Tunnel excavation with EPB: Development of new conditioning agents to reduce the amount of water required for soil conditioning

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Tunnel excavation with EPB: Development of new conditioning agents to reduce the amount of water required for soil conditioning

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ABSTRACT: Tunnel excavation with TBM requires large amounts of water that are necessary for several different applications. When EPB machines are used, an important contribution to the water consumption is due to the soil conditioning, in particular when the excavation is in cohesive formations. The proper amount of liquids necessary for the soil conditioning depends on several aspects (such as geology, type of conditioning agents used, configuration of the TBM, earth pressure applied at the tunnel face, etc.), however values of WIR (Water Injection Ratio = Volume of pure added water/Volume of soil excavated) in the range of 10%-30% are common.

The development of new conditioning agents allows to significantly reduce these amounts of water. The laboratory of the University "Politecnico di Torino" carried out a thorough campaign of tests using a reference clay, whose results show that new conditioning agents allow to save water in a range between 20 and 33% compared to the traditional products. This reduction of the WIR means thousands of tons of water saved for tunnel excavation, with consequent advantages under several points of view: technical, economical, and environmental. The reduction of water means lower volume of tunnel muck, less trucks necessary to transport the muck to its destination, which means lower CO_2 emissions due to downscaled logistics, etc. All these advantages are more and more relevant nowadays, especially in those countries where water has become a precious and scarce resource.

The paper describes the tests carried out and obtained results.The advantages of these new conditioning agents are presented in detail and contextualized in the view of a sustainability approach in tunnel construction.

Keywords: Tunnelling, TBM, EPB, Soil conditioning, New products, Water, Environment

1 INTRODUCTION

Mapei S.p.A., is at the forefront of innovation in sustainable TBM operations by developing new products capable of reducing the environmental impact of mechanized tunnelling. This has resulted in a wide range of products dedicated to reducing the amount of CO_2, emissions and the overall environmental impact of a TBM project.

As is well known, water is a very valuable resource and an increasingly rare commodity, which in the later years is demanding an increase in sensibility regarding the way it is utilised, especially in territories where its scarcity makes it even more of a precious asset to be carefully managed.

TBM tunnelling, similarly to many other industrial processes, requires a massive amount of water to be performed. The non-contaminated portion of water employed in mechanized tunnelling jobsites is continuously re-used during the activity, such as the water used for the cooling systems of the TBM. Part of the water is instead lost into the muck, such as the groundwater extracted during the excavation or the large water quantities which are necessary for soil conditioning during the excavation itself, especially when cohesive grounds are excavated.

The main issue stands in the fact that some soils, in order to be excavated with EPBs, require large amounts of liquid to be added, either as pure water (defined by the parameter of WIR = Water Injection

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Ratio) or in foam generation. Moreover, greater values of WIR are generally required in order to condition cohesive soils with particularly high stickiness, such as clays, mudstone, shale, etc.

Since soil conditioning constitutes the greater part of the water needs of these jobsites, reducing the environmental impact of soil conditioning can also be linked to reducing the amount of water used in TBM tunnelling projects.

1.1 *Creating a new type of soil conditioning agent*

As part of Mapei's Water Saving Program (WSP), a new range of products have been specifically introduced to allow for a reduction of the WIR parameter.

In this paper we will describe the experimental phase of Polyfoamer ECO WSP and Mapedisp ECO WSP when applied in comparison with a reference soil conditioning product.

In detail, the following chapters have been produced to describe the operational methods for carrying out laboratory tests aimed at the characterisation of a clay extracted from a quarry near Reggio Emilia, in accordance with the technical partenership between DIATI of the Politecnico di Torino and Mapei S.p.A.

The new generation products were designed and manufactured with a view to achieving good conditioning of the clays by reducing the amount of water required by the soil to be conditioned.

The laboratory tests performed are:

- Mini flow test.
- Mini slump and flow table test.
- Slump test.
- Dynamic adhesion test.

1.2 *Reference nomenclature*

The following nomenclature for technical parameters has been adopted throughout the entire experimental phase.

w_n (%) – natural water content, computed on the dry weight of the soil;

w_{add} (%) – additional water content, calculated on the dry weight of the soil;

w_{tot} (%) – total water content, calculated on the dry weight of the soil;

c w/w (%) – concentration of the solution calculated as weight of conditioning agent per 100 g of soil;

c v/v (%) – volume concentration of foaming agent on volume of generating liquid;

φ_{BJ} (mm) – base diameter of the sample in the mini slump test, before application of the jolts;

φ_{AJ} (mm) – base diameter of the sample in the mini slump test, after application of the jolts;

h_{BJ} (mm) – height of the sample in the mini slump test, before application of the jolts;

h_{AJ} (mm) – height of the sample in the mini slump test, after application of the jolts;

w_{saved} (%) – amount of water saved. Percentage value computed on the w_{add} value of the considered conditioning and the w_{add} value of the reference soil conditioning;

T (Nm) – average torque value, calculated in the dynamic adhesion test.

For the calculation of water contents, percentage values are rounded. Values with a decimal part greater than or equal to 0.5 are rounded up, values with a decimal part less than 0.5 are rounded down.

2 UTILIZED MATERIALS

The purpose of the experimentation described in this report is to study, by means of laboratory tests, the conditioning of "Reggio" clay using specific conditioning agents for clays. Specifically, 3 different soil conditioning agents supplied by Mapei S.p.A. have been tested, defined as follows:

- reference conditioning agent - "REF";
- next-generation conditioning agent - "Polyfoamer ECO WSP";
- next-generation additive - "Mapedisp ECO WSP".

Both the soil conditioning products as well as the clay used in the experimental phase will be described thoroughly in the following paragraphs.

2.1 *"Reggio" clay*

The clay soil used for the experiments was supplied to the Tunnels & Underground Space Research Center of the Turin Polytechnic University directly by Mapei S.p.A., in hermetically sealed containers carrying a total of approximately 400 kg of material. The mineralogical analysis, certified by the supplier (Movimento Terra e Trasporti Ruggi) of the clay and carried out semi-quantitatively by XRD spectrometry showed the following composition:

- Clay Material: 43%
- Feldspar: 19%
- Quartz: 35%
- Other: 3%

The Atterberg limits are instead:

- Liquid limit: 54%
- Plastic limit: 30%

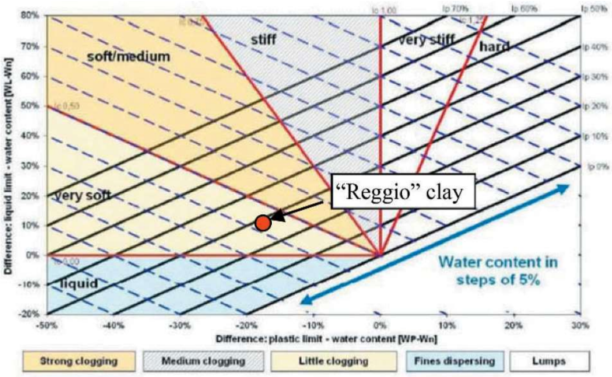

Figure 1. Thewes graph for "Reggio" clay.

Further analysis based on the Atterberg limits and the natural water content equal to 13%, shows that "Reggio" clays could be classified as prone to clogging risk, as shown in Figure 1.

The material was then processed in order to make it suitable for the planned tests.

Specifically, two different types of clays were produced:

- dry crushed clay (w_n = 0 %), hereinafter referred to by the acronym "DCC"
- chip clay (w_n = 12.6 %), hereinafter referred to by the acronym "NCC".

Figure 2. Clay samples used in the laboratory for the test campaign. DCC (left) e NCC (right). The difference in color is due to the different water content in the samples.

The two variants of clay material employed in the tests can be seen in Figure 2, while their particle size distributions are shown in Figure 3.

2.2 *Conditioning agents*

Conditioning agents play a key role for the correct conditioning of soils, expressly in clayey ones (Peila et al., 2016). For this testing campaign, three different specific conditioning agents for clays were used in addition to water taken from the water network of the metropolitan city of Turin. Specifically:

a) "REF" (reference) conditioning agent. "Traditional" foaming agent, formulated with anionic surfactants of the SLES (Sodium-Lauryl -Ether-Sulphate) type, characterised by the following chemical composition reported on the safety data sheet in section 3: alcohols, C12-14, ethoxylates, sulphatates, sodium salts; CAS number: 68891-38-3, 500-234-8; Concentration: ≥ 10% - < 20%;
b) "Polyfoamer ECO WSP" conditioning agent. Next generation foaming agent, formulated with the aim of reducing the amount of water required in comparison to 'traditional' foaming agents;
c) "Mapedisp ECO WSP" additive. A next-generation dispersing additive, to be used in combination with foam to further reduce the amount of water required for conditioning.

3 LABORATORY TEST CAMPAIGN

The two types of tests carried out on the conditioned samples, namely Mini Flow tests and Mini Slump/Flow Table tests, will be described in detail in the following paragraphs.

3.1 *Mini flow tests*

The mini flow test campaign was performed according to the procedure described in the article published in an international scientific journal: C. Todaro, A. Carigi, L. Peila, D. Martinelli, D. Peila, Soil conditioning tests of clay for EPB tunnelling, Underground Space, Volume 7, Issue 4, 2022, Pages 483-497, ISSN 2467-9674.

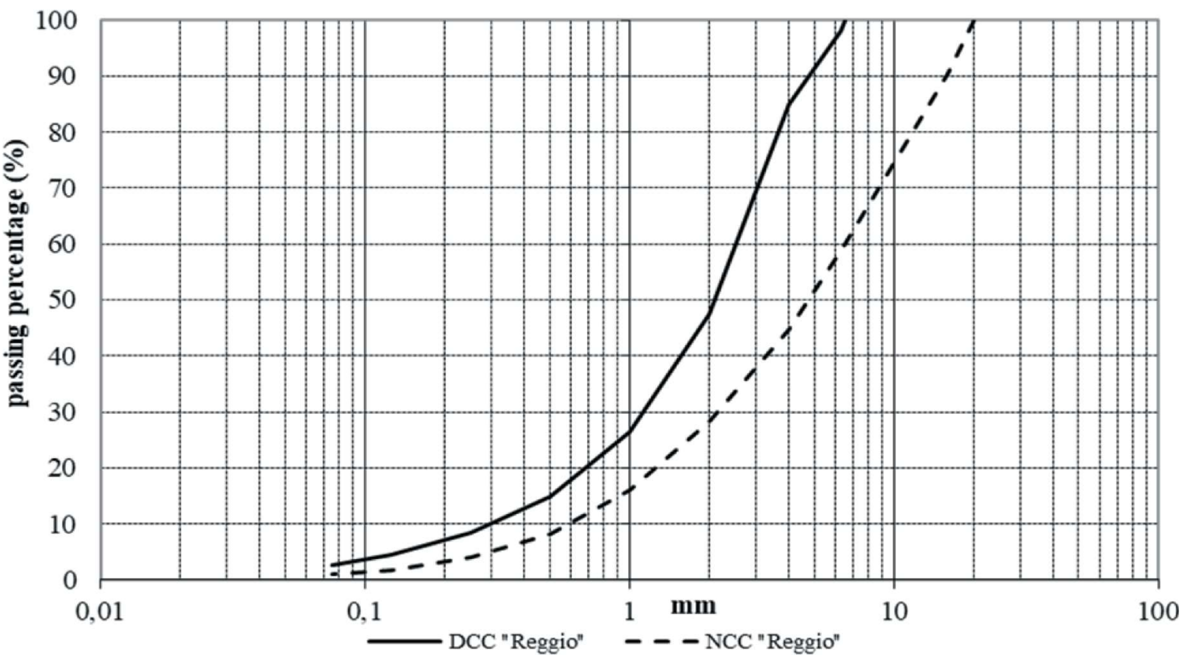

Figure 3. Grain size distributions of the clay samples used for the test campaign.

Mini flow" tests have been recently introduced into the scientific literature and laboratory experimental practises for the characterisation of conditioned clays. These tests involve the use of a mini-cone (Figure 4), a scale reduction of the one used for slump tests (CEN 2009).

The cone base diameter is 44 mm, while its height is 66 mm.

Table 1. Mini flow tests results for "Reggio" clay.

ID	Conditioning agent	w_{add} (%)	flow (%)	slump (%)	w_{saved} (%)
6	REF	90	16	24	/
7	Mapedisp ECO WSP	90	126	84	0
8	Polyfoamer ECO WSP	90	126	83	0
9	Mapedisp ECO WSP	70	43	56	22
10	Polyfoamer ECO WSP	75	61	69	17

Figure 4. Mini flow cone front and from-above views.

3.1.1 *Mini flow test results*

The obtained results are shown in Table 1, while pictures of performed tests can be seen in Figure 5. Flow and slump values refer to height and diameter of the conditioned material downstream of the cone lift (computed on the dimensions of the mini-flow cone) and are shown in percentage value. The amount of conditioning agent, which remained constant for all tests (ID 6-10), is 0.5 g, equivalent to a dosage on the treated soil in concentration w/w equal to 0.5%.

Regarding results on "Reggio" clay specimens, given the same dosages used in terms of the amount of water added and the amount of conditioning agent (ID 6, 7 and 8), adopting the new generation products results in flow values increased by around 8 times and slump values were more than three times as much. Polyfoamer ECO WSP in the ID 10 test shows flow and slump values approximately 4 and 3 times higher than in the ID 6 comparison test, despite the fact that the amount of water added is approximately 17% less than in the reference test.

The specimen treated with Mapedisp ECO WSP (ID 9), although made with a w_{saved} of 22%, shows values for flow and slump respectively about 3 and 2 times higher in relation to those obtained in the reference (ID 6).

Figure 5. Mini Flow tests for "Reggio" clay. IDs are labelled.

3.2 *Mini slump tests*

The tests performed by using the mini slump (geometries shown in Figure 6) involve the use of NCC "Reggio" clay, which is characterised by its natural water content. The mixing of the soil with the correct amount of water and foam is carried out until a homogenous material is achieved. The conditioned material thus obtained is then placed inside a mini slump cone, using the surface of the flow table as a base support. A first slump test is thus performed, and the values of the base diameter (φ_{BJ}) and height (h_{BJ}) are measured. Fifteen jolts are then applied at a height of 25 mm after which base diameter (φ_{AJ}) and height (h_{AJ}) are measured.

Table 2. Mini slump and flow tests results.

Test ID	Conditioning agent	w_{add} (%)	w_{tot} (%)	φ_{BJ} (mm)	h_{BJ} (mm)	φ_{AJ} (mm)	h_{AJ} (mm)	flow (%)	slump (%)	w_{saved} (%)
1	REF	45	58	114	57	171	104	71	31	/
2	Polyfoamer ECO WSP	45	58	160	75	211	104	111	31	0
3	Polyfoamer ECO WSP	35	48	116	49	174	96	74	36	22
4	REF + Mapedisp ECO WSP	45	58	145	70	202	104	102	31	0
5	REF + Mapedisp ECO WSP	38	50	141	63	195	104	95	31	17

The cone base diameter is 100 mm, while its height is equal to150 mm.

The density value of the “Reggio” clay γ = 1.786 kg/L was used as a constant for all mini slump test campaign.

The conditioning parameters, which have been kept constant for all tests, are:

- c(%): 2.0
- FER(-): 8
- FIR(%): 60

Figure 6. Mini-slump tool.

3.2.1 *Mini slump test results*

The results are summarized in Table 2, while images of the test for ID5 are shown in Figure 7 as example. The values for flow and slump are referring to height and diameter values measured after the jolts, calculated in comparison to the original mini slump dimensions. ID 4 and ID 5 tests have been carried out with a conditioning procedure which made use of Mapedisp ECO WSP with a fixed dosage of di 0.8 g over 1500 g of clay, corresponding to a dosage of 1 kg of polymer over 1 m^3 of soil in situ. The additive dosage, in the range of one tenth of a gram, is negligible for the calculation of water content. For the calculation of w_{saved}, ID 2-5 refer to ID 1.

Considering the use of Polyfoamer ECO WSP, while keeping the water content and conditioning parameters constant (comparison between test ID 1 and 2), the flow percentage increases by about 1.5 times, from a value of 71% to a value of 111%. Considering instead tests ID 1 and 3, equivalent results in terms of flow are obtained by conditioning the soil with a w_{saved} of 22%.

If, on the other hand, we consider the conditioning obtained by adding Mapedisp ECO WSP to the REF, keeping the water content and conditioning parameters constant (comparison between test ID 1 and 4), the flow percentage increases by about 1.5 times, from a value of 71% to a value of 102%. Considering instead tests ID 1 and 5, similar results in terms of flow are obtained by conditioning the soil with w_{saved} equal to 17 %.

The “slump” parameter is irrelevant, with values in the range of 30-36% regardless of the conditioning they were subjected to.

Figure 7. ID5 mini slump test pictures before jolting (left) and after (right).

3.3 *Slump tests*

he slump test is probably the first that was used for characterise the conditioned soil even if it was originally applied to cohesionless soils (Peila et al., 2009; Borio abd Peila, 2011; Peila et al., 2013). The slump test campaign has been performed in compliance with the procedure described in the article published in the international scientific journal: C. Todaro et al. (2022).

The slump tests foresaw the use of NCC “Reggio” clay, which is characterised by its natural water content.

3.3.1 *Slump tests results*

The results obtained are summarised in Table 3 while images of the tests performed can be found in Figure 8, Figure 9,Figure 10, 11 and 12.

Test ID 5 was carried out with a conditioning which employed Mapedisp ECO WSP with

Table 3. Slump test results.

Test ID	Conditioning agent	w_{add} (%)	w_{tot} (%)	Slump A (cm)	φ_A (cm)	Slump B (cm)	φ_B (cm)	Slump C (cm)	φ_C (cm)	w_{saved} (%)
1	REF	32	45	19	28	11	25	25	49	/
2	Polyfoamer ECO WSP	22	34	13	27	0	20	17	34	33
3	Polyfoamer ECO WSP	26	38	17	34	5	22	22	41	20
4	REF	26	38	12	23	1	20	18	38	/
5	REF + Mapedisp ECO WSP	26	38	16	30	7	21	24	46	20

a fixed dosage of 2.02 g on 12000 g of clay, equivalent to 0.3 kg of polymer on 1 m^3 of soil in situ. The amount of additive, in the order of one gram, is negligible when calculating water content. For the calculation of w_{saved}, ID 2-3 refers to ID 1, while ID 5 refers to ID 4.

The analysis of a slump test is not only based on the numerical value of the slump at the cone. In all materials, but especially in clay materials, other parameters must be considered such as the overall homogeneity of the sample, its pulpy consistency and stickiness. Only from the careful evaluation of all these parameters can an overall judgement of the slump test be considered reliable. The writers, in order to facilitate reading, introduced a simple scale of pulpy consistency (1 - not very pulpy; 5 - very pulpy) and stickiness (1 - not very sticky; 5 - very sticky). The evaluations in terms of pastiness and stickiness were made after the execution of slump B and C.

Slump A
Pulpy consistency: 4
Stickiness: 2
Additional comments:
pulpy soil, presence of chips in the pulp.

Slump B
Pulpy consistency: 3.5-4
Stickiness: 3-3.5
Additional comments: /

Slump C
Additional comments: material is too fluid, hence it overflows out of the plate after being jolted. Presence of chips are in part loose and not blended into the "creamy" pulp.

Figure 8. ID 1 slump tests.

Slump A
Pulpy consistency: 3-3.5
Stickiness: 2-2.5
Additional comments: pulpy soil, presence of chips in the pulp.

Slump B
Pulpy consistency: 4
Stickiness: 3.5
Additional comments: homogeneous material, presence of chips in the pulp.

Slump C
Additional comments: homogeneous material, well-conditioned soil.

Figure 9. ID2 slump tests.

Further comments for direct comparisons of "REF" tests and the other conditioning combinations are listed below:

ID 1 vs ID 2: Slumps A are comparable in terms of pulpy consistency and stickiness. Slumps B are also comparable, although ID 2 is characterised by a w_{saved} of 33%. It should also be considered that ID 1 - slump C is an unacceptable slump as it is excessively fluid. In fact, the conditioned soil leaked abundantly from the plate downstream of the execution of the shots, whereas ID 2 - slump C shows a slump at the cone in the ranges, without any material leaking from the plate.

ID 1 vs ID 3: Slumps A are comparable in terms of pulpy consistency and stickiness. Slumps B are also comparable, although ID 3 is characterised by a w_{saved} of 20%.

ID 3 - slump C shows a slump value at the cone in the range, with no material escaping from the plate.

Slump A
Pulpy consistency: 3
Stickiness: 1.5-2
Additional comments: homogeneous material, slightly less homogeneous than slump A of test ID 2.

Slump B
Pulpy consistency: 4
Stickiness: 3.5
Additional comments:
very homogeneous material.

Slump C
Additional comments: homogeneous material, well conditioned soil.
Many chips are disrupted, while the pulp is embedding the remaining chips.

Figure 10. ID3 slump tests.

ID 4 vs ID 5: Conditioned soils with equal water content. Comparing Slump As, the better result obtained in ID 5 in terms of pulpy consistency is evident. ID 5 - slump B was less stiff than the corresponding ID 4 - slump B (with slump values at the cone of 7 and 1 cm respectively), as well as showing a more limited stickiness. ID 5 - slump C slightly off the plate but with fewer chips and more paste than ID 4 - slump C.

ID 3 vs ID 4: Conditioned soils with equal water content. ID 4 - slump A is slightly stickier than ID 3 - slump A. ID 3 - slump C was much pulpier than ID 4 - slump C. It should be noted, however, that ID 4 - slump C exhibited a high degree of stickiness during lifting of the cone, which was not the case in ID 3 - slump C.

Slump A
Pulpy consistency: 2
Stickiness: 3.5
Additional comments:less homogeneous material, the creamy outside hides the chips, which are still hard to the touch.

Slump B
Pulpy consistency: 2.5
Stickiness:4
Additional comments: less pulpy yet very sticky material, the cone would not detach easily from the conditioned material.

Slump C
Additional comments: homogeneous material, scarce presence of non-disrupted chips.

Figure 11. ID4 slump tests.

Slump A
Pulpy consistency: 3.5-4
Stickiness: 2.5
Additional comments: homogeneous material, creamy paste.

Slump B
Pulpy consistency: 3.5
Stickiness: 2.5
Additional comments: homogeneous material, creamy paste.

Slump C
Additional comments: Homogeneous material, well conditioned, chips present but with small. Slight excess of fluidity, with limited material falling out of the plate downstream of the jolts.

Figure 12. ID5 slump tests.

3.4 *Dynamic adhesion tests*

The dynamic adhesion test campaign was carried out on the basis of the procedure described in Todaro et al. (2022) and Carigi et al. (2023).

The dynamic adhesion test is based on the rotation of an aluminium disc, 120 mm in diameter and 10 mm thick, placed in contact with the clay material under specific conditions in order to assess the developed adhesion. The test, specifically designed for the study of clays, involves placing the disc in rotation within the material to be tested, with a constant rotation of 90 rpm (Figure 13). The clay material then adheres to the surface of the disc and the contact is ensured by applying a pressure of 1 bar to the conditioned material. The pressure is applied by means of a plate which, pushed by 2 hydraulic pistons, moves downwards in contact with the soil, thus making sure that the intended pressure is applied to the conditioned soil. The test provides important information about the resistance exerted by the clay soil to the rotation of the disc, due to the adhesion/clogging forces typical of clay soils. During the test, the torque required to ensure a constant disc rotation speed is constantly measured and recorded.

Dynamic adhesion tests foresaw the use of NCC “Reggio” clay, conditioned by its natural water content.

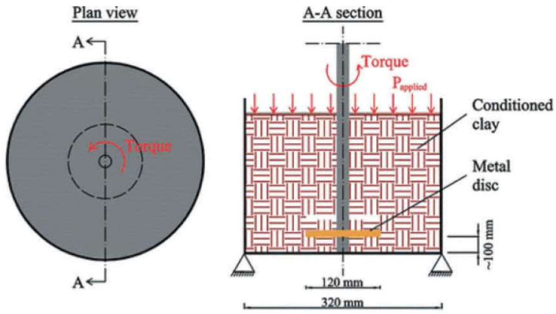

Figure 13. Schematic diagram and picture of the dynamic adhesion test apparatus. 1. steel container; 2. torque transducer; 3. hydraulic pistons; 4. steel cover; 5. hydraulic unit.

Table 4. Dynamic adhesion tests results.

Test ID	Conditioning agent	w_{add} (%)	w_{tot} (%)	c (%)	FER (-)	FIR (%)	T (Nm)	w_{saved} (%)
1	REF	27	40	2	8	45	4	/
2	Polyfoamer ECO WSP	23	35	2	8	45	3	17
3	REF + Mapedisp ECO WSP	23	35	2	8	42	4	17

3.4.1 *Dynamic adhesion test result*s

The conditioning parameters of the tests and the results obtained in terms of average torque T (Nm) and w_{saved} are shown in Table 4 while Figure 16 shows the trends in torque as a function of time. The average torque was calculated over the 300 s of the actual test, after the pressure stabilisation transient phase which lasted an average of 120 s for all 3 tests. This reduction in FIR was evaluated in agreement with the commissioning company's technicians in order to maximize adhesion phenomena during the test, consistent with obtaining good conditioning results.

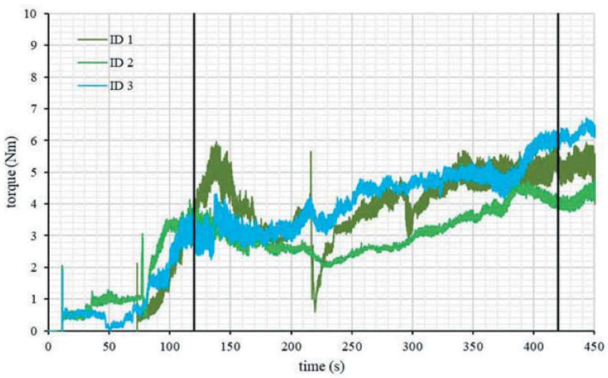

Figure 14. Torque over time graph for dynamic adhesion tests.

The reference test, i.e. ID 1 is highlighted in grey color. ID 3 was carried out by conditioning using Mapedisp ECO WSP with a fixed dosage of 2.55 g per 15000 g of clay, equivalent to 0.3 kg of polymer per 1 m^3 of soil in place. The amount of additive, in the order of a gram, is negligible for the purpose of calculating the water content. For the calculation of w_{saved}, ID 2-3 refer to ID 1.

Figure 15 shows some shots of the significant phases of the dynamic adhesion test. For illustrative purposes only, the images shown refer to ID 1.

Figure 15. Dynamic adhesion test ID 1. Material completely poured into the steel container (left), material at the end of the test (right), extraction and visual analysis of the disc (right).

An analysis of Figure 14 shows that the 3 torque trends as a function of time are very similar, despite the fact that IDs 2 and 3 were carried out with a w_{saved} of 17%. Regardless of the test considered, the torque values never exceeded the value of 7 Nm, an indication that the conditioning used ensures that adhesion/clogging phenomena are controlled. The T values, between 3 and 4 Nm, also show a high degree of similarity in the behaviour of the materials tested with dynamic adhesion testing.

4 FINAL CONCLUSIONS

The study of the conditioning of clays is a complex analysis which is difficult to carry out using a single type of laboratory test. In the present study, the conditioning of the "Reggio" clay was evaluated by means of tests considering both homogenised clay (obtained from the DCC sample) and clay in chips (NCC sample), conditioned with products specifically designed and manufactured for the conditioning of cohesive materials.

The different conditioners adopted, adjusted each time depending on the type of test carried out, highlighted the effectiveness of Polyfoamer ECO WSP and Mapedisp ECO WSP (the latter used as an additive alongside a reference conditioning agent) in guaranteeing good conditioning, comparable to that obtained with REF, while using reduced quantities of added water.

Specifically speaking, mini-flow and mini-slump tests denoted a potential water saving ranging from 17 to 22 % when comparing samples conditioned with Polyfoamer ECO WSP to the ones conditioned with the REF conditioning agent. Similar results (w_{saved} = 17-22%) for the same tests were observed by comparing the samples treated using REF with an addition of Mapedisp ECO WSP with the ones conditioned using REF only.

With Slump tests, the best results highlighted a potential water saving between 20 and 33% using Polyfoamer ECO WSP.

Dynamic adhesion tests evidenced samples treated with next generation products, which are the ones conditioned with either Polyfoamer ECO WSP or with a combination of REF and Mapedisp ECO WSP result in a potential water saving of 17%.

In conclusion, with regard to technical performance parameters, a potential water saving of a minimum of 17 % has been consistently observed, denoting a great potential for the reduction in water demand for TBM jobsites which would result in a significantly lower environmental impact as well as an economical advantage.

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