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Evaluation of the Geo-Mechanical Properties Property Recovery in Time of Conditioned Soil for EPB-TBM Tunneling

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Abstract: The soil conditioning is a process of fundamental importance during the excavation of tunnels with Earth Pressure Balance full face machine. The soil conditioning is achieved through the addition of foam at the excavation face and in the bulk chamber that modifies the natural soil properties from solid-like to fluid-like with a pulpy behavior. Clearly, a material with a pulpy or fluid-like consistency is not suitable for the construction of embankments of landfill or for other civil purposes. It is therefore important to have a procedure able to identify how long it is necessary before the conditioned soil recovers its geo-mechanical properties, since this knowledge is needed at the design stages from a logistic point of view. The paper proposes and discusses a procedure to find out whether and when the conditioned soil gets back to its original properties. The procedure foresees direct shear tests, vane tests, Proctor tests, and rotational mixer tests at different time schedules from the production of the conditioned soil in the laboratory. The conditioned soil samples have been cured in a controlled environment up to 60 days from the conditioning. Thanks to these tests, it is possible to assess if and when the soil recovers its natural behavior or if a permanent alteration is induced. The proposed procedure has been applied to a standard alluvial soil showing that most of the original properties of the soil are recovered already after seven days from the conditioning. The carried-out tests have shown that the procedure is feasible and easy to apply.

Keywords: EPB tunneling; soil conditioning; muck disposal; TBM machines

1. Introduction

The use of earth pressure balance (EPB) full face tunnel boring machines (TBM) is expanding in the tunneling industry, since these machines can excavate a tunnel in soil, also below the water table, with excellent production and safe jobsite conditions. The EPB-TBMs have also a great versatility, in terms of excavated soils, thanks to the use of conditioning agents. Those conditioning agents modify the soil behavior to make it suitable to apply a uniform counterpressure at the excavation face, to stabilize it, to counterbalance the water pressure, and to reduce the friction between the muck and the metallic parts of the machine. The most frequently used conditioning agent is foam, which is obtained with the use of surfactant agents that are injected from nozzles located on the cutterhead and in the bulk chamber [1,2].

The key aspect in the design is therefore the correct assessment of the conditioning amount and conditioning products in order to make the original soil, excavated by the cutterhead, fluid, highly compressible, and less permeable [2–6] and also to reduce wear on the mechanical parts of the machine [7,8]. Those properties, that are designed to avoid the compaction of the soil in the bulk chamber and that are fundamental for a proper behavior of the machine [9], become a major issue in the soil disposal phase.

Due to design criteria used for the conditioning, it is clear that it will be necessary for the construction company to wait for the conditioning agents to degrade and for their action to disappear [10,11]. In other words, it is necessary that the excavated soil recovers its original properties before being disposed in the final landfill or being used for earth embankments.

Currently, some authors address the issue of reuse of the muck of tunneling excavation, focusing on the use of rock chips as aggregate [10–12], or on the use of the excavated soil in combination with cement [13,14] or lime [15]. Perugini [16] suggested the applicability of the reuse of conditioned clay in the production of cement. Tommasi et al. [17] addressed the problem from a geotechnical point of view, analyzing the recovery of geo-mechanical properties through fall cone tests, Atterberg's limits, and Proctor tests for a tunnel case study.

Based on the abovementioned aspects, it is important for the designs to have a simple but standard procedure able to quantitatively evaluate how the property recovery develops in time, since the whole jobsite performances depend on this time. For example, if the soil has to remain in the jobsite for a long time, there is the need for large surface dedicated to soil storage and higher cost due to storage in a temporary landfill or a slow-down of the excavation must be taken into account.

Here is presented a procedure aimed to evaluate the temporal development of the geo-mechanical properties of the muck after the soil conditioning. A preliminary series of tests has been performed for up to 60 days and three commercial conditioning agents have been used. The soil has been studied with vane tests, direct shear tests, modified Proctor tests, and rotational mixer tests, a prototype device [18].

2. Materials and Methods

The procedure for the geo-mechanical assessment of the properties of conditioned soil vs. time is briefly described in the following. The first step is the geotechnical characterization of the soil and the assessment of the optimal conditioning set that has to be developed following the steps suggested in previous studies [19–21].

In order to evaluate the behavior of the soil with the aim of building an embankment, it is important to define its geo-mechanical and compactability properties. The suitability of a certain soil for the abovementioned purpose can be assessed by performing the modified Proctor test, the vane test, the direct shear test, and the rotational mixer test.

The modified Proctor test has to be performed according to the standard AASTHO T193 [22], both on natural soil and conditioned soil, while the vane test has to be performed according to the standard ASTM D2573 [23]. Due to the very low mechanical resistance of the conditioned soil, the test device had to be modified. The vane dimension has been increased to a diameter of 54 mm and a height of 109 mm to have more sensibility for the measurement when large-size grains are present. The ratio between the torque necessary to create a cylindrical failure surface and the area of the surface itself is the used index and it is named scissometric index (I_{sc}). Concerning the direct shear test, it was performed according to the standard ASTM D3080 [24] by using a cylindrical shear box with a diameter of 50 mm and a height of 30 mm (before the consolidation). The test has been performed using the consolidation vertical stresses of 50 kPa, 100 kPa, and 200 kPa. Finally, the rotational mixing test device is a prototype equipment developed in the Tunnelling and Undeground Space Centre (TUSC) Laboratory of Politecnico di Torino by Martinelli [18] to study the shear properties of a large volume of soil. It consists of a cylindrical tank, with a height of 613 mm and a diameter of 600 mm, with an internal coaxial shaft on which are installed 6 horizontal blades (Figure 1). The tank is filled with soil and the torque necessary to rotate the shaft at the constant speed of 30 rpm is measured. The average value obtained in the first 300 s of rotation is the measured value.

To have values to which to compare the parameters measured on the conditioned soil, the tests must be performed also on the natural soil conditioned simply with different water contents, ranging from 0% to the total water content of the conditioned soil (natural water content plus the added free water, plus the water added with the foam).

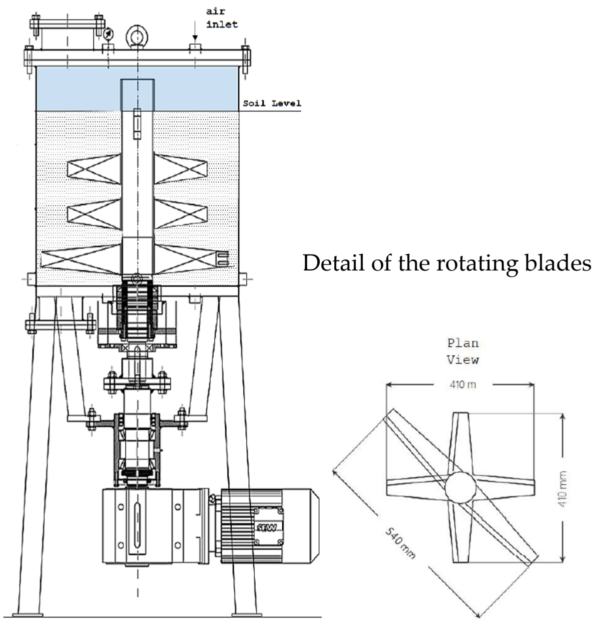
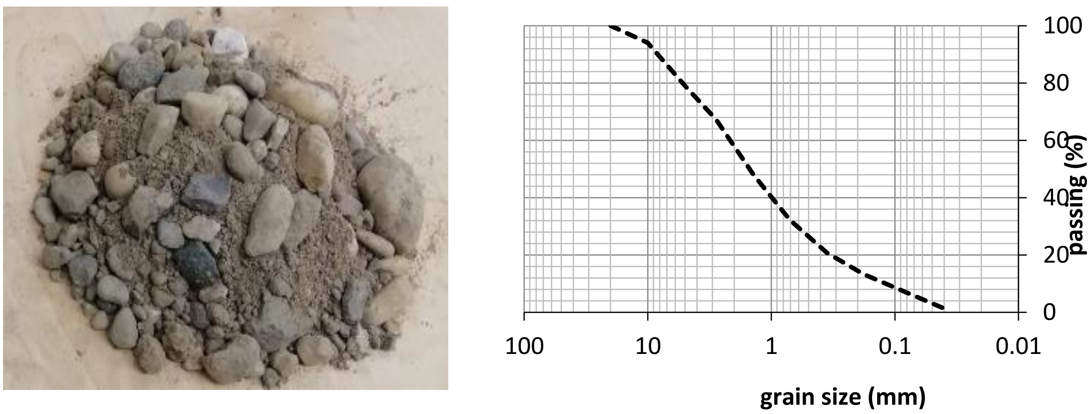


Figure 1. Rotational mixer test device scheme. Modified from Martinelli [18].

In the procedure, the soil has to be separated in three granulometric fractions due to the fact that each different test can be properly performed respecting its proper grain size constrain. In more depth, a maximum grain size ranging from 0 mm to 60 mm is suitable for the rotational mixer tests; 0–20 mm is the acceptable grain size range for the slump tests, the modified Proctor tests, and the vane tests, while finally forming 0 mm to 4.75 mm for the direct shear tests. For every grain size distribution, the test sample is stored in an open box with the following size: 350 mm × 250 mm and a thickness of 200 mm, and the conditioned soil inside has a thickness of 150 mm. During the curing time, the soil is not mixed and is not subjected to atmospheric agents.

The tests are carried out immediately after the production of the conditioned soil, and then after 1, 3, 7, and 28 days from the conditioning. It should be signaled that the procedure also permits to perform tests at longer time periods, as needed.

To verify the feasibility of the proposed procedure, laboratory tests have been carried out on an alluvial soil frequently encountered during the excavation of soil tunnels in North of Italy. In the following, the properties of soil, of the conditioning, and the main results are discussed. The soil has the grain size distribution depicted in Figure 2b, where is also shown a picture of a sample of soil (a). According to the UNI EN ISO 146800, the soil can be classified as sandy gravel.



(**a**) (**b**)

Figure 2. Picture of the tested soil (**a**) and grain size distribution (**b**).

The optimal conditioning set has been studied, for three different commercial conditioning agents, following the procedure suggested by Peila et al. [19], to have a set of data very close to what can be found in a real tunnel jobsite. The conditioning agents, named A and B below, are foaming agents based on alcohols, C12–C14, ethoxylated, sulfates, and sodium salts (content between 20% and 25%), while C is a foaming agent based on biodegradable anionic surfactants, mainly sodium laureth sulfate (content between 5% and 10%). The conditioning set is usually described using the following parameters, as it is usually done in the study of soil conditioning for EPB TBM excavation [19–21]:

- total water content: $w_{tot} = \frac{Weight\ of\ water}{Weight\ of\ dry\ mass} \times 100$ (%), where the water is the sum of the natural water, the free water added to the sample, and the water added in the foam;
- concentration of foaming agent in the fluid: $c = \frac{Volume\ of\ conditioning\ agent}{Volume\ of\ liquid\ generator} \times 100$ (%);
- Foam expansion ratio: $FER = \frac{Volume\ of\ foam}{Volume\ of\ liquid\ generator}$; that, globally, describes the quality of the foam;
- Foam injection ratio: $FIR = \frac{Volume\ of\ foam}{Volume\ of\ soil} \times 100$ (%); that, globally, describes the quality of the conditioning.

The results of the used conditioning parameters related to the three conditioning agents are summarized in Table 1. They represent the optimal conditioning as defined previously [18], and in Figure 3, the results of the slump test on conditioned soil are shown [23,24].

Table 1. Conditioning set parameters for the three studied conditioning agents.

Conditioning Product	w_{tot} (%)	c (%)	FER (-)	FIR (%)
A	11.0	1.1	20	30
B	11.0	1.0	20	30
C	11.0	2.0	14	20

(**a**) (**b**) (**c**)

Figure 3. Picture of the slump test for the three tested products (**a**) Product A; (**b**) Product B; and (**c**) Product C.

3. Results and Discussion

3.1. Modified Proctor Test

The modified Proctor test has been successfully performed only after 7 days from the conditioning, since, for lower curing times, the soil has exhibited a behavior that was too fluid to be compacted.

In Figure 4, the obtained results concerning the three conditioning agents and a curing time of 7 days are given and plotted together with the curve of the natural soil. It is possible to observe that, for each product, after 7 days from the conditioning, a dry density comparable to the one of the natural soil is reached; that means that the soil has totally recovered its behavior.

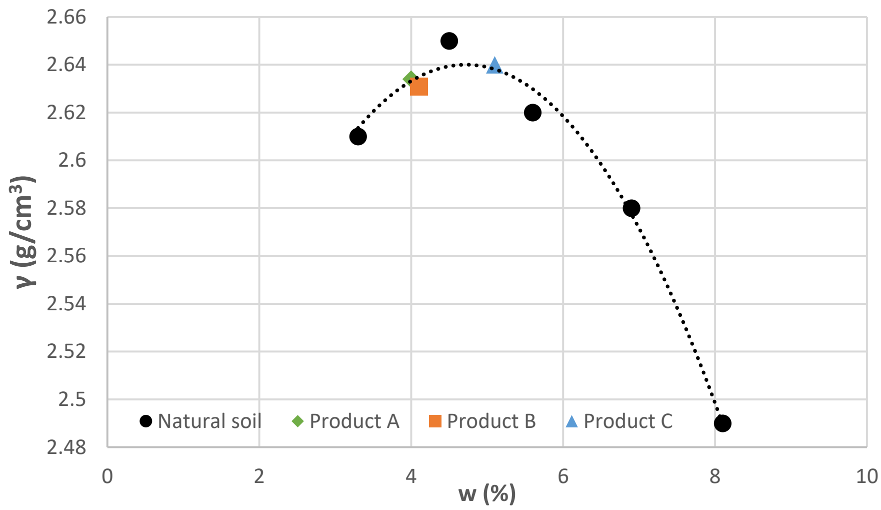
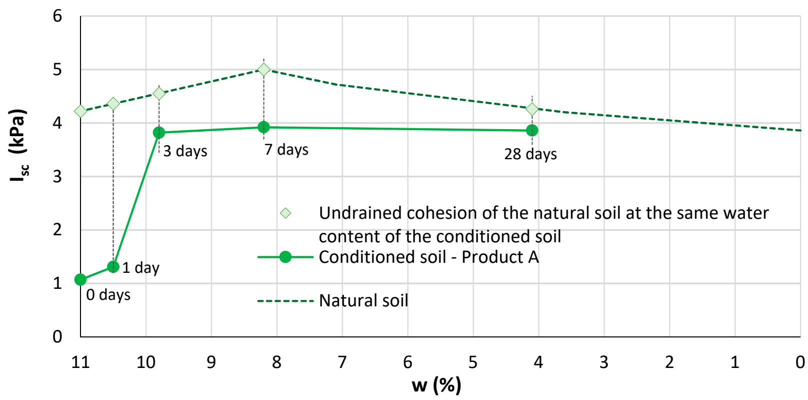


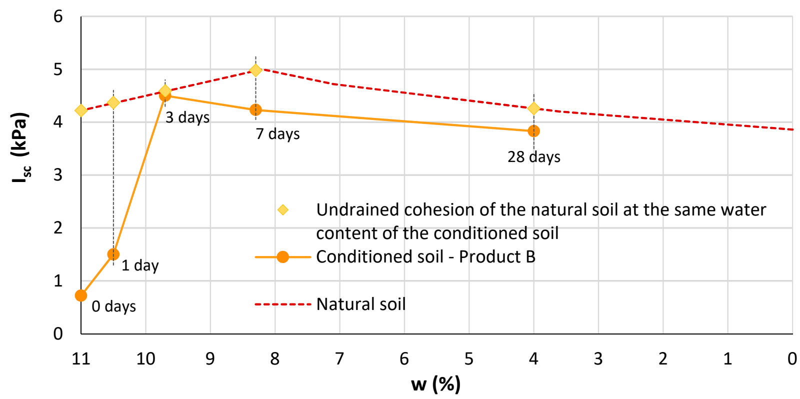
Figure 4. Results of the modified Proctor test for products A, B, and C at 7 days after the conditioning.

3.2. Vane Test

In Figure 5, the results of the vane test for each conditioning agent are given. It is possible to observe that the value measured for the natural soil is almost entirely for each of the three conditioning agents after 28 days from the soil conditioning. Otherwise, after a time laps of 7 days, only the product C (chemically the more biodegradable) recovers completely its original value.

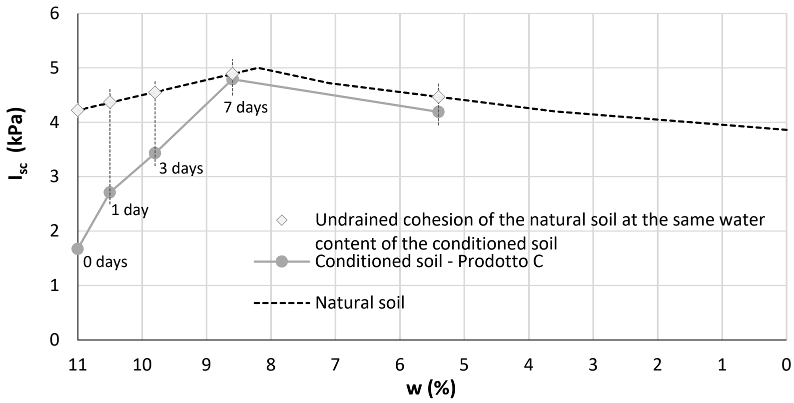


(**A**)



(**B**)

Figure 5. *Cont.*

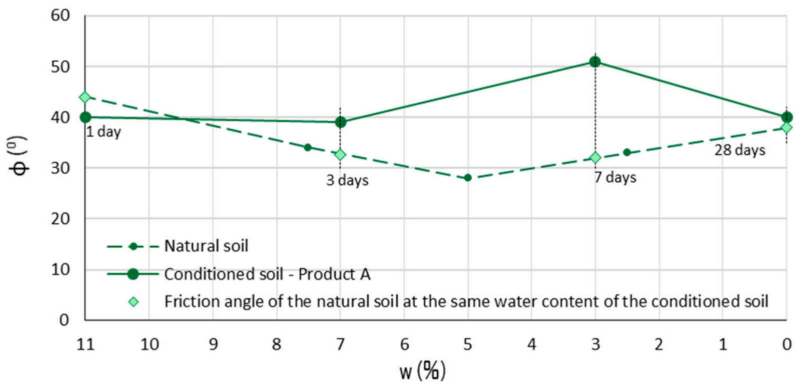


(C)

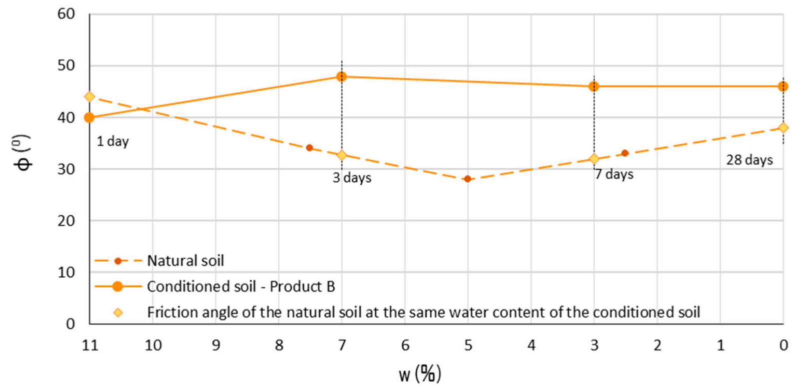
Figure 5. Results of vane test for products A, B and C. (**A**) Results of vane test for products A, (**B**) Results of vane test for products **B**; (**C**) Results of vane test for products C.

3.3. Direct Shear Test

In Figures 6 and 7, the results of the direct shear tests are given for the three conditioning agents, both in terms of drained friction angle and drained cohesion. It is possible to observe that the drained friction angle is almost completely recovered after 28 days, while the drained cohesion, on the other hand, shows a reduction due to the conditioning and that the original values are not completely recovered after 28 days. To study if the loss of cohesion is permanent or subject to a very slow recovery, it has been decided, for the product C, to perform tests at 45 days and 60 days. From the results given in Table 2, it is possible to observe that both values reached at 28 days remain stable for up to 60 days without any change. This result is an index that the chemical product has completely disappeared and that does not influence any more the mechanical behavior of the soil.

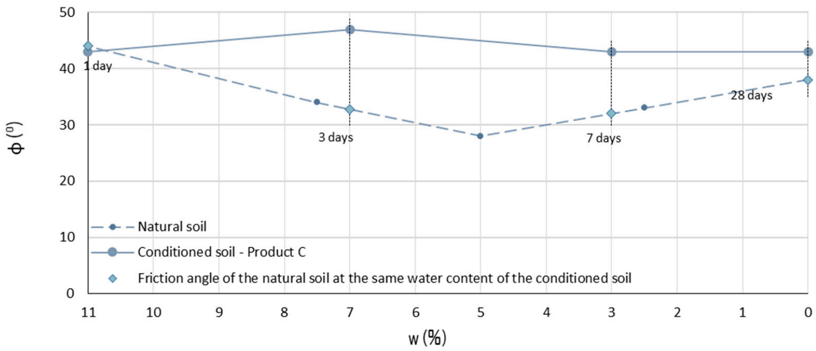


(A)



(B)

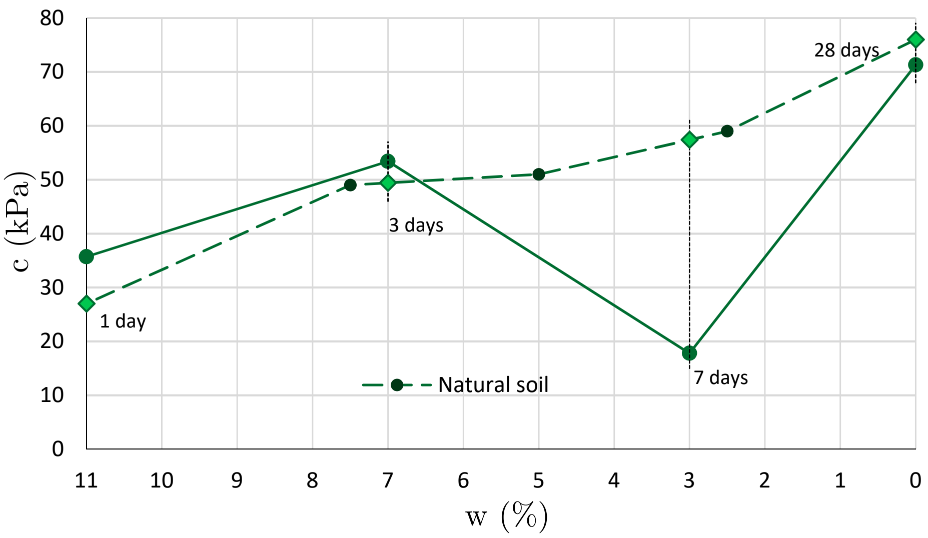
Figure 6. *Cont.*



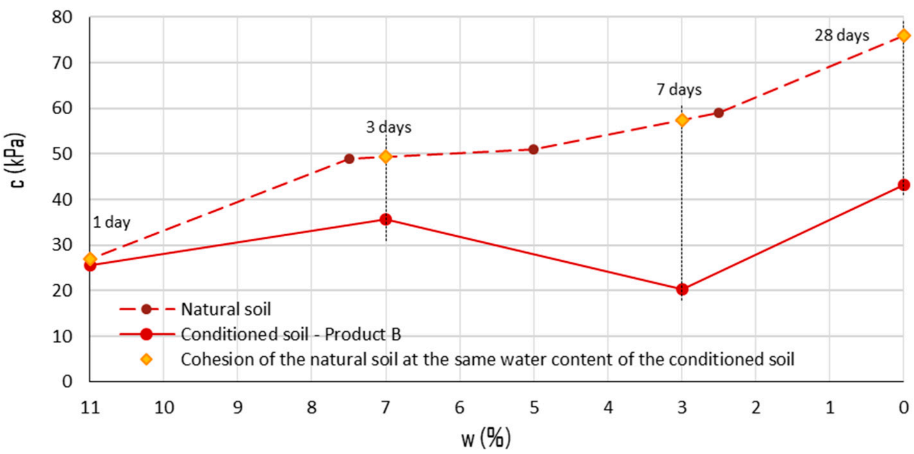
(**C**)

Figure 6. Results of direct shear test for products A, B and C. (**A**) Results of direct shear test for products A—Friction angle; (**B**) Results of direct shear test for products B—Friction angle; (**C**) Results of direct shear test for products C—Friction angle.

It is eventually important to highlight that the soil commonly used for embankments and civil purposes typically has a low fine content and considering that the cohesion is determined on the fraction passing at 4.75 mm, this result has a marginal influence on the global geo-mechanical behavior of the soil to be used for embankments.

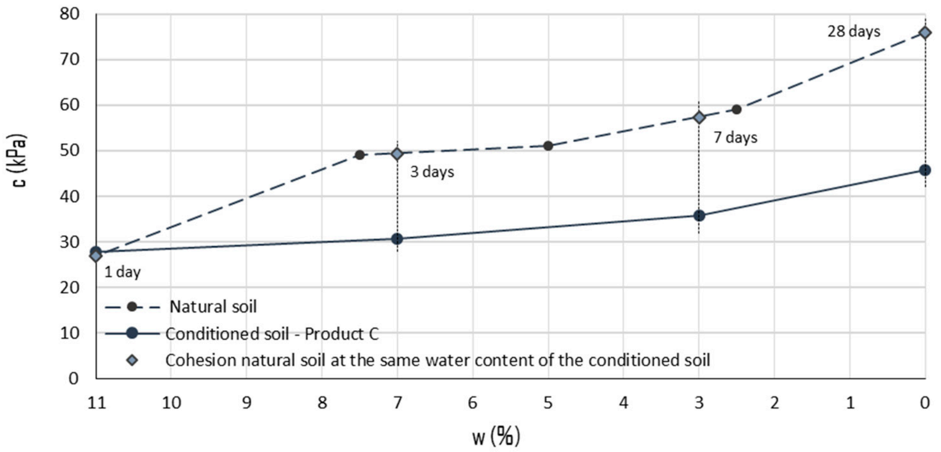


(**A**)



(**B**)

Figure 7. *Cont.*



(**C**)

Figure 7. Results of direct shear test for products A, B and C. (**A**) Results of direct shear test for products A—Cohesion; (**B**) Results of direct shear test for products B—Cohesion; (**C**) Results of direct shear test for products C—Cohesion.

Table 2. Results of the direct shear test at 45 and 60 days compared to the results at 28 days.

Curing Time (Days)	Φ′ (°)	c′ (kPa)
28	43	45.8
45	43	45.8
60	43	45.8

3.4. Rotational Mixer Test

This test is a prototype device used to study the shear resistance of a large volume of soil [18]. In Figure 8, the values of torque on the blades obtained with the three conditioning agents are given. It is possible to see that the soil conditioned with product C has a slower recovery than the soil samples conditioned with products A and B. For each conditioning agent, it is possible to observe a substantial recovery of mechanical properties after 7 days.

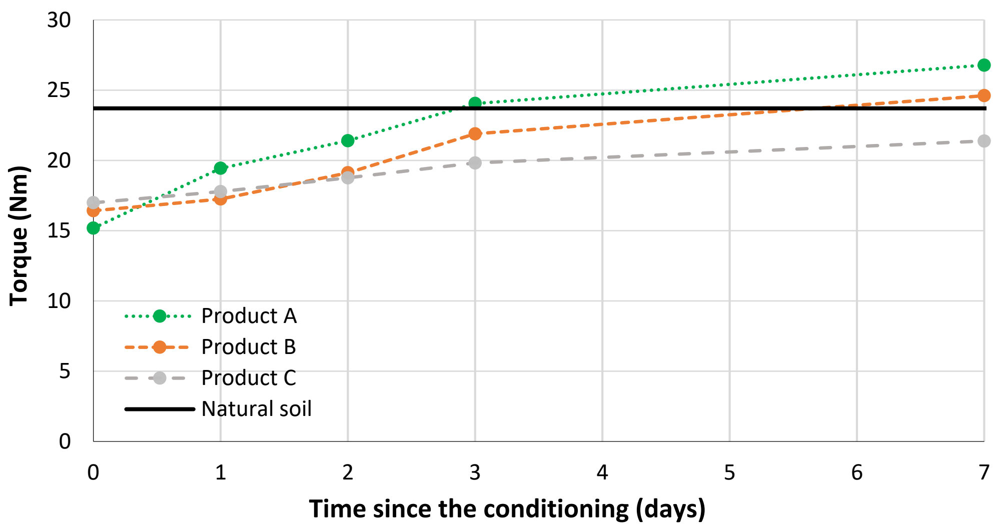


Figure 8. Results of rotational mixer test for products A, B, and C.

4. Conclusions

Due to the great importance of the time needed by the conditioned soil to recover its geo-mechanical properties after the EPB-TBM excavation, in the global management of a tunnel jobsite, it is important for designers to dispose of a standardized and uniform procedure for this assessment. For this reason, a simple procedure based on well-known both geotechnical tests and laboratory conditioning tests has been developed and proposed. The used standard geotechnical tests are the modified Proctor test, the vane test, and the direct shear test, while an innovative test on a large volume of soil has been proposed and used.

To check the feasibility of the procedure, it has been tested on a very common alluvial soil that can be found in EPB-TBM projects. The purpose of this set of tests was to check the procedure applicability. The obtained results have shown that the procedure is simple and feasible.

In detail, the obtained results show that the conditioned soil, at the same water content, recovers all its original geo-mechanical properties in a short time. After 7 days from the conditioning, most of the properties are very close to the ones of the natural soil, and after 28 days, no substantial differences can be observed, with the exception of the cohesion that maintains a certain difference.

It is appropriate to highlight that this procedure faces the limitation of not taking into account the variability of conditions in which the material will cure on the jobsite and the natural variability of the material at the tunnel face, and it is affected by scale problems comparing the volume of the soil treated by the machine and the volume of the laboratory samples.

Nevertheless, the procedure is easily applicable to any jobsite and it appears to be a good design tool for understanding the rate at which the material recovers its geo-mechanical properties and to correctly design the jobsite logistics and plants.

Author Contributions: Conceptualization of the tests and analysis of the results: A.C., C.T., and D.M.; development of the tests: A.C., C.A., C.T., and D.M.; writing—original draft: A.C.; work supervision: D.P. All authors have read and agreed to the published version of the manuscript.

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References

1. Vinai, R.; Oggeri, C.; Peila, D. Soil conditioning of sand for EPB applications: A laboratory research. *Tunn. Undergr. Space Technol.* **2008**, *23*, 308–317. [CrossRef]
2. Thewes, M.; Budach, C.; Bezuijen, A. Foam conditioning in EPB tunnelling. In *Geotechnical Aspects of Underground Construction in Soft Ground*; Viggiani, G., Ed.; CRC Press: Boca Raton, FL, USA, 2012; pp. 127–135.
3. Martinelli, D.; Todaro, C.; Luciani, A.; Peila, D. Use of a large triaxial cell for testing conditioned soil for EPBS tunnelling. *Tunn. Undergr. Space Technol.* **2019**, *94*, 103–126. [CrossRef]
4. Peila, D.; Picchio, A.; Martinelli, D.; Dal Negro, E. Laboratory tests on soil conditioning of clayey soil. *Acta Geotech.* **2016**, *11*, 1062–1074. [CrossRef]
5. Carigi, A.; Luciani, A.; Todaro, C.; Martinelli, D.; Peila, D. Influence of conditioning on the behaviour of alluvial soils with cobbles. *Tunn. Undergr. Space Technol.* **2020**, *96*, 103–225. [CrossRef]
6. Todaro, C. Analysis on the penetration of foams in excavation with EPB. *Geoing. Ambient. Min.* **2016**, *147*, 49–52.
7. Salazar, C.G.O.; Todaro, C.; Luciani, A.; Boscaro, A.; Peila, D. Preliminary study of wear induced by granular soil on metallic parts of EPB tunnelling machines. *Geoing. Ambient. Min.* **2016**, *148*, 67–70.
8. Salazar, C.G.O.; Todaro, C.; Bosio, F.; Bassini, E.; Ugues, D.; Peila, D. A new test device for the study of metal wear in conditioned granular soil used in EPB shield tunnelling. *Tunn. Undergr. Space Technol.* **2018**, *73*, 212–221. [CrossRef]
9. DAUB. Recommendations for selection and evaluating tunnel boring machines. *Tunnel* **1997**, *5*, 20–35.
10. Grenni, P.; Barra Caracciolo, A.; Patrolecco, L.; Ademollo, N.; Rauseo, J.; Saccà, M.L.; Mingazzini, M.; Palumbo, M.T.; Galli, E.; Muzzini, V.G.; et al. A bioassay battery for the ecotoxicity assessment of soils conditioned with two different commercial foaming products. *Ecotoxicol. Environ. Saf.* **2018**, *148*, 1067–1077. [CrossRef]

11. Firousei, Y.; Grenni, P.; Caracciolo, A.B.; Patrolecco, L.; Todaro, C.; Martinelli, D.; Carigi, A.; Hassanpour, J.; Peila, D. The most common laboratory procedures for the evaluation of the EPB TBMs excxavated material ecotoxicity in Italy: A review. *Geoing. Ambient. Min.* **2020**, *162*, 44–56.
12. Gertsch, L.; Fjeld, A.; Nielsen, B.; Gertsch, R. Use of TBM much as construction material. *Tunn. Undergr. Space Technol.* **2001**, *15*, 374–402.
13. Zhang, C.; Yang, J.; Fu, J.; Wang, S.; Yin, J.; Xie, Y. Recycling of discharged soil from EPB shield tunnels as a sustainable raw material for synchronous grouting. *J. Clean. Prod.* **2020**, *268*, 121947. [CrossRef]
14. Scröfelbauer, T.; Schreitl, B.; Kitzler, C. S1 Danube-Lobau tunnel—Recycling of tunnel spoil material. *Geomech. Tunn.* **2009**, *5*, 633–642. [CrossRef]
15. Oggeri, C.; Fenoglio, T.M.; Vinai, R. Tunnel spoil classification and applicability of lime addition in weak formations for muck reuse. *Tunn. Undergr. Space Technol.* **2014**, *44*, 97–107. [CrossRef]
16. Perugini, V. Low energy nobilitation of clay waste from tunnelling. In Proceedings of the ITA-AITES World Tunnel Congress 2019, Naples, Italy, 3–9 May 2019.
17. Tommasi, P.; Lollino, P.; Di Giulio, A.; Belardi, G. Investigation on the geotechnical properties of a chemically conditioned spoil from EPB excavation, a case study. In Proceedings of the ITA-AITES World Tunnel Congress 2019, Naples, Italy, 3–9 May 2019.
18. Martinelli, D. Mechanical Behaviour of Conditioned Material for EPBS Tunnelling. Ph.D. Thesis, Politecnico di Torino, Torino, Italy, 2016.
19. Peila, D.; Martinelli, D.; Todaro, C.; Luciani, A. Soil conditioning in EPB shield tunnelling—An overview of laboratory tests. *Geomech. Tunn.* **2019**, *12*, 491–498. [CrossRef]
20. Thewes, M.; Budach, C. Soil conditioning with foam during EPB tunnelling. *Geomech. Tunn.* **2010**, *3*, 256–267. [CrossRef]
21. Peila, D.; Oggeri, C.; Borio, L. Using the slump test to assess the behavior of conditioned soil for EPB tunnelling. *Environ. Eng. Geosci.* **2009**, *15*, 167–174. [CrossRef]
22. AASHTO. *Guide for Design of Pavement Structures*; AASHTO T193; AASHTO: Washington, DC, USA, 1993.
23. ASTM. *Standard Test Method for Field Vane Shear Test in Cohesive Soil*; ASTM D2573-01; ASTM: West Conshohocken, PA, USA, 2003.
24. ASTM. *Standard Test Method for Direct Shear Tests of Soils under Consolidated Drained Conditions*; ASTM D3080; ASTM: West Conshohocken, PA, USA, 1990.