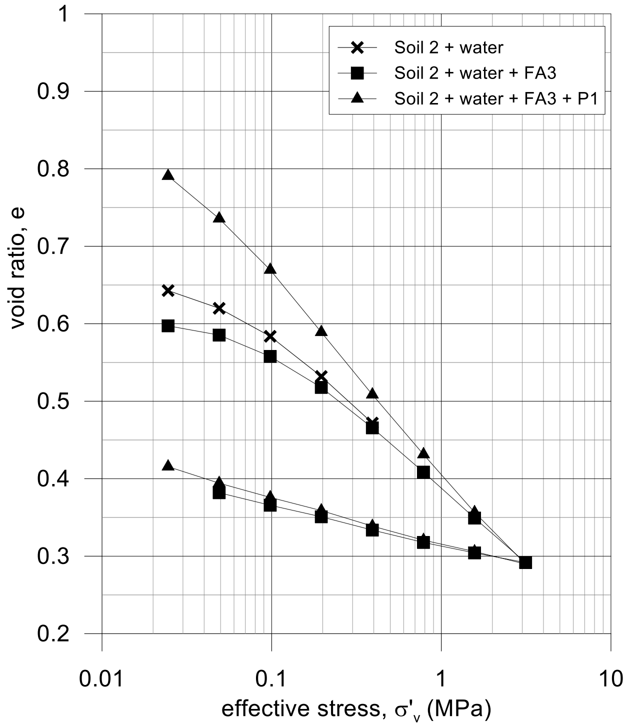

Figure 13. Oedometer compression curves.

These results are consistent with the recorded increase of the liquid limit and, realistically, they suggest that the effects due to the polymer will occur within the soil for longer when compared to those of the foaming agents.

5 CONCLUSIONS

Soil conditioning during mechanized tunnelling offers a series of advantages. A major benefit regards fine grained soils which when treated with chemicals attain the right consistency necessary to apply a homogeneous pressure at the front-face. Another benefit the reduction of natural adhesion hence minimizing the clogging risk.

The first aim of this study was to verify the effectiveness of several commercially available chemicals from major international suppliers used for tunnelling in clayey soils. Adhesion tests were performed using two different fine grained soils (S1 with a high clay content and S2 with a high sand content), three different foaming agents and a polymer from different suppliers.

Mixing tests were performed and, using the classification proposed by Thewes, results were compared to identify the clogging potential of each sample. Each test was performed on several samples of the two soils using different amounts of added water and different values of the conditioning parameters *FER* and *FIR* to create a homogeneous mixture with the proper consistency for TBM-EPB.

Tests were also performed on the two soils without any chemical addition in order to determine the intrinsic relation between adherence and *Ic* and to have a point of comparison to evaluate the effectiveness of the three products.

The experimental results show that:

1. in the range of the correct consistency, adherence is high for S1 (with higher *Ip* and clay content) and medium for So2 (with a lower *Ip* and higher sand content);
2. tested chemicals have different effects on the tested soils; for S2 significant effects were provided by the addition of FA2 and FA3+P1; FA1 and FA3 were not able to induce appreciable reductions in adherence. For S1 all the tested chemicals were effective except for FA3+P1. However, among the conditioned S1 samples, adherence did not reach values below 10%, confirming that, due to the soil features, for S1 it is harder to obtain a clear reduction in adherence.

Correct treatment ensures low soil consistency, related to extremely low values of the undrained shear strength, in the range of 0.2÷4.0 kPa.

Therefore, the first task in a spoil reuse project is to considerably reduce the water content of the treated soil and consequently analyse its mechanical properties.

The second aim of this study was to verify whether conditioning impacts these properties. Conventional geotechnical tests were performed on S2 treated with two different chemicals (FA3 and FA3+P1). Shear box and oedometer tests were executed on samples of conditioned soil, dried at room temperature up to the optimum water content and compacted.

The results, if compared with similar tests carried out on soil samples mixed only with water, show that:

1. there are no observable effects of the chemicals on soil strength; for all tested samples behaviour is mainly frictional and the friction angle is about 23°;

2. the intrinsic compressibility of the soil treated with FA3 coincides with that of the untreated samples; the addition of polymer P1, on the other hand, provides an increase in compressibility cin keeping with the higher liquid limit showed in the samples treated with P1.

The different behaviour shown by the two soils treated with the same chemicals is under investigation. Further research is necessary to study the chemical and physical interaction, focusing on several features which may have a key role in affecting the adherence behaviour of a fine-grained soil, such as mineral composition, the soil sample preparation modality and the specific composition of the chemicals used.

It may be concluded that the effectiveness of the chemical treatment used must be assessed in relation to the soil to be excavated, and that site-specific studies are necessary to identify the most effective combination of product, dosage and conditioning parameters.

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