Effect of Chemicals in Clogging Risk Reduction for TBM-EPB Application

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ABSTRACT

Over the last decade several tunnel excavations in difficult conditions were successfully performed using TBM-EPB technology with the help of soil conditioning agents that, in fine-grained soils, have proved to be particularly effective in reducing the clogging risk.

TBM excavation performances are strictly related to the management of the injection of these products. Consequently, a preliminary study on the typologies and dosages of chemicals required to reduce the clogging risk in the soil to be excavated has become a key component of good tunnel design.

Several methodologies and laboratory test equipment were developed worldwide to quantify the effects of the interaction between chemicals and soil particles; even if often there are no commonly accepted standards for the execution of these tests, several charts for the classification of the clogging risk have been provided.

The scope of the research presented is to underline how specific features of natural soil (grain size distribution, mineralogical content, plasticity and consistency) affect the clogging tendency of fine-grained soil and how the injection of chemicals can modify it.

Adherence was studied through mixing tests and pull out cone and plate tests, performed on several samples of different soils from actual tunnel excavation projects, untreated as well as treated with several commercial products from the main European suppliers.

The results of the analyses and laboratory tests performed provide useful data that can help improve the currently available clogging risk classification charts as well as propose a classification for the reduction of the clogging risk related to the injection of chemicals specifically suited for EPB applications.

Keywords max: Earth Pressure Balance (EPB), soil conditioning, laboratory research, clogging risk chart.

1. INTRODUCTION

TBM-EPB technology is currently one of the most common method to perform mechanized tunnel excavation. The improved machines now available and the soil conditioning by foam injection have made this technology more effective in complex geological contexts ([1], [7], [9]). EPB technology is successfully applied in urban areas where the special challenge is to limit surface settlements [13].

The conditioning activity entails the remoulding of the excavated soil into a homogeneous paste that facilitates not only the excavation, allowing to properly apply a pressure to the front face by completely filling the excavation chamber ([7], [9]), but also the transport and disposal of the spoil. It reduces wear and tear of the excavation tools and in fine grained soil it plays a key role reducing its natural adhesion tendency, often defined as clogging. In fact, clayey soils often stick to the digging tools and to the metal parts of the machine head slowing or impeding the excavation process.

In detail the clogging is the sum of different contributions: one is the adhesion of the soil, which is affected by soil grain size distribution, soil consistency, suction and chemical interaction between soil particles and the steel surface; another is a shear force at the interface between soil and steel, which is affected by grain size distribution, soil consistency and soil stress state.

There are several published researches describing test devices and procedures developed to deeply investigate the adhesion phenomenon: the works of Hammoud and Boumekik [4] with the ring shear apparatus, of Merritt [8] that reproduced a laboratory cochlea in Cambridge, the work of Zumsteg, Plötze and Puzrin [16] that introduced the Hobart mixer as test apparatus and the studies based mainly on pull-out test performed by Spagnoli, Feinendegen and Rubinos [11] and by Karami Aznadaryani *et al.* [6], only to cite a few.

There are a series of different classification schemes proposed for the clogging risk, the major two are provided by Thewes and Burger [15] and by Hollmann and Thewes [5] that, as we will see later in the discussion of the results, express the risk of clogging essentially as a function of the plasticity of the soil and its consistency index.

The role of the chemical products in clogging risk reduction can be divided into three different components: the one played by bubbles which keep separated from each other and from the metallic tools of the cutter-head the soil portion removed by the cutters (namely lumps), the role of the water injected through the foam which modify the consistency of the soil and the role of the injected chemicals which react with clay particles going to affect the molecular bonds.

The aim of this study is to share some results of an experimental activity useful to improve the classification scheme for the clogging risk for natural fine grained soil. The same results and the same scheme can be used to underline the effects of soil conditioning activities in reduction of clogging risk.

2. LABORATORY APPARATUSES AND TESTS

2.1. The laboratory foam generation system

The schematic plan of the laboratory foam generation system used in this research is described in figure 1. The plant, visible in the original version in figure 2, is available in the geotechnical laboratory of the Dept. of Structural and Geotechnical Engineering of Sapienza University of Rome.

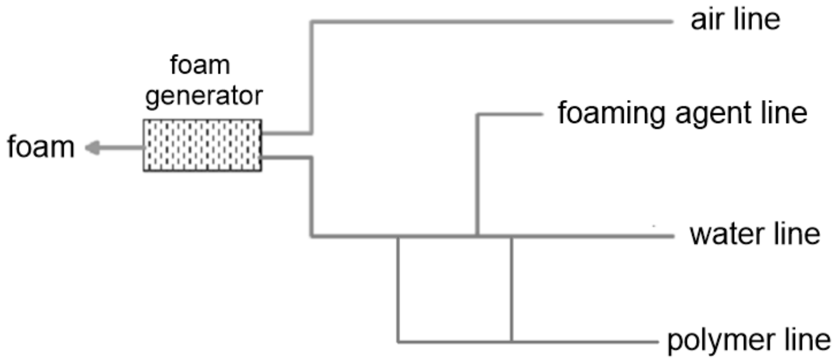

Figure 1. Laboratory foam generation system: schematic plan.

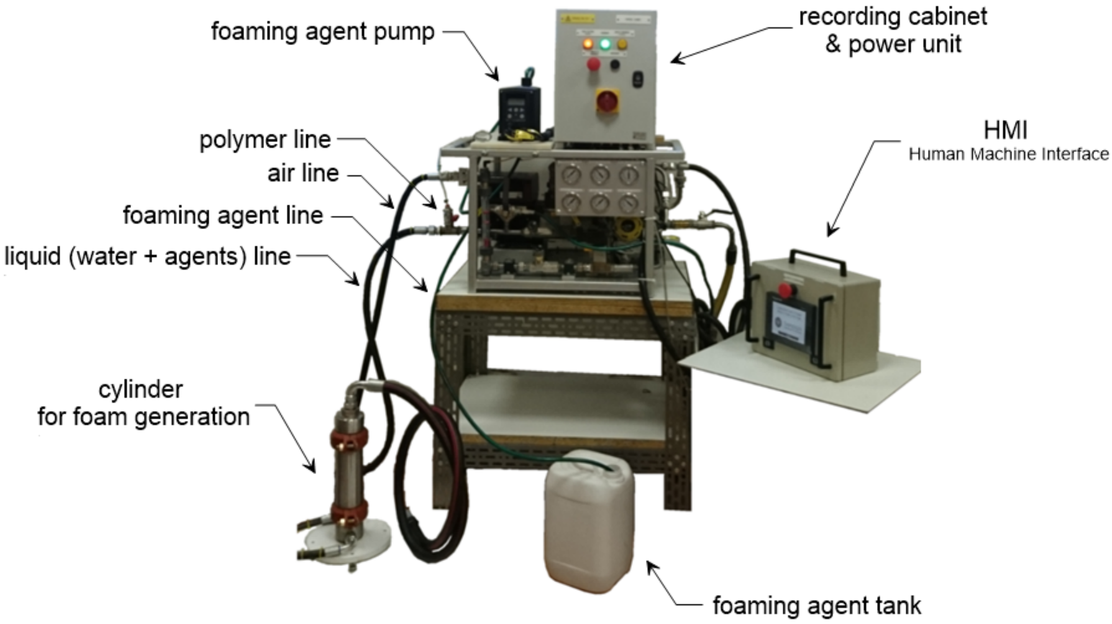

Figure 2. Picture of the laboratory foam generator system used in this study.

The system is composed by four main lines with their respective links, measurement system and control point of flow and pressure: air line, water line, foaming agent line and polymer line.

Water and air pressure, as well as the flow of water, air and the foaming agent can be regulated by pressure gauges and flow meters on the machine and their values can be changed in real time during foam generation. All these parameters are monitored through the HMI (Human Machine Interface) unit.

Properties of the foam generated are described by selected parameters:

$$Cf = 100 \cdot \frac{m_{f.ag.}}{m_{sol.}} \quad \text{(Concentration Factor of the product)} \quad (1)$$

$$FER = \frac{V_f}{V_{sol.}} \quad \text{(Foam Expansion Ratio)} \quad (2)$$

$$FIR = 100 \cdot \frac{V_f}{V_s} \quad \text{(Foam Injection Ratio)} \quad (3)$$

where $m_{f.ag.}$ is the mass of foaming agent used and m_{sol} is the mass of foaming solution; V_f is the volume of foam, V_{sol} is the volume of foaming solution and V_s is the volume of the soil.

2.2. The mixing test apparatus

The mixing test, which laboratory device is shown in Figure 3, was conceived to empirically quantify the clogging potential of soft soil mixtures [18] measuring the amount of soil that remains attached to the flat beater after a fixed time of mixing. The adherence is measured through the stickiness ratio λ, defined as the ratio between the weight of soil sticking to the mixing tool and the total weight of soil involved in the mixing process.

Figure 3. Mixing test laboratory apparatus [10].

2.3. The pull-out test apparatus

The pull-out test, in its version with the conical tool, was suggested by Feinendegen *et al.* [3] to investigate the tendency of clayey soils to adhere to the metallic parts of the cutter-head of the TBM. The sample of soil is compacted in a standard proctor device, a steel cone is inserted into a pre-drilled cone shaped cavity and loaded for 10 minutes. The load is then taken off and the specimen is placed in a test stand where the cone is pulled out at a velocity of 5 mm/min. The tensile forces and the displacements are recorded.

A modified version is set up at the DISG laboratory, applying the same principle but using a concave plate instead of the cone, as shown in Figure 4.

Figure 4. Pull out plate test laboratory apparatus.

The main advantage of this configuration is to improve the contact between the steel and the soil because the plate is pushed directly on the other half of the spherical joint leaving a thin layer of soil in between, eliminating possible unevenness or air bubbles which can be created pre-drilling the cavity for the cone insertion.

3. SOIL SAMPLES AND CHEMICALS USED

3.1. The soil samples used

To explore a wide range of natural fine grained soils, six samples of soils coming from different tunnel excavation project sites, with grain size distribution curves and Atterberg's limits executed on the material passing the n° 200 sieve (shown in Figures 5 and 6), were examined. The soils can be classified as silty clays and clayey silts, with a percentage of sand and gravel that varies from 0 % (S1, S3, S6) to about 30 % (S2, S4, S5) and covering a range of plasticity indexes that goes from 6 to 38 %.

Relevant activity indexes, *A*, from 0.5 to 1.32 as reported in Figure 6 are representative of inactive and active clays.

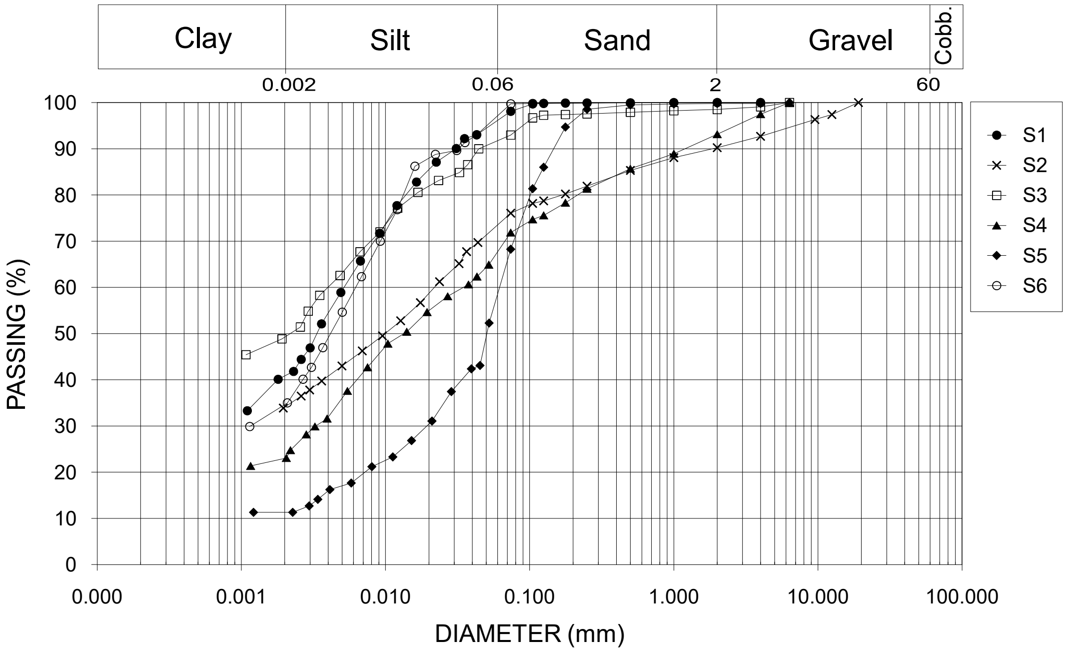

Figure 5. Grain size distribution of natural soil samples selected for the experimental activity from real TBM excavation project.

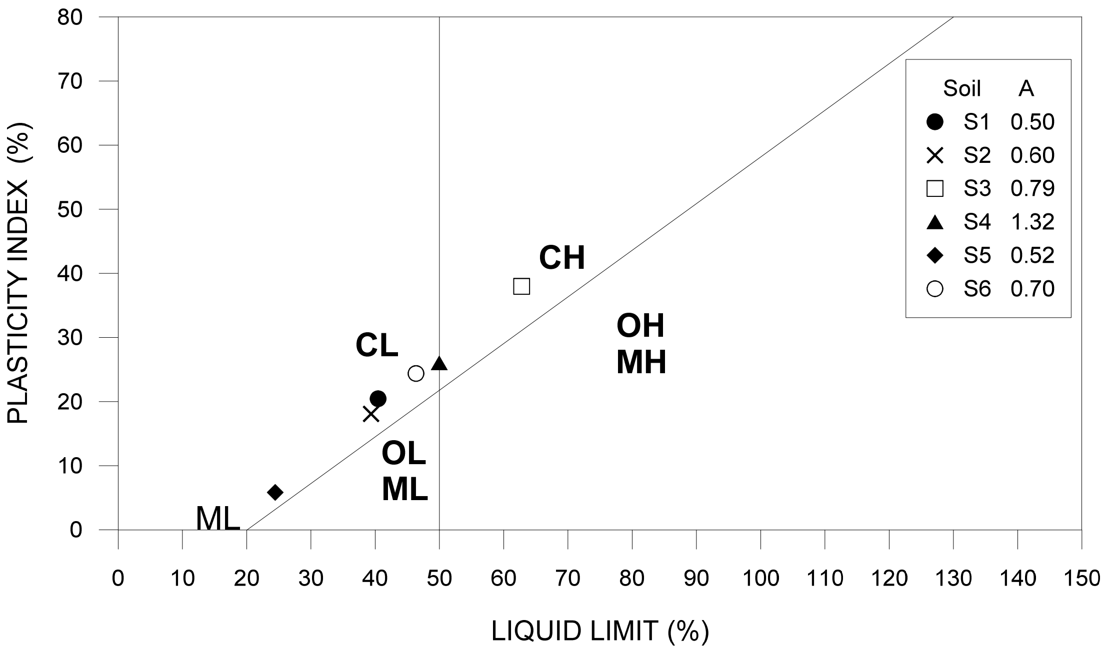

Figure 6. Casagrande plasticity chart of natural soil samples selected for the experimental activity from real TBM excavation project.

The samples were prepared drying the soils at room temperature, eliminating the coarser portion of each soil when necessary and eventually grinding the soil in lumps of less than two millimetres of diameter. The tests here described were executed on the untreated soil, i.e. adding only water up to achieve the selected consistency, as well as on the treated soil, adding at the same time water and foam (and the polymer when planned) in a mixing apparatus to simulate the effects of injection of foam during excavation.

3.2. The foaming agents used

In order to study the effectiveness of the injection of chemicals into the soil, different products were considered in the experimental activities; all the chemicals used are commercial products currently used in tunnel mechanized excavation projects with TBM-EPB technology.

The products are foaming agents mainly composed by anionic surfactants which are injected as foam into the soil to be excavated; the foaming agents are sometimes combined with polymeric additives in order to increase their effectiveness.

Given the variety of the chemical composition of these products and wanting to have a sufficiently broad idea of their effects with respect to the risk of clogging, different products and different dosages have been analyzed; in the next chapters foaming agents will be named FA and the polymers P.

4. EXPERIMENTAL RESULTS

4.1. Preliminary evaluations

As common in literature, the results herein presented are expressed as functions of the consistency index *Ic*, because this parameter is well related with the clogging potential and with the success of the treatment, but its correct assessment is not obvious when chemical products are involved. In fact, if assessing Atterberg's limits is simple on natural soil, during this research some products were proved to change the liquid limit of not negligible quantities, making difficult a direct comparison of the effectiveness of the treatment at fixed *Ic*.

Furthermore, considering the real scale, fine grained soils are likely to be chopped in lumps by the cutter head of the TBM, so that the injected foam acts mainly on the external surface of these lumps creating a "biphasic" paste, solid and fluid, for which is not easy to assess a value of *Ic*.

The following results should be therefore regarded as a necessary step for the comprehension of the whole complex phenomenon starting from homogeneous soil samples.

4.2. Mixing test results

Results of the mixing test performed on untreated samples at different *Ic* values are shown in Figure 7 together with the clogging potential fields proposed by Thewes [12]. The maximum adherence is measured for values of *Ic* that range from 0 to 0.5, a range shifted toward lower consistency indexes with respect to that observed for bentonite [5].

Being the adherence a phenomenon related to the physical and chemical properties of the clayey minerals as their specific surface and polarity, the activity index of a soil should influence the maximum stickiness ratios measured and reasonably change the correspondent field of *Ic*. It can be noted that for almost all the samples these maximum values are instead very similar, about 70%, apart from the results of S5, which has the lower plasticity index and is the only sample that shows a significantly different curve, proving that this influence exists but appears to be poorly grasped by this kind of test.

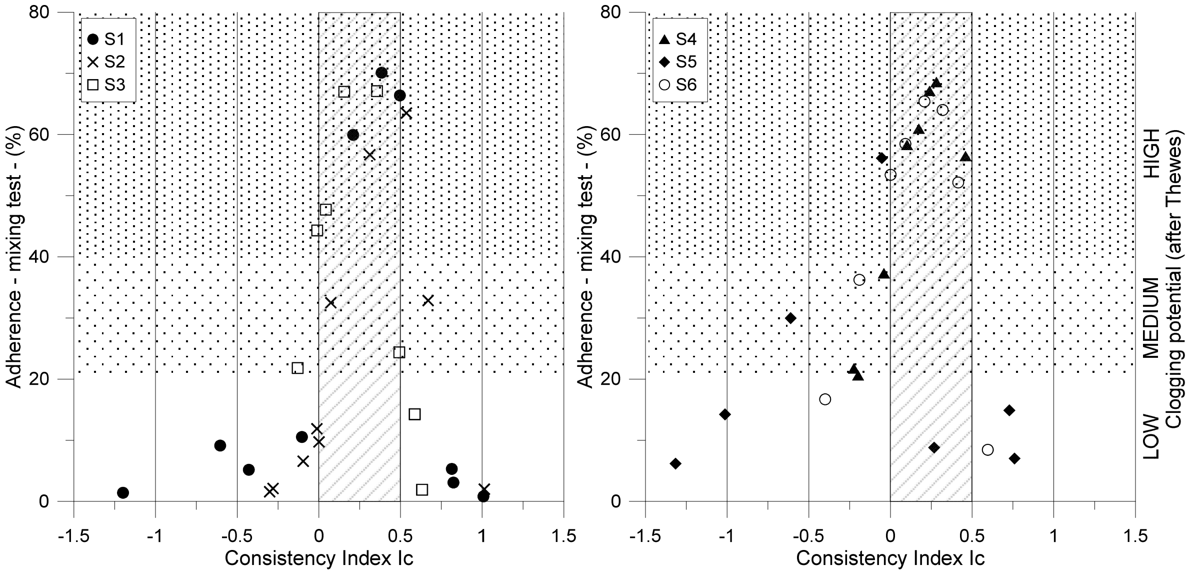

Figure 7. Typical evolution of the adherence, measured performing mixing tests, with Ic.

4.3. Clogging classification scheme for the mixing test

The mixing test results presented above were divided according to their clogging potential [12] and represented on the clogging risk classification proposed on the basis of studies on bentonite slurries and extended to EPB applications by Hollmann and Thewes [5] in Figure 8: it can be noted as the field of high clogging obtained from stickiness measurements is, without scattering, in the range of consistency indexes from 0 to 0.5, while the range defined as “strong clogging” goes from 0.5 to 0.75.

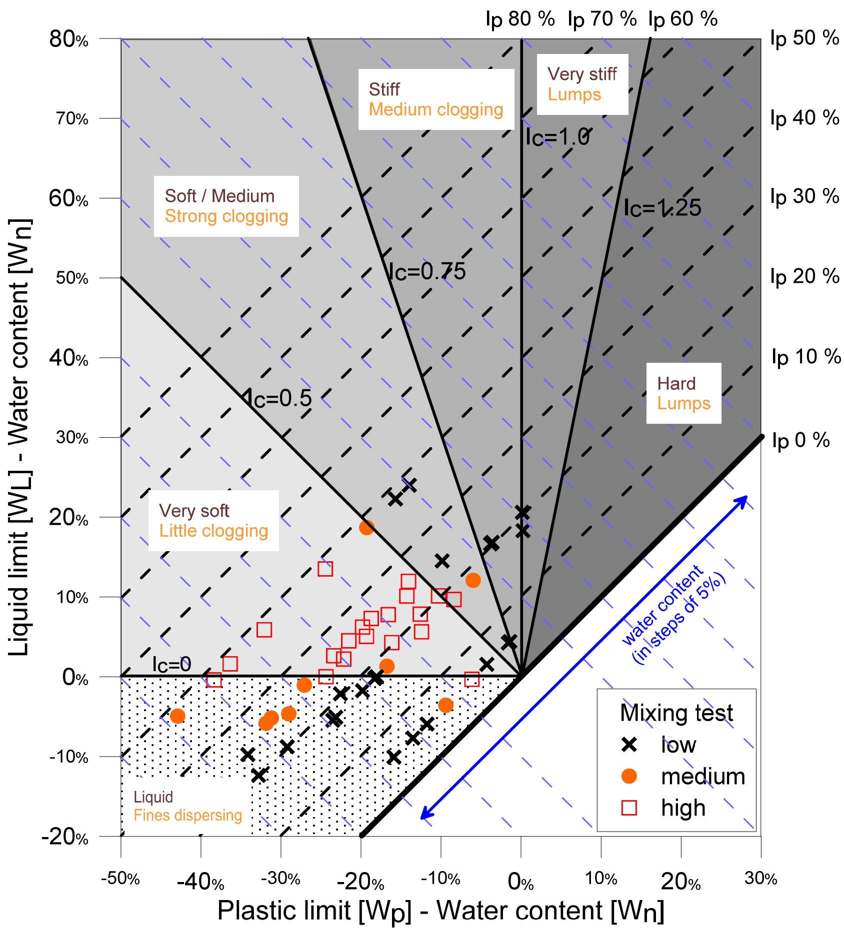

Figure 8. Mixing test results placed on the clogging risk classification after Hollmann and Thewes [5]

4.4. Pull out

Results of the plate pull out test performed on untreated samples at different *Ic* values are shown in Figure 9. The test, in its modified version, provides results substantially in line with those of the mixing test for natural soils, but some differences can be underlined. A significant result is that the maximum adherence measured in terms of tensile force seems more sensitive to the kind of soil, showing different values according to each soil plasticity index and thus improving the measurement of the clogging risk for soils with lower amount of clay, which show a lower adhesiveness not recorded with the mixing test.

The curves appear slightly shifted right of the field of *Ic* values between 0 and 0.5 and three of the soils (S4, S5 and S6) show a tail after the peak tensile force that can be due to suction phenomena not observed in the mixing test. Such results suggest that mixing and pull out tests are influenced differently by the same index properties, an issue worth of further investigation that can be probably explained considering the stresses induced by the test procedures, in fact the steel beater of the mixing apparatus exerts a friction that is not involved when the plate is pulled from the soil, which apply only tensile stresses.

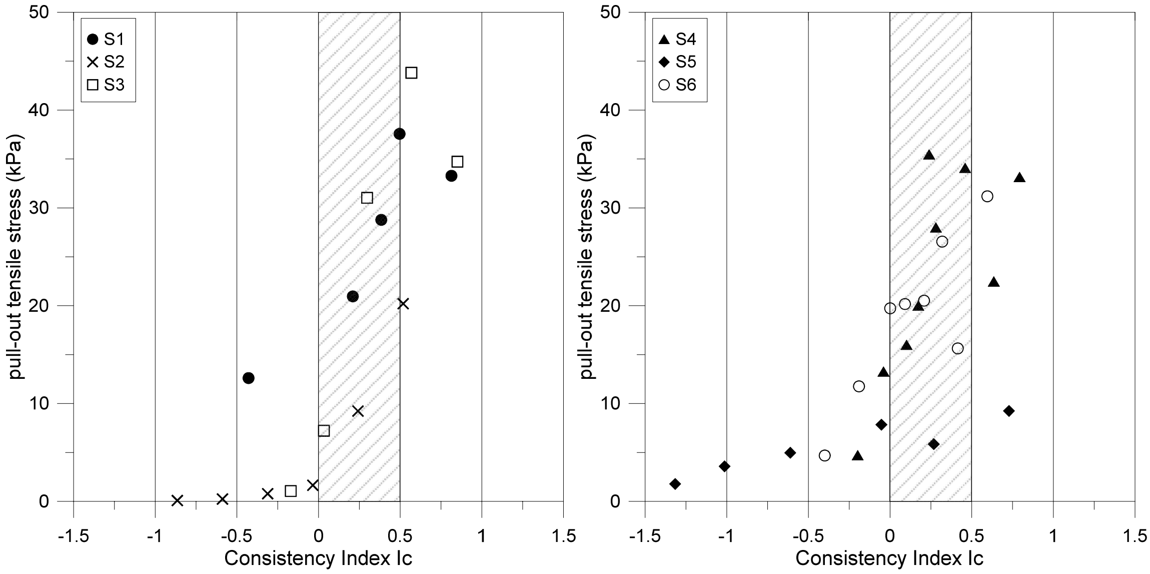

Figure 9. Evolution of the adherence with Ic, measured performing pull-out tests.

4.5. Effect of injected chemicals

From a series of preliminary tests it seems to emerge that the evaluations on the effectiveness of a given product or of a determined dosage can be carried out indifferently using the mixing test or the pull out test; this because, as can be seen in the figure 10, comparing a single sample of soil before and after conditioning, the results of the pull-out and of the mixing test are in good agreement.

On the basis of these and other similar results [10], it was decided to define the effectiveness of a given conditioning in terms of clogging reduction expressed as a percentage of the value shown by the natural soil at the same *Ic* value.

Conditioning is defined as "*moderately effective*" if it produces a reduction of adherence between 0 and 25% of the natural adherence, "*effective*" between 25 and 60% and "*very effective*" for a reduction of over 60%.

As can be seen in the same figure 10, depending on the dosage the same product may be moderately effective or very effective.

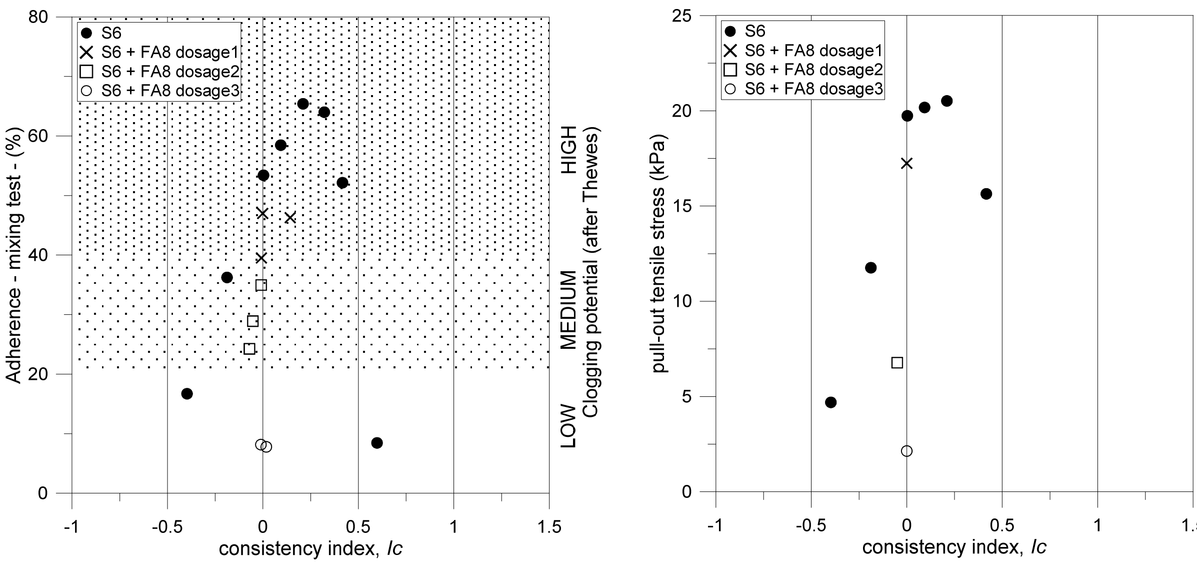

Figure 10. Effect of the chemical soil conditioning process on the adherence measured.

5. DISCUSSION

From the clogging risk classification in Figure 8 it can be noted that the range defined as “strong clogging” in the classification proposed by Hollmann and Thewes corresponds to values of Ic higher than those obtained for the six soils examined. This is probably due to the different mineralogy and overall consistency of the soils considered: in fact, as the high plasticity indexes shift the range of high clogging potential toward higher consistency indexes, also the *Ic* values change if measured on the material in the excavation chamber or on a homogeneous sample. The influence of these index properties could be deeply studied acquiring a more robust knowledge of the soil mineralogical content and relate it to the results of tests that involve only shear or tensile stress while measuring adherence, because the test procedure has been proven to affect the observed adherence.

Furthermore, the range corresponding to high clogging risk, *Ic* between 0 and 0.5, is indeed the consistence to be achieved for creating the soil paste that assures a successful excavation with EPB. This goal is difficult to obtain without the aid of the chemical treatment, that effectively reduce the adherence at the desired values of *Ic*, as shown in Figure 10. The tests here described are useful for an evaluation of the products effectiveness, for a comparison among different products or different dosages (combination of Cf, FER, FIR and added water) or evaluate the effect of a specific polymer

6. CONCLUSION

An experimental activity on the natural clayey soils behavior has been conducted to deepen the knowledge on the relation between the soils features and the clogging risk for TBM-EPB tunnelling application.

Several different soil samples were selected to perform an extensive experimental activity involving the execution of mixing tests and pull-out tests; the same tests were performed on the selected soil samples after a conditioning process with chemicals injected using a laboratory device particularly developed to simulate the TBM injection plant.

Recorded data have allowed to underline the diversity of the behavior of fine-grained natural soils with respect to the current literature knowledge as well as the relation between some parameters, as activity and grain size distribution, and the clogging risk.

From a comparison between the results of the mixing tests and pull-out tests some observations of practical utility emerged, as the effectiveness of the pull-out test in emphasizing the variety of behaviors of soils with different characteristics and the suitability of both tests for the assessment of clogging risk reduction due to the action of conditioning agents.

On the basis of the results of the tests performed on the conditioned soil samples, a criterion was proposed to evaluate the effectiveness of chemical injection based on the reduction of the natural phenomenon of clogging.

7. FUTURE DEVELOPMENTS

During the present experimental activity some aspects emerged that merit further studies; in particular, since many of the presented results are expressed through the consistency index, it will be necessary to deepen the theme of the chemical interaction between fine-grained soil particles and chemicals which affects the variation of the Atterberg’s limits partially recorded.

An issue worth of further investigation is the interaction occurring inside the excavation chamber between different portions of fine-grained soil (namely lumps) which are removed from the front and only partially homogenized in the conditioned soil mass.

Finally, the effect of the significant number of chemical compounds and additives currently used in TBMs remains to be investigated.

8. 8. AKNOWLEDGEMENTS

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