Soil conditioning tests of clay for EPB tunnelling

Available online at www.sciencedirect.com

ScienceDirect

Underground Space xxx (xxxx) xxx

www.keaipublishing.com/undsp

Soil conditioning tests of clay for EPB tunnelling

C. Todaro [a,b,*], A. Carigi [a], L. Peila [a], D. Martinelli [a,b], D. Peila [a,b]

[a] DIATI, Politecnico di Torino, Italy

[b] IGG, CNR, Italy

Received 8 March 2021; received in revised form 31 October 2021; accepted 14 November 2021

Abstract

Tunnelling with earth pressure balance – tunnel boring machine (EPB-TBM) in clayey soil requires a careful conditioning to reduce the effect of clogging and stickiness. In the last decade, many researches have been carried out to understand how to reduce these negative behaviors using conditioning agents, and different laboratory test procedures have been proposed using both powdered clay and clay chips to quantify and assess the effect of conditioning in terms of reduction of clogging and stickiness. In this paper a review of the various proposed tests is presented. Unfortunately, it can be seen that no unified assessment method on the soil conditioning is available and therefore the designers do not have consistent data on which their choices are based. The present research proposes a laboratory test methodology to study clay conditioning taking both the behavior of chips and powdered clay into account. The proposed procedure has been applied on two different clays, and the test results are presented and discussed to show how the proposed methodology could be applied.

Keywords: Tunnel; EPB-TBM; Soil conditioning; Laboratory tests

1 Introduction

The growth of earth pressure balance – tunnel boring machine (EPB-TBM) applications in the last decades has induced the researchers to develop research focused on the key parameters of soil conditioning both for cohesionless soils and clay formations.

The correct management of a clayey soil is complex since often clogging, adhesion and re-aggregation must be faced. Clogging occurs when the cutterhead openings are completely plugged, while adhesion occurs when the steel surfaces of the machine are completely covered by the excavated material; the re-aggregation phenomenon happens when the excavated clay creates a new compact mass inside the bulk chamber (Hollmann & Thewes, 2012; Zumsteg et al., 2013a, b). These phenomena can induce a reduction of the excavation speed and an increase in the required cutterhead torque. In a limited number of cases, they can lead to the complete blockage of the screw conveyor or the cutterhead and may cause damage to the machine and an increase of the excavation cost. A good review of these concepts is presented by Alberto-Hernandez et al. (2017). The assessment of the clogging potential is usually done using the standard clay geotechnical indexes (i.e., the water content, the plasticity index, and the consistency index) as clearly discussed by Thewes (1999) and by Hollmann and Thewes (2012, 2013), and its rating at the design stage is essential. Galli and Thewes (2014) discussed the development of the water balance in clayey support medium in EPB-TBM and focused the problem of the behavior of the clay chips in the mix that has been later focused and deeply discussed by Peila et al. (2016).

The proposed testing for assessment of clay conditioning is not unique, and each research group has developed its own procedure. Industry and designers need a standardized and widely recognized scheme able to provide simple and comparable data. For the above-mentioned reasons,

* Corresponding author.

https://doi.org/10.1016/j.undsp.2021.11.002

Please cite this article as: C. Todaro, A. Carigi, L. Peila et al., Soil conditioning tests of clay for EPB tunnelling, Underground Space, https://doi.org/10.1016/j.undsp.2021.11.002

a set of laboratory tests of clay conditioning is presented and discussed considering both tests on powdered clay and on clay chips.

2 State of the art on conditioning of clay

Most of the available studies use powdered clay samples that are then mixed with the conditioning agent to study their behaviors with different types of devices. This procedure is acceptable to study small-scale adhesion, but to correctly study the EPB tunnelling process, it is also necessary to consider samples made of chips with bigger size (Peila et al., 2016). As a matter of fact, during the excavation process, a clayey soil is not reduced into powder by the action of the cutter head, but both clumps and clay powder are produced by the tools and by the secondary fragmentation into the chamber.

The most frequently used clay conditioning agents are foaming agents and water, when injected, which can produce a soft mud to allow the mutual sliding of the clumps, thus minimizing the risk of re-aggregation. Since foam has a limited effect on clogging and adhesion (Zumsteg et al., 2013b), it is usually combined with polymers to lubricate the clay and to minimize its stickiness (Langmaack & Feng, 2005; Peila et al., 2016).

Various researchers have developed different testing methods in order to evaluate the conditioned clay behaviour with reference to EPB tunnelling. The slump test is probably the first that was used since it allows evaluation of the conditioned soil rheology and was originally applied to cohesionless soils (such as silt, sand, and gravel) (Peron & Marcheselli, 1994; Quebaud et al., 1998; Peña, 2003; Peila et al., 2009, 2013; Borio & Peila, 2011; Thewes et al., 2012; Galli & Thewes, 2019). It is important to highlight that, in clay, this test procedure cannot be used alone and must be integrated with further testing. It gives a global overview of the mass behaviour, but it does not provide sufficient indications on the clogging and adhesion phenomena.

The tests most frequently proposed for clay are addressed to evaluate the behaviour of a powdered clay paste conditioned or not conditioned when it is in contact with steel. The mixing test was originally used by Psomas (2001) and Zumsteg et al. (2012, Zumsteg et al., 2013a, Zumsteg et al., 2013b) who used a Hobart mortar mixer. Recently Garroux de Olivera et al. (2018, 2019) proposed an updated procedure where an assessment of the clogging potential was defined by mixing the clay with a Hobart mixer and weighing the mass of material stuck on the beater, comparing this with the whole amount of mixed material. These authors improved the way used to detach the clay from the beater by dropping it from a fixed height. The same test has been used by Kang et al. (2021).

The lateral adhesion test (adhesion associated with sliding, carried out with different schemes by various researchers) was used to measure the adhesion between the conditioned soil and a metallic element (Quebaud et al., 1998; Zimnik et al., 2000; Peila et al., 2016). The adhesion test, carried out by placing a steel cylinder upon the soil sample and then pulling up while measuring the adhesion force, was introduced by Thewes (1999), Thewes and Burger (2005), and Sass and Burbaum (2009); while Feinendagen et al. (2010) proposed to use the cone pull-out test. Zumsteg et al. (2013a, 2013b) and Peila et al. (2016) developed testing devices to evaluate the shear resistance on a metallic disc rotating in the conditioned soil under different pressures and speeds. Finally, Vinai et al. (2008) used slump test combined with a screw conveyor extraction test for a complete assessment of soil conditioning for cohesionless soil, but it provides very effective information also for clay conditioning and should be used when the geological situation is complex, for example in mixed faces.

Due to the great variability of the available tests, there has been the need of a scheme for an assessment procedure on clay conditioning that considers the tests on both powdered clay and clay chips to provide a standard framework.

3 Materials and methods

The proposed assessment procedure foresees a set of tests that globally allow a homogeneous analysis of the behavior of the conditioned soil.

The detailed proposed tests and the test procedures are shortly described in the following. It is important to highlight the great importance of the sample quality, which should be representative of the soil that will be encountered during the excavation by the machine, and it should be considered how to prepare the mix in laboratory by mixing the soil with the conditioning agent (i.e., foam) that should be close to the real one.

An additional important aspect to be considered is that the laboratory tests have the sample size much smaller than the one on the jobsite, hence a scale factor cannot be neglected (due to the diameter of the TBM and the characteristics of the cutter head), and operative conditions are different (time and temperature during the excavation). However, such laboratory tests are a useful tool to address the approximate conditioning parameters that will have to be confirmed during the operative phases of the machine through the monitoring of the measured data.

3.1 Description of the procedures and of the test devices

3.1.1 Mini-flow test

The mini-flow test procedure is similar to the slump test procedure (Peila et al., 2009), but it is carried out using a small truncated cone (Fig. 1). It is used for studying the effect of conditioning on a clay mainly reduced to powder, i.e., the effect of the conditioning agent at a small scale level. The conditioning agent is added to the clay powder in the form of fluid instead of foam.

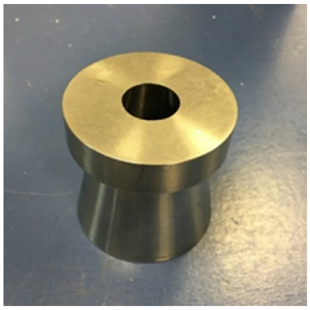


Fig. 1. Mini-flow cone with geometric dimensions: Height of the truncated cone is 60 mm; Diameter of the upper face is 20 mm; Diameter of the lower face is 44 mm.

The test procedure is as follows:

(1) A dry clay sample of about 100 g is crushed into powder with a single grain no more than 5 mm, and then inserted in a small plastic bucket with a volume of 1 dm^3;
(2) The needed water and the conditioning agent are mixed at the requested percentage in a separate bucket. The fluid is manually mixed for about 10 s;
(3) The fluid produced at step 2 is poured into the soil, and mixed by hand using a spatula usually for about 3–5 min until a homogeneous mix (made of powdered clay and conditioning fluid) is obtained: no more clay grains should be visually observed in the conditioned soil;
(4) The mini-flow cone is positioned on a perfectly smooth surface of glass, and then filled with the mix and immediately lifted;
(5) The obtained mini slump is observed, and the diameter of the bottom and the height of the mini slump are measured.

3.1.2 Hobart mixer and flow table test

This test is carried out using the Hobart mixer (Fig. 2) (EN 196-1, CEN, 2016) to mix the soil and the conditioning agent. A slump cone with the size on a flow table is shown in Fig. 3. The Hobart device is used to mix a sample made of clay chips with the conditioning agents; after the mixing, the conditioned sample is inserted in a mini-slump cone and then lifted. After these steps, the slump is subjected to a flow table action and the behaviour of the mix is then assessed. The measured parameters are the base diameter and height immediately after the lifting of the cone (before jolting: Φ_{BJ} and h_{BJ} respectively) and after the flow table is activated (after jolting: Φ_{AJ} and h_{AJ} respectively).

The conditioning agent is added to the clay chips as foam and if a polymer is used it can be added during the mixing process directly on the mixture.

The test procedure is as follows:

(1) A clay chip sample of 500 g is inserted in the mixing bowl of the Hobart mixer device with a capacity of 5 dm^3;
(2) The foam is then added to the sample and they are mixed for 30 s with the Hobart device at a speed of 140 r/min and a revolution of the bowl of 62 r/min, as suggested by Zumsteg et al. (2012). The mixing process is then stopped, the beater is cleaned, the removed material is inserted in the bowl again, and then the mixing phase is repeated for 30 s;
(3) The mini-slump cone is filled with the material taken from the bowl and immediately lifted;
(4) The obtained mini slump is observed and the base diameter and height (Φ_{BJ} and h_{BJ}) are measured;
(5) The flow table is activated and 15 jolts are given to the slump with a frequency of 1 jolt/s;
(6) The obtained mini slump is observed and the base diameter and height (Φ_{AJ} and h_{AJ}) are measured.

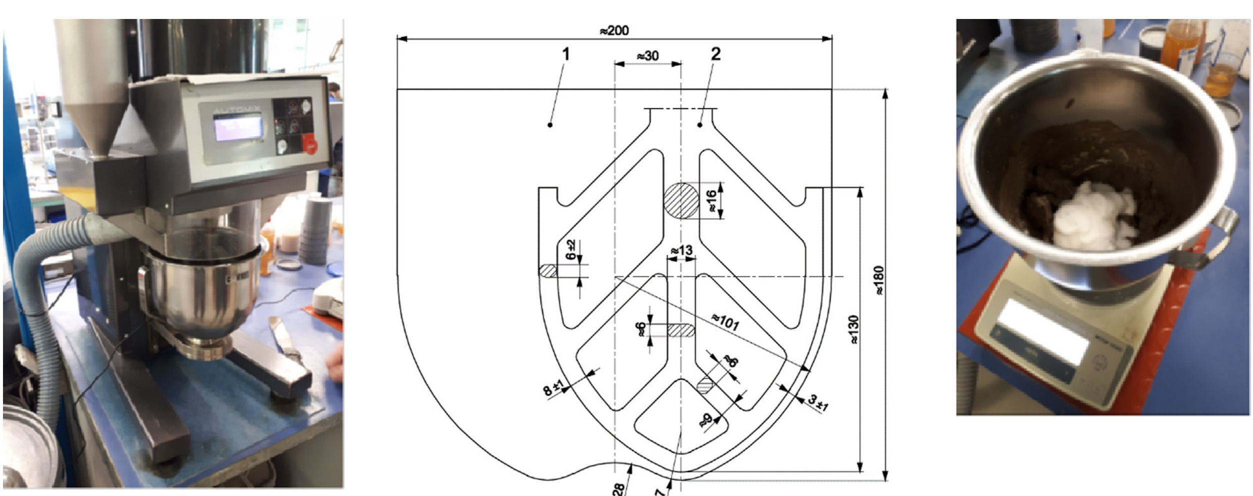


Fig. 2. From left to right Hobart mixer assembled, B-flat beater and mix device bowl with the soil and foam before mixing (Unit: mm).

Fig. 3. The mini cone on the flow table filled with soil and after the lifting of the mini-slump cone. The dimensions of the used mini-slump cone are: Height is 60 mm; Diameter of the upper face is 70 mm; Diameter of the lower face is 100 mm.

3.1.3 Slump test

This test is carried out using the slump cone usually used for standard fresh concrete tests (CEN, 2009; Peila et al., 2009). The test is developed on samples made of clay chips; it is a relatively large-scale test with a cone height of 300 mm, an upper face dimeter of 100 mm, and a lower face diameter of 200 mm.

The conditioning agent is added to the clay chips as foam and, if a polymer is used, it can be added during the mixing process directly into the mixture.

The test procedure is as follows:

(1) A clay chip sample of 15 kg is inserted in a concrete mixer with a volume of 0.25 m^3, then the added water is poured in the bowl and mixed for 10 s at a rotation speed of 25 r/min. Alternative methods for mixing can be used based on the laboratory expertise, but their feasibility should be discussed and approved;
(2) The foam is added to the soil and the bowl is rotated till a homogeneous mix is obtained (rotation time ranging from 2 min to 5 min). Alternative methods for mixing can be used based on the laboratory expertise, but their feasibility should be discussed and approved;
(3) The slump cone is filled without any action to compact the filling in the cone, and the cone is immediately lifted;
(4) The obtained slump is observed and measured (Slump A);
(5) The material is then collected, inserted again in the bowl, and mixed for another 5 min;
(6) The slump cone is filled and immediately lifted;
(7) The obtained slump is observed and measured (Slump B);
(8) The flow table (with the following size 760 mm × 760 mm), on which the cone test was done, is activated, and then the slump is subject to 15 jolts obtained with a drop of 15 cm and a frequency of 1 jolt/s;
(9) The obtained slump conditions are observed (Slump C).

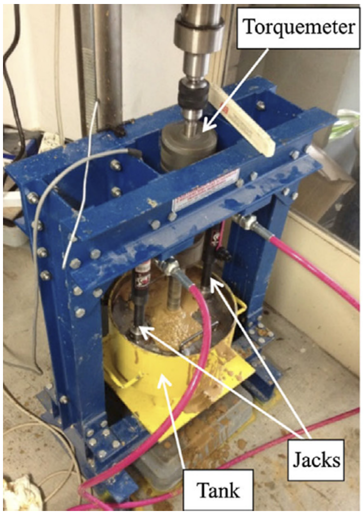
3.1.4 Dynamic adhesion test

The dynamic adhesion test (Peila et al., 2016) is based on the rotation of a steel disc into a tank full of clay chips that are mechanically pressurized with a constant pressure of 0.1 MPa (Fig. 4). The test allows to assess the resistance offered by the soil to the motion of the disc due to the adhesion of the soils to the disc. During the test, the required torque is measured.

The conditioning agent is added to the clay chips as foam and if a polymer is used it can be added during the mixing process directly into the mixture.

The test procedure is as follows:

(1) The sample is prepared by mixing the 15 kg of clay chips with water and foam in a concrete bowl of a volume of 0.25 m^3. The preparation of the sample is the same as that for the slump tests;
(2) The lower part of the tank is filled and compacted by hand to limit the number of visible voids in the mass;
(3) The disc (diameter = 120 mm) with its supporting beam is positioned in the device;
(4) The tank is then completely filled with the conditioned clay chips in layers of 100 mm. Special attention is paid to guarantee a good contact between the disc and the conditioned clay;



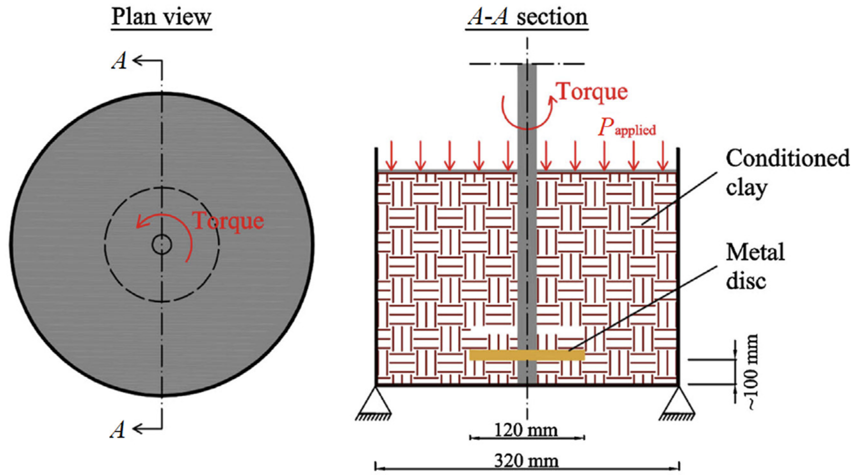


Fig. 4. Scheme of the dynamic adhesion test device. The metallic disk has a diameter of 120 mm and a thickness of 10 mm (Peila et al., 2016).

(5) The upper plate is then positioned and a pressure ($P_{applied}$), equal to 0.1 MPa is applied on the upper surface;
(6) The rotation of the disc is then started with a speed, ω, of 90 r/min, and the torque, T, is recorded for 300 s.

3.1.5 Foam production and key parameters of foam conditioning

The foam at the laboratory scale should be produced using a foam generator able to manage the foam as it is done on an EPB machine. The key parameters that describe the foam conditioning are summarized in Table 1. FER, is a "quality index" of the foam: low values describe "wet" foam, typically adopted in clayey soil, while high FER values (usually larger the 10) are those of "dry" foam, commonly used for sand and gravel. FIR is a "quantitative index" of the treatment describing that much foam is introduced in the soil. These values are usually measured at atmospheric pressure to have information on the calculation of these parameters at different pressure values, and it is possible to consider the equations reported by Mori et al. (2018).

Table 1
Parameters for the soil conditioning design.

Parameters	Definition
Added water, w_{add} (%)	$w_{add} = \frac{\text{added water weight}}{\text{dry soil weight}} \times 100$
Generator liquid concentration, c (%)	$c = \frac{\text{foaming agent volume}}{\text{generator liquid volume}} \times 100$
Foam expansion ratio at atmospheric pressure, $FER_{(0)}$	$FER_{(0)} = \frac{\text{foam volume}}{\text{generator liquid volume}}$
Foam injection ratio at atmospheric pressure, $FIR_{(0)}$ (%)	$FIR_{(0)} = \frac{\text{foam volume}}{\text{soil volume}} \times 100$
Polymer injection ratio, PIR (%)	$PIR = \frac{\text{polymer volume}}{\text{soil volume}} \times 100$
Treatment ratio, TR	$TR = \frac{\text{foaming agent weight}}{\text{soil weight}}$

3.2 Interpretation of test results

In the following is given a summary of the interpretation of the results that can be obtained by the various proposed tests.

3.2.1 Mini-flow test

The mini-flow test is used to understand how the fine particles interact with water and conditioning agent and it gives information about the characteristics of the lubricating paste that remains between the clay chips (Galli & Thewes, 2014; Peila et al., 2016). It allows to get simple comparisons between the various conditioning agents and different amounts of water content. The assessment is done in a qualitative way by checking if there is a homogeneous widening of the mini-slump. This test allows to compare the action of different types of conditioning agents on a clay powder on a small scale to make a preliminary choice, while the conditioning sets (i.e., amount of the conditioning agent as a foam) is done using the other types of tests described in the following.

3.2.2 Flow table test

The flow table test gives indications about the behaviour of the clay clumps when mixed with foam and, eventually, polymers. The assessment requires that the material flows in a regular way during the test, and it does not show a rigid behaviour.

3.2.3 Slump test

This test involves a larger amount of conditioned mass made of clay clumps than the flow table test. In the test, the following technical aspects are taken into account: a good plasticity of the conditioned mass after the lifting of the cone and after the jolting (that is assessed by observing the homogeneity and measuring the lowering of the cone itself), the homogeneous flow of the mass during the jolting and the minimal release of water and foam from the conditioned mass. The behaviour of the conditioned mass during and after the jolting process is considered important for the assessment since it allows to understand if the conditioning permits the lessening of the material stickiness and the regular flow in the chamber. A value of slump, after jolting, of the order of 15–25 cm can be considered as a reference.

3.2.4 Dynamic adhesion test

This test allows to compare different conditioning sets by considering the values of the measured torque and the torque trend during the test. If the torque value grows during the test, this is an index that the material has a potential to reconsolidate in the chamber.

4 Carried out tests

To verify the feasibility of the proposed procedure and the quality of the obtained results, a set of tests on two different clays have been carried out and two different conditioning agents have been used.

4.1 Used materials

For each clay, two different soil samples have been prepared and used:

(1) dry crushed clay, herein called "DCC", obtained by drying the clay in an oven following the geotechnical standards and then crushing it using a laboratory crusher. This procedure has been used to prepare the samples for the mini-flow test;
(2) clay chips with a grain size of 1–2 cm, herein called "NCC", obtained by manually separating the clay mass into chips (the average density of this soil, as measured by filling a tank of known volume with the chips without any compaction, is about 1.9 kg/L).

Figure 5 reports the grain size curve of the two samples for the two clays. The clay A has a natural water content of 22% (by weight), while clay B has a natural water content of 5% (by weight).

Table 2
Atterberg's limits of clay A and clay B.

Clay	Liquid limit (LL)	Plastic limit (LP)	Plastic index (LL-LP)
A	44%	20%	24%
B	43%	25%	18%

The Atterberg's limits are reported in Table 2, and the positions of the two clays on the clogging assessment diagram proposed by Hollmann and Thewes (2013) are reported in Fig. 6.

4.2 Used conditioning agents

Two different types of foaming agents have been used in the tests:

CSA1: a standard foaming agent, made up of surfactant (SLES) at a concentration in water ranging from 10% to 20% by weight;
CSA2: the same foaming agent made up of a surfactant (SLES) at a concentration in water ranging from 10% to 20% by weight, with the addition of a new type of polymer specifically designed for clay conditioning (anti-stickiness). The product is marketed by the Mapei Group with the commercial name of Polyfoamer FLS.

When used, the foam with both the conditioning agents has been produced with the following parameters: the surfactant concentration in the generation fluid is 2.0% by weight and the foam expansion ratio is 8.

The foam has been produced using the foam generator described by Vinai et al. (2008), which allows to obtain foam with properties very close to those of the foam produced in an EPB machine.

5 Test campaign on clay A

5.1 Results of the mini-flow test

Tests 1, 2, and 3 have been carried out on the soil with a water content of 50% by weight. From the results of all

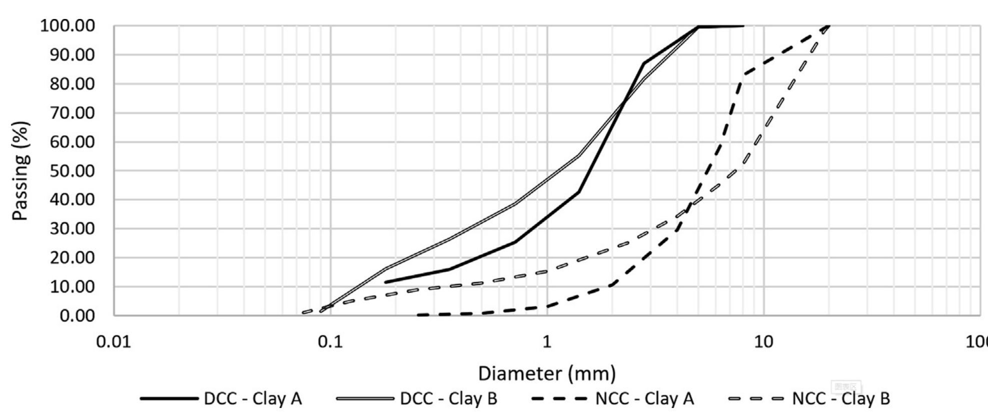


Fig. 5. Grain size distribution of clay A and B.

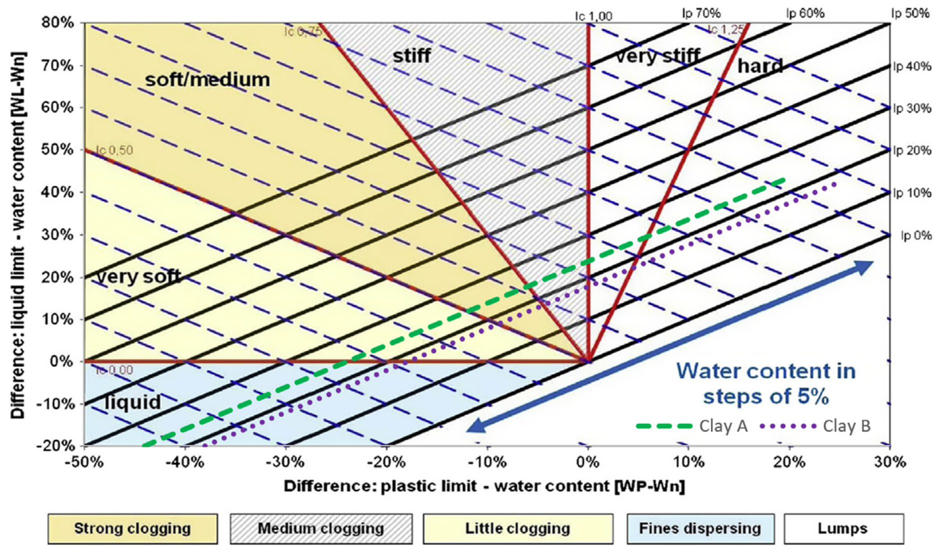


Fig. 6. Position of the two studied clay with variable water content reported on the clogging assessment diagram proposed by Hollmann and Thewes (2013).

Table 3
Results of the mini-flow test performed on clay A.

Parameters	Test							
	1	2	3	4	5	6	7	8
Added water (percentage in weight with reference to the soil) (%)	50	50	50	60	60	60	40	40
Conditioning agent content (g)	–	1	1	–	1	1	1	1
(Percentage of the added water in weight) (%)		(2%)	(2%)		(1.7%)	(1.7%)	(2.5%)	(2.5%)
Conditioning foaming agent	–	CSA1	CSA2	–	CSA1	CSA2	CSA1	CSA2
Φ (diameter of the slump) (mm)	44	53	66	76	94	91	45	66
H (height of the slump) (mm)	51	29	21	18	11	11	40	18
Percentage of widening with reference to the original truncated cone diameter (%)	0	20	50	73	114	107	2	50
Percentage of lowering of the sample with reference to the original truncated cone height (%)	15	52	65	70	82	82	33	70

mini-flow tests (Table 3), it is possible to compare the behaviour of the soil without conditioning agents and with the conditioning agent. Although both the conditioned samples show good results in terms of obtained widening and lowering, the sample conditioned with CSA2 is less rigid than the one conditioned with CSA1. Tests 4, 5, and 6 have been carried out on the soil with a water content of 60% by weight. Those tests show a comparison between the behaviour of the soil without conditioning agents, with CSA1 and with CSA2. Even though 60% of water gives to the soil very high flowability, the sample conditioned with CSA2 shows higher widening than the one conditioned with CSA1. From these results, it can be concluded that the use of both conditioning agents gives to the soil higher flowability than that using only water. Tests 7 and 8 have been carried out on the soil with a water content of 40% by weight. Although both the conditioned samples show good results in terms of obtained widening and lowering, the sample conditioned with CSA2 is less rigid than the one conditioned with CSA1.

Furthermore, it is possible to observe that the new type of conditioning foaming agent CSA2 chemically designed with addition of a special polymer, leads to the better flowability of the clay with less water content (as shown in Table 4).

5.2 Results of the flow table test

The results of these tests confirm the results obtained with the mini-flow test: the conditioning foaming agent CSA2 can better improve the fluidity of the conditioned clay with reference of the action of the conditioning agent CSA1 (as shown in Table 5).

For all the performed tests, the measured values of Φ_{BJ} and h_{BJ} were of 100 mm and 60 mm respectively.

With a water content of 50% and FIR = 50%, the conditioning agent CSA2 improves the widening of the slump diameter from 18% (obtained with CSA1) to 28%, while with FIR = 80% the widening of the slump diameter increases from 32% to 43%. Slump photos of the flow table test performed on clay A are depicted in (Table 6).

5.3 Results of the slump test

The carried-out tests show that with the chosen set of conditioning parameters with both the conditioning agents, it is always possible to get good quality conditioning of the studied clay. The conditioning agent CSA2 improves the technical performances, in terms of better fluidity and pulpy behaviour of the conditioned clay.

The procedure highlights the effect of time on conditioned soil (Slump A and Slump B). The conditioned material with CSA2 shows an improvement of the pulpy behaviour in time, which is different from the conventional conditioning agents. This effect can be useful in EPB tunnelling when the material is inside the chamber. The results of the slump test and the test data are summarised in Tables 7 and 8. It is important to highlight that according to the slump test campaign, a good conditioning is obtained with a less amount of water content compared to the flow table assessment (Table 5), even if the used amount of foam (FIR) was the same. This result is linked to the shorter time of mixing (i.e., the less amount of mixing energy added to the soil). Since the machine cutterhead has a slow motion, the results of the slump tests can be considered more representative at a large-scale test such as this one.

In Test 1, the conditioned soil shows a behaviour influenced by time as can be seen comparing Slump A and B

Table 4
Photos of the mini-flow test performed on clay A.

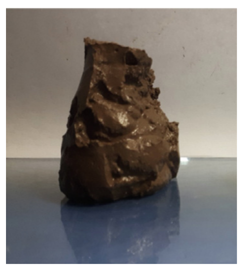
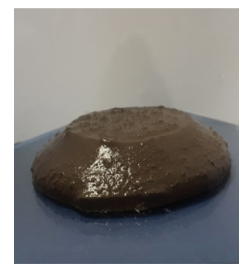
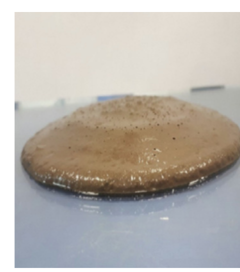
Test 1 $w = 50\%$ No foaming agent		Test 4 $w = 60\%$ No foaming agent	
Test 2 $w = 50\%$ CSA 1		Test 5 $w = 60\%$ CSA 1	
Test 3 $w = 50\%$ CSA 2		Test 6 $w = 60\%$ CSA 2	
Test 7 $w = 40\%$ CSA 1		Test 8 $w = 40\%$ CSA 2	

Table 5
Results of the flow table test performed on clay A.

Parameters	Test			
	1	2	3	4
Amount of clay (g)	500	500	500	500
Water content (percentage in weight with reference to the soil) (%)	50	50	50	50
Conditioning foaming agent	CSA1	CSA2	CSA1	CSA2
FIR (%)	50	50	80	80
Φ_{AJ} (mm)	118	128	132	143
h_{AJ} (mm)	47	42	40	28
Percentage of widening with reference to the original truncated cone diameter after jolting (%)	18	28	32	43
Percentage of lowering of the sample with reference to the original truncated cone height after jolting (%)	30	22	33	53

Table 6
Slump photos of the flow table test performed on clay A.

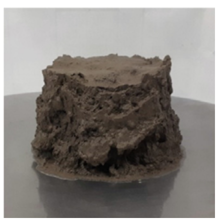
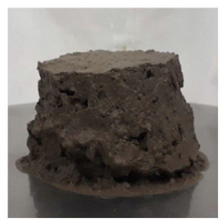
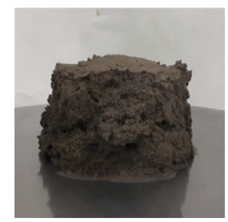
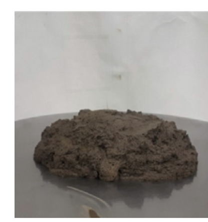
	Test 1	Test 2	Test 3	Test 4
Before jolting				
After jolting				

Table 7
Results of the standard slump test performed on clay A.

Parameters	Test	
	1	2
Water content as percentage in weight with reference to the soil, w (%)	35	35
Conditioning foaming agent	CSA1	CSA2
FIR (%)	50	50
Drop of Slump A (mm)	150	150
Drop of Slump B (mm)	30	120
Drop of Slump C (mm)	190	220
Average diameter of the slump after the 15 jolting (mm)	380	400

(time interval between the execution of the two tests is of about 15 min). After 15 jolts there is a separation between the foam, the finer grains of the sample and the chips. The material is medium-well conditioned with an average pulpy behaviour.

Also in Test 2, the conditioned soil shows a behaviour that is influenced by time as can be seen comparing the slump cone shapes A and B. The mix is always well conditioned with a pulpy behaviour changing with time: average in test A, good-average in test B, and very good in test C. This fact is probably due to the time action of the polymer inserted in the foaming agent.

The conditioned soil after both test A and test B shows better conditioning than Test 1 in terms of higher pulpy behaviour and less rigid slump. After the 15 jolts, the separation between the foam, the finer parts and the chips is really limited and the material is well conditioned.

5.4 Results of the dynamic adhesion test

The tests were carried out with the same conditioning sets of test 1 and test 2 reported in Table 7, and the results are reported in Fig. 7.

It is possible to observe that at the end of the test, the torque measured with the conditioning agent CSA1 is 6.5 N•m, while that with the conditioning agent CSA2 is 3 N•m with a reduction of more than 50%.

Table 8
Photos of the standard slump test performed on clay A.

	Slump A	Slump B	Slump C
Test 1			 After jolting
Test 2			 After jolting

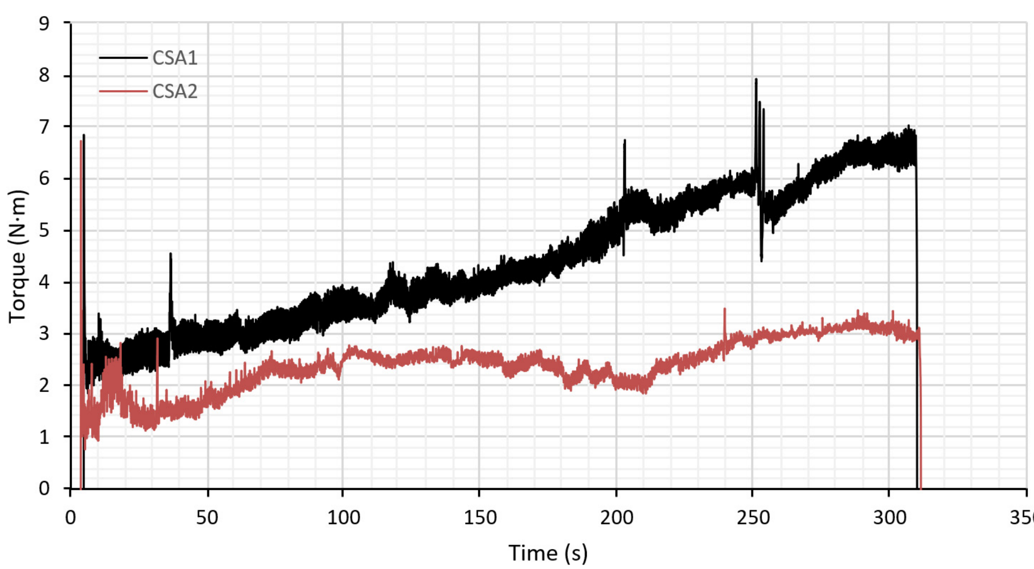


Fig. 7. Measurement of the torque on the disk during the dynamic adhesion test on clay A.

Table 9
Results of the mini-flow test performed on clay B.

Parameters	Test								
	1	2	3	4	5	6	7	8	9
Added water as percentage by weight with reference to the soil, w (%)	70	60	60	60	50	50	50	65	65
Conditioning agent content (g)	–	–	1	1	–	1	1	1	1
(Percentage of the added water by weight) (%)			(1.7%)	(1.7%)		(2%)	(2%)	(1.5%)	(1.5%)
Conditioning foaming agent	–	–	CSA1	CSA2	–	CSA1	CSA2	CSA1	CSA2
Φ (diameter of the slump) (mm)	96	62	63	69	49	52	59	84	88
H (height of the slump) (mm)	8	27	21	17	42	38	27	12	11
Percentage of widening with reference to the original truncated cone diameter (%)	118	40	42	56	11	19	33	90	100
Percentage of lowering of the sample with reference to the original truncated cone height (%)	86	55	64	72	29	37	54	81	81

Also it is important to highlight that when using the CSA2 the torque is about constant througth all the test, while with CSA1 there is a significant increase of the torque value.

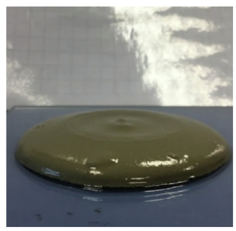
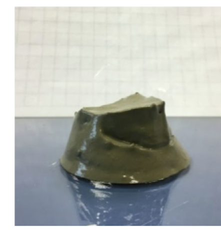
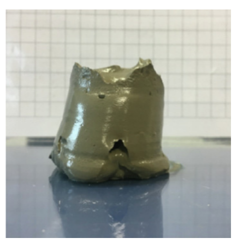
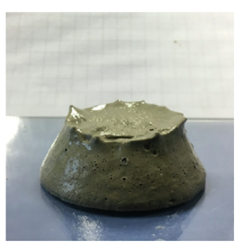
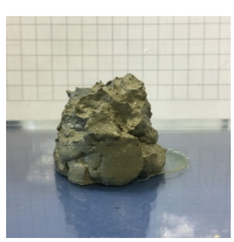
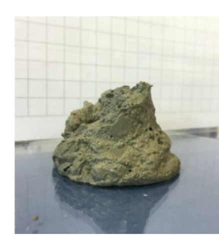
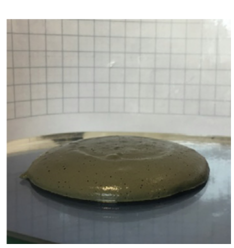
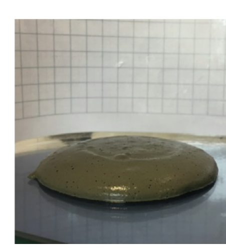
These results are in good agreement with the previous ones. When using CSA1 the torque value has the tendency to increase its behaviour, while CSA2 shows a much more stable behavior during the test time.

6 Test campaign on clay B

6.1 Results of the mini-flow test

Test 1 has been performed with a water content equal to 70% of the soil but without the addition of conditioning agents, while tests 2, 3, and 4 have been carried out on the soil with a water content of 60% by weight but with

Table 10
Photos of the mini-flow test performed on clay B.

Test 1 $w = 70\%$ No foaming agent		Test 2 $w = 60\%$ No foaming agent	
Test 5 $w = 50\%$ No foaming agent			
Test 3 $w = 60\%$ CSA 1		Test 4 $w = 60\%$ CSA 2	
Test 6 $w = 50\%$ CSA 1		Test 7 $w = 50\%$ CSA 2	
Test 8 $w = 65\%$ CSA 1		Test 9 $w = 65\%$ CSA 2	

conditioning agents (Tables 9 and 10). The sample conditioned with CSA2 shows good results in terms of obtained widening and lowering, while the sample conditioned with CSA1 shows a slight increase of widening and lowering compared to the one conditioned only with water but lower than those conditioned with CSA2.

Tests 5, 6, and 7 have been carried out on the soil with a water content of 50% by weight, and the results are in good agreement with those of tests 1, 2, and 3 showing how the samples conditioned with CSA2 are less rigid than those conditioned with CSA1.

6.2 Results of the flow table test

The results of these tests confirm those obtained with the mini-flow test even if the conditioning agent is added in form of foam to the clay. The conditioning foaming agent CSA2 can better improve the fluidity of the conditioned clay with reference of the action of the conditioning agent CSA1, but both CSA2 and CSA1 show better improvement of the behaviour compared with the use of water only (Tables 11 and 12). For the tests 1, 2, and 3, the measured values of Φ_{BJ} and h_{BJ} were of 100 mm and 60 mm respectively, while for test 4 the measured values of Φ_{BJ} and h_{BJ} were of 105 mm and 50 mm respectively. With a water content of 35% and FIR = 80%, the conditioning agent CSA2 improves the widening of the slump diameter from 29% (obtained with CSA 1) to 58%, while with FIR = 50% the widening of the slump diameter increases from 67% to 79%.

6.3 Results of the slump test

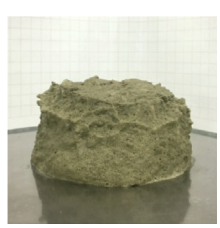
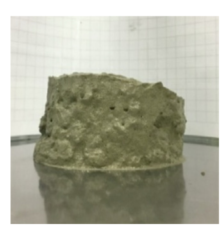
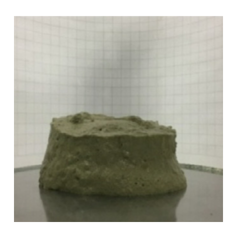
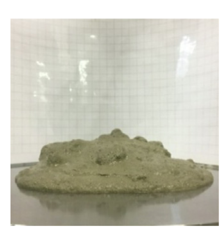
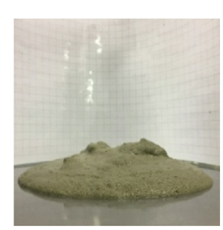
The slump tests have been performed using the conditioning parameters of Table 13. The tests have shown that the pulpy consistency can be obtained by conditioning done with water and foam (with a FIR of 50%), but only after the jolting of the slump, the drop can be considered acceptable (see Table 14).

Furthermore, it is possible to see that the conditioning agent CSA2 improves the widening of the final slump diameter and the quality of the mass. The obtained results are in good agreement with those of the flow table test.

Table 11
Results of the flow table test performed on clay B.

Parameters	Test			
	1	2	3	4
Amount of clay (g)	500	500	500	500
Water content (as percentage by weight with reference to the soil) (%)	35	35	45	45
Conditioning foaming agent	CSA1	CSA2	CSA1	CSA2
FIR (%)	80	80	50	50
Φ_{AJ} (mm)	129	158	167	184
h_{AJ} (mm)	37	29	28	27
Percentage of widening with reference to the original truncated cone diameter after jolting (%)	29	58	67	84
Percentage of lowering of the sample with reference to the original truncated cone height after jolting (%)	39	52	52	55

Table 12
Photos of the flow table test performed on clay B.

	Test 1	Test 2	Test 3	Test 4
Before jolting				
After jolting				

In Test 1, the conditioned soil appears stiff both in slump cone A and B, despite the good pulpy behavior of the soil. After 15 jolts the slump increases and the conditioned soil appears more uniform. The material has average conditioning with a pulpy behavior.

In Test 2, the conditioned soil appears stiff both in Slump A and B, despite the good pulpy behavior of the soil. After 15 jolts the slump increases and the conditioned soil appears uniform. The material is well conditioned with a pulpy behavior. Also in this case (as for Clay A) it is

Table 13
Results of the standard slump test performed on clay B.

Parameters	Test	
	1	2
Water content of percentage by weight with reference to the soil, *w* (%)	30	30
conditioning foaming agent	CSA1	CSA2
FIR (%)	50	50
Slump A (mm)	10 (broken cone and rigid mix)	10 (rigid mix)
Slump B (mm)	10 (rigid mix)	10 (rigid mix)
Slump C (mm)	200	220
Average diameter of the slump after the 15 jolts (mm)	280	370

Table 14
Photos of the standard slump test performed on clay B.

	Slump A	Slump B	Slump C
Test 1			 After jolting
Test 2			 After jolting

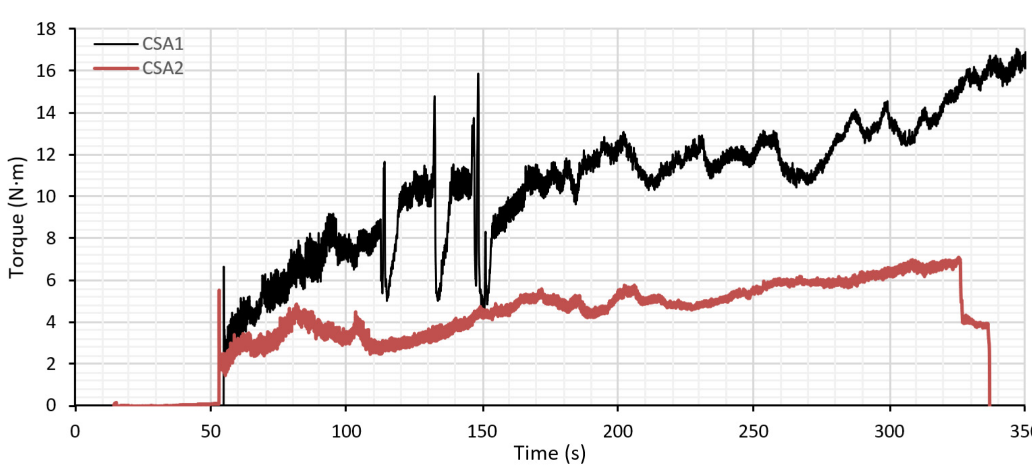


Fig. 8. Measurement of the torque on the disk during the dynamic adhesion test on clay B.

important to highlight that according to the slump test campaign, a good conditioning is obtained with a less amount of water content compared to the flow table assessment (Table 11).

6.4 Results of the dynamic adhesion test

The tests were carried out with the same conditioning sets of tests 1 and 2 reported in Table 13, and the results are reported in Fig. 8.

It is possible to observe that at the end of the test the torque measured with the conditioning agent CSA1 is 16 N•m, while that with the conditioning agent CSA2 is about 6 N•m with a reduction of 69%. Again as for clay A the conditioning with CSA2 allows to keep the torque about constant during the whole test time, while the CSA1 shows a significant increase of the torque.

These results are in good agreement of the previous ones showing the different effects of conditioning of the two tested agents. Furthermore, when using CSA1 the torque value has the trend to increase its behaviour, while CSA2 shows a much more stable behaviour during the test time.

7 General conclusion on the proposed test methodology

Testing and assessement of the conditioning of clay for EPB tunnelling is a complex task and many researchers have proposed different procedures. To make a complete assessement of clay for EPB tunnelling, it is necessay to consider tests on both powderized clay and clay clumps. It is of interest of the designer and the industry to have a standarized procedure able to assess the effects of conditioning on both powderized clay and clumps. In the previous sections, a simple test procedure obtained merging different tests has been proposed and discussed. This scheme allows a complete overview of the effect of conditioning agents on clay and could help the designer to make a proper conditioning choice.

The first two tests must be considered as a preliminary step in the conditioning assessment, and they could address to the choice of the best product to be used by allowing an easy comparison of many different products: the higher the widening and lowering percetnages are, the greater the effect of the tested product on the clay sample is. In order to carry out a suitable choice, both tests must provide a positive results. The mini-flow test gives an indication on how the clay powder reacts with the addition of variable percentages of water and different conditioning agents. Since this test is simple and quick, and it requires a limited amount of clay, a lage number of tests can be carried out to compare various products.

The flow table is used to preliminarily assess the behavior of the clay clumps with foam with a test that again requires a limited amount of foam. As in the case of mini-flow test, high widening and lowering percentages after jolts (for fixed conditioning parameters) are index of a good condtioning product.

The other two tests (i.e., slump test and dynamic adhesion test), should confirm and integrate the preliminary test results. The slump tests provide indication on how a resonable amount of clay clumps mixed in a limited time (as it occures in the EPB machine) behaves and if the mass releases the foam. The slump test result is considered positive if there is no significant release of water and foam from the mass, the global behavior of the conditioned sample is plastic and well homogenized, and the material has good flowability during the jolting. It should anyway remarked that the analysis of the slump test results requires an evaluation by experts, since the quantity of variants that have to be taken into account is very large.

Finally, the dynamic adhesion test provides indication concerning the potential reconsolidation process related to conditioned clay chips. The reconsolidation process can be recognized if there is an increasing trend of the torque in function of the time. Lastly, this test permit to compare the behaviour of different conditioning sets with an immediate comparison of the measured torque.

If these results are not satisfactory, the researhers can use the screw conveyor test described by Vinai et al. (2008), which simulates the EPB machine behavior in the best way, but requires a large amount of clay to be carried out.

The proposed procedure has been applied on two different types of clays using two different commercial conditioning agents. The obtained results have shown that the data obtained with the different tests are consistent, and they allow a very good comparison between different conditioning sets and different conditioning products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank Dr. Dal Negro, Ing. E. Boscaro, Ing. Barbero and Dr. Stefanoni and the Mapei UTT company for their technical and logisitic supports of this research.

This research was supported with Prof. Peila's research found of Politecnico di Torino (finanziamento diffuso).

Authorship contribution statement

Conceptualization and development of the laboratory tests and analysis of the results: Todaro, C., Carigi, A., and Peila, L.; writing the original draft: Todaro, C. and Peila, L.; text review: Martinelli, D. and Peila, D., writing final text: Todaro, C., Carigi, A. and Peila, D.; work supervision and founding: Peila, D. All authors have read and agreed to the published version of the manuscript.

References

Alberto-Hernandez, Y., Kang, C., Yi, Y., & Bayat, A. (2017). Clogging potential of tunnel boring machine (TBM): A review. *International Journal of Geotechnical Engineering, 12*(3), 316–323.

Borio, L., & Peila, D. (2011). Laboratory test for EPB tunnelling assessment: Results of test campaign on two different granular soils. *Gospodarka Durowcami Mineralnymi, 27*, 85–100.

CEN (2016). *Methods of testing cement - part 1: determination of strength*. EN 196–1:2016. European Committee for Standardization, Bruxelles (B)

CEN (2009). *Testing fresh concrete - Part 2: Slump-test*. EN 12350-2:2009. European Committee for Standardization, Bruxelles (B)

Feinendagen, M., Ziegler, M., Azzam, R., Spagnoli, G. & Andferna ´Ndez-Steeger, T. (2010). Ein neues Verfahren zurBewertung des Verklebungspotenzials beim maschinellenTunnelvortrieb mit Erddruckschilden. In: Proceedings of the 31 st Baugrundtagung: pp. 103–110 (in German)

Galli, M., & Thewes, M. (2019). Rheological Characterisation of Foam-Conditioned Sands in EPB Tunneling. *International Journal of Civil Engineering, 17*(1), 145–160.

Galli, M., & Thewes, M. (2014). Investigations for the application of EPB shields in difficult grounds. *Geomechanics and Tunnelling, 7*(1), 31–44.

Garroux de Olivera, D., Thewes, M., Diederichs, M., & Langmaack, L. (2018). EPB tunnelling through clay-sand mixed soils: Proposed methodology for clogging evaluation. *Geomechanics and Tunnelling, 11*(4), 375–387.

Garroux de Olivera, D., Thewes, M., Diederichs, M., & Langmaack, L. (2019). Consistency Index and Its Correlation with EPB Excavation of Mixed Clay-Sand Soils. *Geotechnical and Geological Engineering, 37*(1), 327–345.

Kang, C., Zhou, Y. , & Bayat, A. (2021). Improved index to quantitatively assess clogging potential based on mixing test results. *Tunnelling and Underground Space Technology*, In Press, 104251. https://doi.org/10.1016/j.tust.2021.104251

Hollmann, F., & Thewes, M. (2012). Evaluation of the tendency of clogging and separation of fines on shield drives. *Geomechanics and Tunnelling, 35*(5), 574–580.

Hollmann, F., & Thewes, M. (2013). Assessment method for clay clogging and disintegration of fines in mechanized tunneling. *Tunnelling and Underground Space Technology, 37*, 96–106.

Langmaack, L., & Feng, Q. (2005). Soil conditioning for EPB machines: Balance of functional and ecological properties. In *Procedings of the WTC 2015: Underground Space: Analysis of the Past and lesson for the Future* (pp. 729–735). Istanbul: Taylor & Francis.

Mori, L., Mooney, M., & Cha, A. (2018). Characterizing the influence of stress on foam conditioned sand for EPB tunnelling. *Tunnelling and Underground Space Technology, 71*, 454–465.

Peila, D., Oggeri, C., & Borio, L. (2009). Using the slump test to assess the behavior of conditioned soil for EPB tunneling. *Environmental and Engineering Geoscience, 15*(3), 167–174.

Peila, D., Picchio, A., Martinelli, D., & Dal Negro, E. (2016). Laboratory tests on soil conditioning of clayey soil. *Acta Geotecnica, 11*(5), 1062–1074.

Peila, D., Picchio, A., & Chieregato, A. (2013). Earth pressure balance tunnelling in rock masses : Laboratory feasibility study of the conditioning process. *Tunnelling and Underground Space Technology, 35*, 55–66.

Peña, M. (2003). Soil conditioning for sands. *Tunnels & Tunnelling International, 35*(7), 40–42.

Peron, J.Y., & Marcheselli, P. (1994). Construction of the 'Passante Ferroviario' link in Milan, Italy, lots 3P, 5P, and 6P: excavation by large EPBS with chemical foam injection. *Tunnelling '94*, London, 5–7 July 94, Chapman & Hall, 679–707.

Psomas, S. (2001). *Properties of sand/foam mixtures for tunneling application* [Master's thesis, University of Oxford].

Quebaud, S., Sibai, M., & Henry, J. P. (1998). Use of chemical foam for improvements in drilling by earth-pressure balanced shields in granular soils. *Tunnelling and Underground Space Technology, 13*(2), 173–180.

Sass, I., & Burbaum, U. (2009). A method for assessing adhesion of clays to tunneling machines. *Bulletin of Engineering Geology and the Environment, 68*(1), 27–34.

Thewes, M. (1999). Adhäsion von Tonböden beim Tunnelvortrieb mit Flüssigkeitsschilden (Adhesion of clay soil during tunneling with liquid shields) [Doctoral dissertation, University of Wuppertal] (in German),

Thewes, M., & Burger, W. (2005). Clogging of TBM drives in clay – identification and mitigation of risks. In *Proceedings of the WTC 2005: Underground Space Use: Analysis of the Past and Lessons for the Future*, Taylor & Francis, 737–742.

Thewes, M., Budach, C., & Bezuijen, A. (2012). Foam conditioning in EPB tunnelling. In G. Spagnoli, M. Feinendegen, R. Ernst, & M. Weh (Eds.), *Geotechnical Aspects of Underground Construction in Soft Ground* (pp. 127–135). CRC Press.

Vinai, R., Oggeri, C., & Peila, D. (2008). Soil conditioning of sand for EPB applications: A laboratory research. *Tunnelling and Underground Space Technology, 23*, 308–317.

Zimnik, A. R., Lennart, R. van Baalen, Peter, N.W., Verhoef, D., & Ngan-Tillard, J.M. (2000). The Adherence of Clay to Steel Surfaces. *GeoEng 2000: An International Conference on Geotechnical and Geological Engineering*. Melbourne, Australia.

Zumsteg, R., Plötze, M., & Puzrin, A. M. (2012). Effect of soil conditioners on the pressure and rate-dependent shear strength of different clays. *Journal of Geotechnical and Geoenvironmental Engineering, 138*(9), 1138–1146.

Zumsteg, R., Plötze, M., & Puzrin, A. (2013a). Reduction of the clogging potential of clays: New chemical applications and novel quantification approaches. *Géotechnique, 36*(4), 276–286.

Zumsteg, R., Plötze, M., & Puzrin, A. M. (2013b). Effects of dispersing foams and polymers on the mechanical behaviour of clay pastes. *Géotechnique, 63*(11), 920–933.