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Chemical interaction between fine-grained soil and foaming agents in tunnelling with TBM-EPB

Interaction chimique entre le sol à grains fins et des agents moussants dans tunneling avec TBM-EPB

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ABSTRACT: The use of Tunnel Boring Machines (*TBM*) and particularly the Earth Pressure Balance (*EPB*) technology is one of the most commonly used way to perform mechanized tunnel excavation. The possibility to perform the excavation with high performance, avoiding risk for workers and reducing the induced subsidence, particularly important in urban area, are the main reason of the growing of this technology. The success of the excavation is manly related to the quality of the soil conditioning process obtained by injecting chemicals under the form of foam to the front of excavation and mixing it to the excavated soil. For fine grained soils the interaction between clayey particles and chemicals lead to the variation of the soil features and, particularly, to the reduction of the natural adhesion between soil and cutterhead metallic surface. This paper reports the results of an experimental research activity carried out to measure the temporary and permanent effects of chemical interaction between the chemicals and the clay particles both in terms of physical and mechanical properties. To this aim different clayey soil samples of different mineralogical composition, from European tunnel excavation projects, are treated with foams generated employing different commercial products. Laboratory apparatuses and test procedures specifically developed are employed to quantify accurately the adhesion between soils and metallic surfaces. The systematic comparison between the results obtained on natural and conditioned soil sample provide useful insights on the effects of chemicals on adhesion and on permanent effects on physical and mechanical properties.

RÉSUMÉ: L'utilisation de Tunnel Boring Machines (TBM) et en particulier de la technologie Earth Pressure Balance (EPB) est l'un des moyens les plus couramment utilisés pour effectuer l‘escavation de tunnel entièrement mécanisées. La possibilité d'effectuer l'excavation avec des performances élevées, en évitant les risques pour les travailleurs et en réduisant l'affaissement induit, particulièrement important en zone urbaine, est la principale raison du développement de cette technologie. Le succès de l'excavation dépend en grande partie de la qualité du processus de conditionnement du sol obtenu en injectant des produits chimiques sous forme de mousse à l'avant de l'excavation et en les mélangeant au sol excavé. Pour les sols à grains fins, l'interaction entre les particules argileuses et les produits chimiques conduit à la variation des caractéristiques du sol et, en particulier, à la réduction de l'adhérence naturelle entre le sol et la surface métallique de la tête d‘abattage. Cet article présente les résultats d'une activité de recherche expérimentale menée pour mesurer les effets temporaires et permanents de l'interaction chimique entre les produits chimiques et les particules d'argile, tant en termes de propriétés physiques que mécaniques. À cette fin, différents échantillons de sol argileux de différentes compositions minéralogiques, issus de projets européens d’excavation de tunnels, ont été traités avec des mousses générées à partir de différents produits commerciaux. Les appareils de laboratoire et les procédures d’essai spécifiquement développés ont été utilisés pour quantifier avec précision l’adhérence entre les sols et les surfaces métalliques. La comparaison systématique entre les résultats obtenus sur des échantillons de sols naturels et conditionnés fournit des informations utiles sur les effets des produits chimiques sur l'adhérence et sur les effets permanents sur les propriétés physiques et mécaniques.

Keywords: tunnelling; soil conditioning; chemical interaction; fine-grained soil; surfactants.

1 INTRODUCTION

In the last decades and particularly in the large urban areas, the need to transfer underground part of the infrastructures was only the first step that led to a general re-evaluation of the use of the subsoil, strongly encouraged by the increase in technological solutions and excavation performances. The design and construction of tunnels have been characterized by a relevant technological development that has led to the development of Tunnel Boring Machines (*TBM*), extremely efficient and safe machines able to excavate, to apply a front-face pressure and to install the final lining automatically.

The most developed TBM excavation technology is called Earth Pressure Balance (*EPB*) and provides for the continuous application of a pressure to the face through the same excavated soil suitably additived by injecting chemical agents under the form of foam.

The injected chemicals have the function of generate the foam necessary to modify the features of the soil making it suitable to transfer a pressure to the front to control the effects induced on the surface and to improve the excavation performance minimizing the risks related to the adhesion of soil particles to the metallic parts of the cutterhead, also known as *clogging*.

This technology was developed for the first time in Japan and was successfully exported in USA and in Europe in the projects of Passante Ferroviario in Milan.

Consistently with the exponential diffusion of this technology worldwide, several studies began to be performed and recorded by Nishitake (1990), Babendererde (1991) and Bezuijen *et al.* (1999) constituting in fact the first literature on this subject.

With specific references to the effects of the conditioning process on fine-grained soils must be cited the joint research activity between Cambridge and Oxford leading to studies as Mair *et al.* (2003). Moreover, specific studies were performed on *clogging* potential through the execution of mixing tests and pull out tests by Thewes & Budach (2010), Ziegler *et al.* (2015), Hollmann & Thewes (2012), Zumsteg & Puzrin (2012) and Zumsteg *et al.* (2013).

The effect of conditioning process can be distinguished in three different levels: a) the interaction between the chemical substances and the fine grained soil particles; b) the variation in the water content due to the liquid part of the injected foam; c) the variation of soil saturation due to the air part of the injected foam.

This paper presents a synthesis of a wider experimental activity developed in order to identify the effects of the three individual phenomena on the physical characteristics of the soils isolating them from the others.

2 THE EXPERIMENTAL ACTIVITY

The interaction between fine-grained soils and conditioning agents has been the subject of several experimental activities carried out in the laboratories of Sapienza University of Rome. These studies are performed using a particularly developed foam generation system, described in Sebastiani *et al.* (2017), with components from actual TBM plants to replicate foam generation and injection into the soil and to create soil samples having the same characteristics as the soil inside the TBM excavation chamber.

2.1 *Laboratory tests performed*

An extensive experimental test program entailed: *i)* Atterberg limits evaluations were performed to deeply invesigate the effect of chemicals in soil properties, *ii)* fall cone tests were performed to study the effects of the foam injection on soils undreained strength, *iii)* tests suggested in the cited litherature for the evaluation of the foams effectiveness in modifying che clogging tendency, as mixing tests, were performed and finally, *iv)* direct and ring shear tests were performed to point out the effect of chemicals in soil samples long-term shear strength and compressibility.

2.2 *Soil samples*

Several fine grained soil samples were selected in order to include a wide range of different soil features; the grain size distribution and the main features of each one are showed in Figure 1 and Table 1.

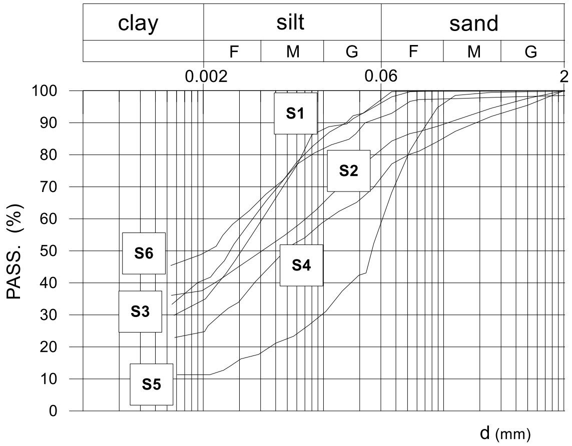

Figure 1. Grain size distribution of the soil samples.

Table 1. Soil sample features.

#	sample (-)	w_L (%)	w_P (%)	IP (%)	A (-)
S1	*Banzi*	40	20	20	0.50
S2	*Firenze*	39	21	18	0.60
S3	*Londra*	63	25	38	0.79
S4	*Bucarest*	50	24	26	1.32
S5	*Roma ARS*	24	19	5	0.52
S6	*Roma AR*	46	22	24	0.70
S7	*Caolino*	59	30	29	0.77
S8	*Bentonite*	417	43	374	29.0

2.3 *Chemicals*

In tunnelling application with TBM-EPB the most commonly used chemicals are surfactant based foaming agents. Surfactants are anphyphylic molecules, consisting of a polar head and a non polar tail.

The polar head nature as wel as the tail length, usually constitued of long straight chain of CH_2 groups, influence the solubility and the surfactant properties.

Regarding the surfactants present in the soil conditioning agent, they are mostly anionic as the *sodium laureth sulphate* (*SLES*), the key-compound in the commercial formulations, because of its low cost, high foaming capacity and appreciable biodegradability in aqueous environment.

The experimental tests, whose results will be discussed in the following, have been performed on several conditioning products (P1, P2, ...) from the main European suppliers. In all the products the main compound, besides the solvent (i.e. water) is the *SLES*. Other components (additives) are present in lower concentration (0.1-5%) for different purposes.

3 RESULTS

Below are briefly summarized few of the results obtained from the cited laboratory tests.

3.1 Effects of surfactants on Atterberg Limits of soils

The comparison of the behaviour of the soil samples mixed only with distilled water and with the addition of different foaming agents allowed to identify the effects of the interaction between surfactants and soil particles on the soil plasticity.

The Figure 2 shows on the Casagrande plasticity chart the Atterberg limits values measured for the soils *Caolino* and *Roma AR* without the conditioning agents (*NC*) and with different products diluited in water at 1%. For *Caolino* it was measured a reduction of the plasticity index associated with a reduction of w_L (5-8%) without appreciable variation in w_P. For *Roma AR* a small redution of w_L was observed beeing the reduction of plasticity index (6%) associate to a similar increase of w_P. Similar results were recorded for the other combination of products and soil samples.

Since the different dots are related to different products used for the soil conditioning, these tests have also made it possible to verify that different products produce slightly different effects due to the chemical composition and specifically to the different dosage of *SLES* in the product.

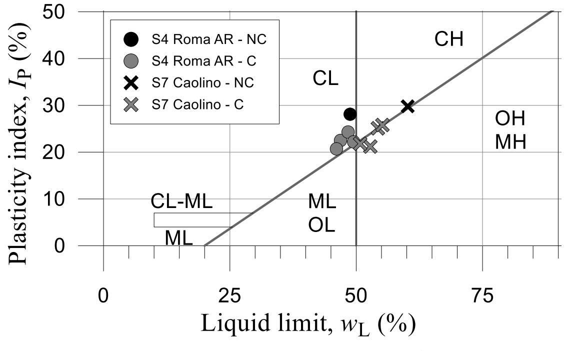

Figure 2. Casagrande plasticity chart for soil samples before (NC) and after (C) the conditioning process.

3.2 Effects of surfactants and foams on mechanical properties of soils

Performing fall cone tests on soil samples before (*NC*) and after the injection water, water and surfactants (tens.) and water and foam (foam) the results in Figure 3 were recorded. The undrained shear strength values, *Cu*, of the samples treated only with water fits perfectly the range of results collected by Mitchell (1976) as well as the results obtained from the tests on the soil samples treated with water and surfactants, showing that no relevant effects due to the presence of surfactants into the soil can be detected. For the soil samples mixed with foam were recorded lower values often beyond the same range; the comparable amount of surfactants in the samples suggests that the variation in *Cu* values should be addressed to the presence of foam, and then of air, into the soil.

Moreover, results show differences in the effect due to the features of the injected foam: the injection of foam generated with *P4* provide an higher *Cu* reduction if compared to the foam generated with P5. On this point, the chemical composition and the content of surfactants of the product may have a determinant role.

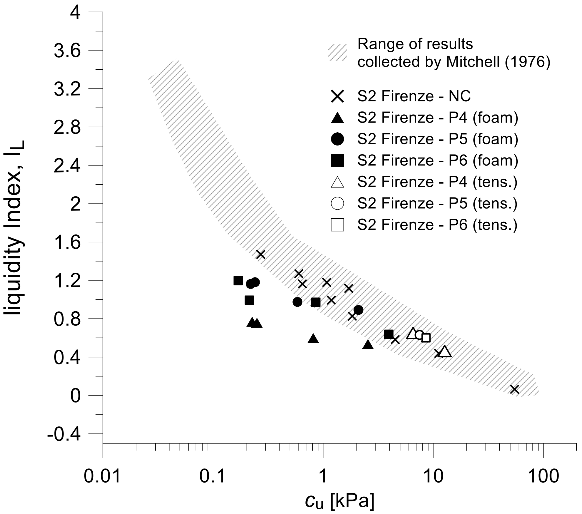

Figure 3. Results of the fall cone tests performed on soil sample S2.

In Figure 4 are presented the results of direct shear tests on reconstituted soil samples and of ring shear tests performed on S2 *Firenze* soil sample just after the injection of P4 product (2% diluition in distilled water). The substancial absence of visible effects on the shear strength confirm that no appreciable effects could be addressed to the surfactants in terms of variation of the mechanical properties of soil samples.

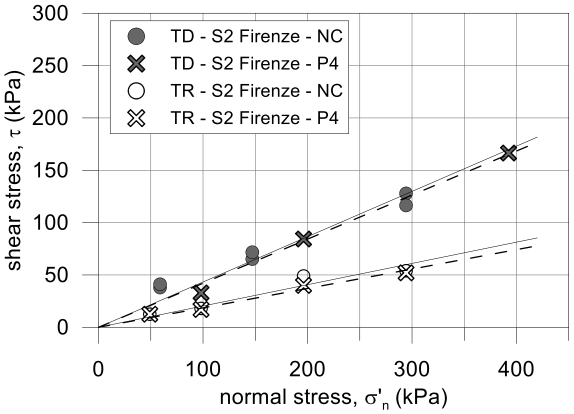

Figure 4. Direct shear test and anular shear test results for samples before (NC) and after the conditioning process with product P4.

3.3 Effects of water and foam on adhesion

In the figure 5 are showed the results of mixing tests performed on different not conditioned soil samples.

As for Ziegler *et al.* (2015) also in this case the trend of the adherence, measured as the ratio between the soil amount sticked on the Hobart mixing tool and the total soil used used for the test as suggested by Thewes (2011), has a peak, corresponding to a high clogging risk, for different consitency index (*Ic)* values and lower adherence values for water contents higher and lower.

The peak seems to have higher values of adherence and higher values of *Ic* for bentonite, that has the highest *IP* (374%), and lower values of adherence related to lower values of *Ic* for *Roma ARS* sample, having the lower *IP* values (5%). These observation suggests that, in addition to the relevant role played by water, also the mineralogical content plays a role in the adherence values and consequently in the clogging phenomenon. The same test is performed on *Roma AR* soil before and after the injection of foam generated using P1 and P4 products, in the same range of dosages, and results are showed in Figure 6.

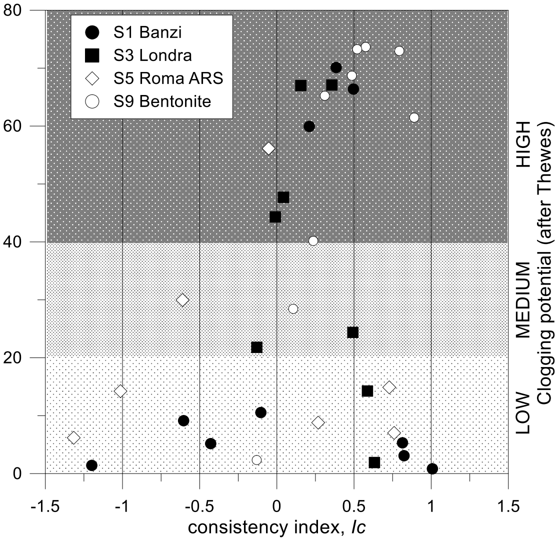

Figure 5. Mixing test results for NC soils.

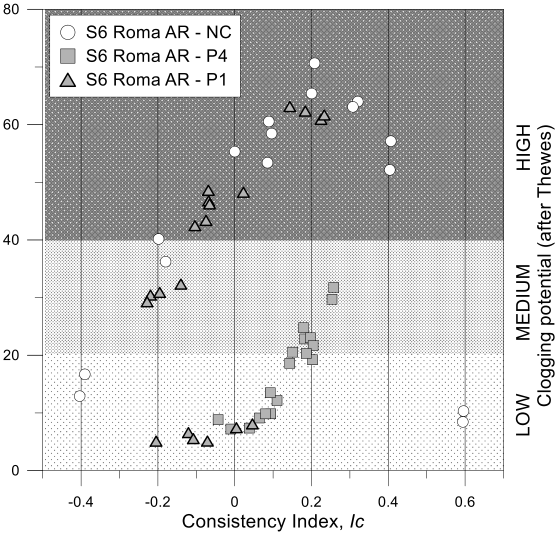

Figure 6. Mixing test results for soil samples before and after the conditioning process with product P1 and P4.

Results show clearly a difference in the effectiveness of the two products: P1, in most cases lead to adherence values close to the ones recorded for the soil NC, while the foam generated with P4 lead to a reduction of adherence values for *Ic* values usually related to high clogging potential, showing again the importance of the air into the soil.

4 CONCLUSIONS

The presented experimental activity allow to point out the effects of water, chemicals and foam in the variation of the properties of the soil in the conditioning process.

Surfactants provide a slight reduction of the plasticity index of soils (Fig.2); chemical composition, dosage and soil properties are parameters clearly affecting this effect. The same surfactants, on the opposite, have no appreciable effects in the variation of the peak and residual shear strength of soil (Fig.3).

The injection of foam and consequently of air into the soil plays a key role in the reduction of the undreained strength (Fig.4) and in the reduction of the clogging risk (Fig.6) determining the effectiveness of conditioning process.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Babenderende S., 1991. “Tunnelling machines in soft ground: a comparison of Slurry and EPB shield machines.” Tunnelling and Underground Space Technology. Vol 6, No2, April-June, pp.

Bezuijen A., Schaminee P.E.L., Kleinjan J.A., 1999. “Additive testing for EPBshields.” Proc. of 12th conference on Soil mechanics and Geotechnical Engineering,Amsterdam, June, Vol. 3, pp. 1991-1996.

Hollmann, F.S., Thewes, M., (2012). Evaluation of the tendency of clogging and separation of fines on shield drives. Geomechanics and Tunnelling 5 (5), 574–580

Mair, R., Merritt, A., Borghi, X., Yamazaki, H., & Minami, T. (2003). Soil conditioning for clay soils. T & T international, 35(4), 29-33.

Milligan, G. (2000). Lubrication and soil conditioning in tunnelling, pipe jacking and microtunnelling: A state-of-the-art review. Geotechnical Consulting Group, London, UK.

Mitchell, J. K. (1976). Fundamentals of soil behavior. New York: John Wiley & Sons.

Nishitake, S. (1990). Advanced Technology realize high performance earth pressure balanced shield. In: Franch issements souterrains pour l' Europe, 291-302, (Legrand, ed.), Balkema, Rotterdam.

Sebastiani, D., Ramezanshirazi, M., Di Giulio, A. and Miliziano, S. (2017). Study on short and "long term" effects of chemicals on fine grained soils for mechanized tunnelling conditioning. Proceedings of the World Tunnel Congress. Bergen, Norway.

Thewes, M., & Budach, C. (2010). Soil conditioning with foam during EPB tunnelling/. Konditionierung von Lockergesteinen bei Erddruckschilden. Geomechanics and Tunnelling, 3(3), 256-267.

Ziegler, M., Feinendegen, M., Englert, K. 2015. Verklebungen beim maschinellen Tunnelvortrieb: Be-wertungsverfahren und deren bautechnische Aussagekraft sowie juristische Aspekte zu vertraglichen Regelungen, Forschung + Praxis 46: STUVA-Tagung 2015, Ernst & Sohn, S. 163 – 171

Zumsteg, R., & Puzrin, A. M. (2012). Stickiness and adhesion of conditioned clay pastes. Tunnelling and Underground Space Technology, 31, 86-96.

Zumsteg, R., Plötze, M., & Puzrin, A. M. (2013). Effects of dispersing foams and polymers on the mechanical behaviour of clay pastes. Géotechnique, 63(11), 920.