

Correlation between flow table test results and plasticity on conditioned clayey soils

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ABSTRACT: The design and execution of good soil conditioning plays a major role in the success of mechanized tunnelling with Earth Pressure Balance Tunnel Boring Machines (EPB-TBMs). During mechanized tunnelling in fine-grained soil, achieving a proper workability of the excavated soil in the working chamber is important to maintain the stability of the excavation face by balancing the pressure in the excavation chamber and in front of the cutting head. Much research has been carried out in recent years and several laboratory tests have been proposed, but a widespread and unified method for predicting the conditioning parameters required to achieve the right workability for clayey soils is still missing and there is a lack of knowledge regarding the correlation between the results of different tests.

WEBUILD and GEEG, innovative startup company of Sapienza University of Rome, conducted several research studies for major underground projects, aimed at improving Italian railways lines. These studies involved an intensive experimental activity focused on investigating the physical and mechanical properties of conditioned fine-grained soils, using the flow table test.

This paper describes the results of the flow table tests carried out on a large number of clayey soils (15) with different grain size distributions and plasticity, conditioned through the addition of water and foam. The results have been systematically analysed, identifying a correlation between the workability of the conditioned soils and their geotechnical properties. This correlation can be of much interest as it allows the use of a quick test, such as the flow table test, to check whether the conditioning process has produced the desired workability.

1 INTRODUCTION

Earth Pressure Balance Tunnel Boring Machines (EPB-TBMs) technology is currently the most often used method to perform mechanized tunnel excavation in soils (Adoko et al., 2017; Gong et al., 2012; Repetto & Fidelibus, 2017, Sebastiani et al., 2019; Rostami & Tahernia, 2024) and it is especially employed in urban areas due to the special challenge of limiting surface settlements (Thewes and Budach, 2010; Shen et al., 2014; Miliziano & de Lillis, 2019). This technology requires the control of face support, which is a major issue in EPB tunnelling. Continuous support of the tunnelling face must be provided by the excavated soil itself, which should completely fill the working chamber (EFNARC, 2005). The support pressure has to balance the earth pressure and the water pressure, therefore the support medium has to meet several requirements in the excavation chamber and the screw conveyor to make the application of pressure to the excavation face and the extraction of material to the conveyor belt easier and more uniform (Bezuijen & Talmon, 2008) and to correctly dampen the pressure along the screw conveyor. Since the soil does not possess these characteristics, conditioning of the excavated material is often necessary (Thewes et al. 2010). The boundaries of soil conditions for the use of this tunnelling method are continually expanding, especially in coarse-grained soils, not least due to the development and use of new chemical additives.

The injection of foams and polymers at the cutter head, in the pressure chamber and in the screw conveyor can modify the soil properties and offer various benefits, such as the reduction of torque and energy consumption of the machine, the reduction of wear of the cutting tools and other mechanical components and the reduction of clogging potential of sticky clays. In general, a plastic paste, with suitable compressibility (Mori *et al.*, 2015), small adhesion and low clogging potential (Schroer and Thewes, 2023), is regarded as the optimum supporting soil mass (Milligan, 2000; EFNARC, 2005). For all these reasons, a quick experimental identification of the workability of the excavated material during the excavation process and an appropriately adjusted conditioning of the soil can help to make EPB excavations safer, more cost-efficient and easier to plan in the future. (Schröer *et al.* 2023). Nowadays, for the investigation of the workability of the excavated soil the slump test, which originates in the concrete industry (UNI EN 12350-2, 2019), is predominantly used (Peila *et al.* 2009). However, many further studies have proposed additional methodologies and experimental tests to overcome some of the limitations of the slump test alone (de Oliveira *et al.* 2016; Mori *et al.*, 2018; Schröer *et al.* 2023; Sebastiani *et al.*, 2025).

To overcome these issues and still obtain information about workability/flow behaviour and mechanical characteristics of the conditioned clayey soil, the authors performed an experimental investigation of the physical and mechanical properties of conditioned fine-grained soils using the flow table test, as suggested by many authors (Galli (2016) and Todaro (2022) among others). The flow table test is proposed in the literature for measuring the physical and mechanical properties of conditioned soils. It is most often used to verify the correct dosage of conditioning agents in the laboratory and on site. The presented experimental campaign involved about 250 tests carried out on different types of fine-grained soils and allowed to find meaningful correlations with the soils plasticity index. The results are also useful as an on-site verification tool, as they provide a first evaluation of the workability and water content expected from a conditioned soil.

2 MATERIALS AND METHODS

2.1 Tested soil

The experimental activity involved the analysis of 15 different fine-grained soils sampled along the EPB tracks of several railway extension projects in Italy.

For all these samples, geotechnical characterization tests were performed to determine the grain size distribution, the Atterberg limits and the activity of the clay fraction. After this preliminary characterization, for each soil, various specimens were conditioned varying the main conditioning parameters and numerous tests (as Hobart mixing test, pull-out test and vane test) were performed, including the flow table test.

Table 1 lists the grain size distributions and Atterberg limits determined according to ASTM D6913, ASTM D4318 and AGI Recommendations. LL, PL and PI represent respectively the liquid limit, the plastic limit and the plasticity index, also presented in Figure 1 (left), while A is the activity, also shown in Figure 1 (right).

Table 1. Grain size distribution and Atterberg limits for the tested soils.

sample (-)	clay (%)	silt (%)	sand (%)	gravel (%)	LL (%)	PL (%)	PI (%)	A (-)
S1	50	38	10	2	94	33	61	1.2
S2	71	26	3	-	84	36	49	0.7
S3	45	42	13	-	56	17	39	0.9
S4	47	51	2	-	62	26	37	0.8
S5	47	52	1	-	65	29	36	0.8
S6	37	47	16	-	58	23	45	0.9
S7	28	49	23	-	53	26	27	1.0
S8	44	44	10	2	50	24	26	0.6
S9	34	38	21	7	59	34	25	0.7

S10	32	63	5	-	49	24	25	0.8
S11	40	49	10	1	55	30	25	0.6
S12	38	57	5	-	41	21	20	0.5
S13	17	33	44	6	42	22	20	1.2
S14	5	35	40	20	40	26	14	2.8
S15	25	70	5	-	36	26	10	0.4

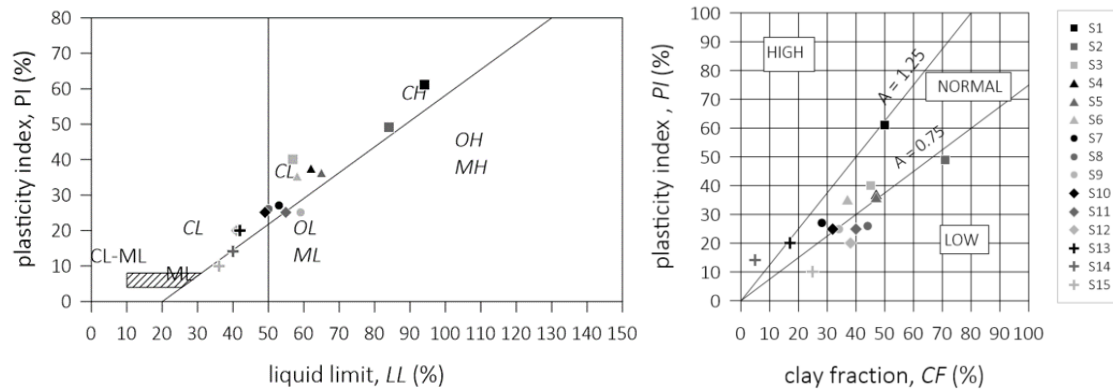


Figure 1. Casagrande plasticity chart (left) and activity distribution (right).

2.2 Soil conditioning

EPB excavation technology was originally developed in Japan to tackle the excavation of fine-grained soils in which the Slurry Shield (SS) technology produced unsatisfactory excavation performance.

As briefly mentioned above, EPB technology involves the injection into the soil of foaming agents and additives for proper management of the excavation. In detail, soil conditioning is mainly necessary to:

- modify the properties of the excavated soil to maintain a correct pressure distribution in the excavation chamber (which is applied to the excavation face by the material itself);
- modify the properties of the excavated soil to allow a proper flow of the soil from the excavation chamber towards the conveyor belt;
- reduce, if necessary, abrasion of the surface of metal excavation tools and, in general, friction and temperatures inside the excavation chamber;
- reduce, if necessary, the tendency of the soil to adhere to the metal surfaces of the digging tools, reducing the torque and decreasing the risk of blockage of the TBM head (clogging effects).

In the presented experimental investigation, the foam was produced using a foam generator developed to exactly replicate in all of its main aspects the foam generation system used on the TBMs employed in the Italian railway projects. This generator was meticulously designed and is available at the Department of Structural and Geotechnical Engineering, Sapienza University of Rome. A detailed description of its characteristics is reported by Sebastiani et al. (2019).

The characteristic parameters of the foam are in fact the same as those measured in real time during the excavation and therefore allow a comparison between what was obtained in laboratory and what was tested on site, taking due account of the inevitable differences between the site and the laboratory (scale effect). The possibility of reproducing the generation of foam in this way increases the accuracy of the tests and, as has been amply demonstrated (Sebastiani et al. 2018), increases the quality and stability of the foam itself.

The conditioning parameters that can be regulated during the injection of foams with EPB-TBM are: concentration factor (Cf), foam expansion ratio (FER), foam injection ratio (FIR) and

water added during excavation (WIR), as described in detail by Merritt (2004), EFNARC (2005) and many other authors. These parameters are strongly dependent on the type of soil to be excavated, are preliminary predicted from laboratory tests performed using samples from the job-site and then are adjusted on site with a trial-and-error process observing TBM performances.

To investigate, at a laboratory scale, the behaviour of a fine-grained soil to be excavated through EPB-TBM, it is helpful to perform some tests not only on the foaming agents (Marsh viscosity, density) and on the foams (half-life time) but also on the conditioned samples (Hobart mixing test, pull-out test, fall cone test, ...). To obtain information about workability and mechanical characteristics of the conditioned soil, the flow table test can be also performed.

As anticipated, in this paper the focus is on the results of flow table tests performed on conditioned clayey samples. These results can help to understand how soil workability changes as the plasticity index and the grain size distribution of fine-grained soils varies, while at the same time varying the water content and the conditioning parameters.

2.3 Flow table test

The flow table test is one of several tests that can be used to evaluate the workability of specimens and is commonly used for mortar (UNI EN 1015-3, 2007).

It requires the equipment shown in Figure 2: a circular, smooth platform mounted on a lifting and release mechanism that allows the table to be raised and dropped freely, a small truncated cone-shaped mould that is filled with the material to be tested, a metal tamper necessary to compact the specimen within the mould.

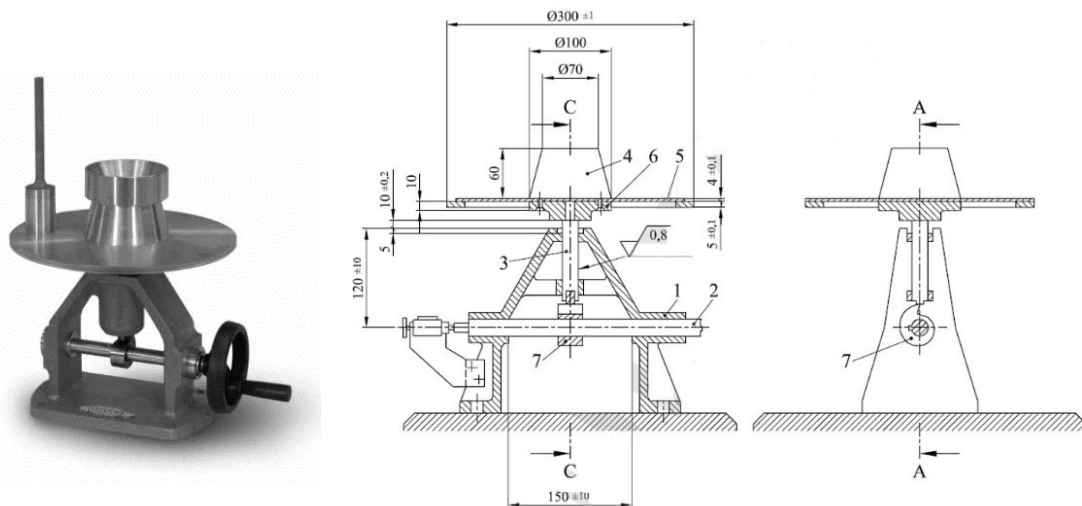


Figure 2. Flow table apparatus (left); flow table apparatus scheme (from UNI EN 1015-3, 2007, right).

The test procedure is as follows:

- the mould is placed at the centre of the flow table and filled with the specimen in 3 layers. Each layer is slightly compacted with the tamper to eliminate any relevant air void;
- once completely filled, the mould is lifted vertically to allow the material to spread horizontally;
- the flow table is then raised and dropped repeatedly (15 times, then another 10 and then another 15) from a specific height (10 mm). This movement causes the material to flow and spread out on the table's surface;
- after each cycle of raising and dropping, the final diameter of the spread material is measured (thus after 15, 25 and 40 drops). The test result is expressed as the final diameter after certain number of drops (i.e. D15 is the diameter after 15 drops).

3 RESULTS AND DISCUSSIONS

The workability/flow behaviour of all the clays involved in this activity was tested by means of flow table tests. All the samples were conditioned varying not only the conditioning agents, but also all the important parameters of the conditioning process (*Cf*, *FER*, *FIR*, ...). The flow behaviour of the samples varies with the spread diameter, from 10 cm, equal to the initial diameter of the mould, to over 30 cm.

To understand how plasticity affects the results of the flow table test (and consequently the flow behaviour of each soil), Figure 4 reports the results obtained for three soils (S2, S5 and S12) with different plasticity.

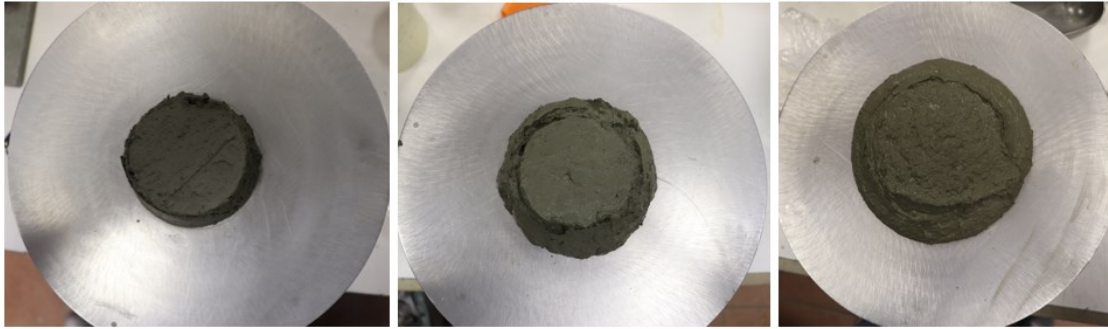


Figure 3. Flow table tests on sample S9: D15= 10 cm (left), D15=12cm (center), D15=15 cm (right).

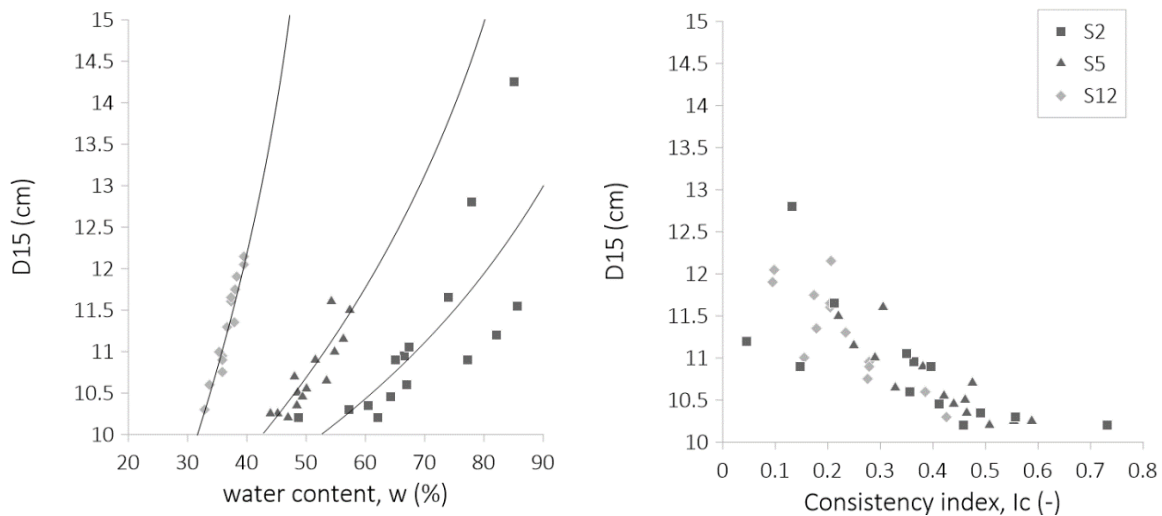


Figure 4. Flow table results for S2, S5 and S12 in relation with the total water content (left) and with the consistency index (right).

It can be noted in Figure 4 (left) that for S12, characterized by plasticity index PI equal to 20%, a small variation in water content leads to significant differences in terms of D15; while for S2, with a PI equal to 41%, to obtain the same variation of D15 a greater quantity of water is required. The experimental results of each soil were approximated with second-order equations and the difference of behavior is easily noticeable. These interpolations are only valid in a range of water contents corresponding to consistency indexes of interest for tunnelling applications.

Since these three soils are characterized by not only different plasticity, but also different grain-size distribution and mineralogy, it can be useful to analyze these data through further processing. Therefore, in Figure 4 (right) the D15 are presented in relation with the consistency index. By introducing the consistency index instead of the water content, since it is linked to the plasticity through the Atterberg limits, any differences in the behaviour of the soils can be associated with other geotechnical characteristics. From the previous figure, however, it can be observed that the

experimental results seem to be aligned along a single trend, thus suggesting that it is the plasticity that plays a key role in the flow behaviour of the soil.

Representing about 250 results obtained in terms of spread of the diameter (D15) for all the soils examined in this study (Fig. 5), it can be noted that soils with similar plasticity behave similarly (with the notable exception of S6, whose behavior still needs further investigation).

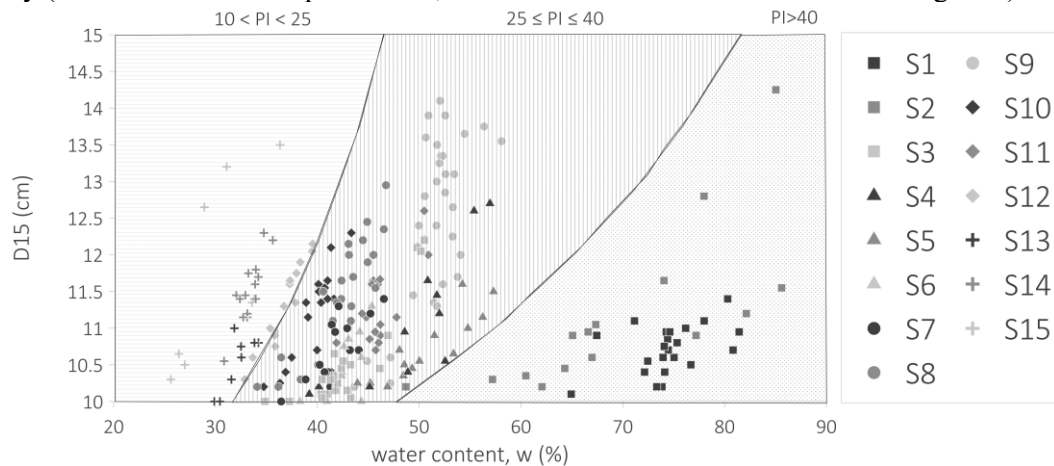


Figure 5. Flow table results.

In detail, soils characterized by plasticity index between 10 and 25% (such as S13, S14 and S15) show a major gradient, almost linearly distributed, compared to those with PI higher than 40% (such as S1 and S2). In between these two ranges an intermediate trend can be observed. Moreover, it is interesting to notice that results of D15 between 10 and 15 cm obtained from low plasticity soils are fairly concentrated at water content values close to 25-30%, while high plasticity values have varying water content values between 60% and 80%. The results, while representing a continuous variation in behavior, were used to identify 3 main areas as shown in Figure 5:

- range 1: $10 < PI < 25$, which includes soils S12 to S15 with low water content values;
- range 2: $25 \leq PI \leq 40$, which includes soils S3 to S11 with intermediate water content values;
- range 3: $PI > 40$, which include soils S1 and S2 with high and highly variable water content.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

The joint research activity developed in the last 5 years by GEEG and Webuild is aimed at investigating the behaviour of conditioned soil in different geological and geotechnical contexts, exploring the differences between different soils, different laboratory tests and, in the next future, between laboratory evidence and real on-site conditions.

Since the slump test cannot be a useful tool both in the laboratory and in situ (Schröder & Thewes, 2023), in this paper the response of the flow table test was analysed with the aim of integrating it into control measures during TBM excavations. The experimental campaign here discussed involved 15 fine-grained soils from real tunnelling projects in Italy and more than 250 flow tables tests.

From a general perspective, the results look promising and seem to be sufficiently sensitive to varying water content and varying intrinsic properties of the fine-grained soils. Through this extensive activity it was possible to investigate whether and how different parameters of each fine-grained soil influence the results of the flow table test and how the flow table test is able to capture the effects of the soil conditioning process. A direct positive correlation between D15 and water content for soils with different PI was observed and the spectrum of results was divided into three fields.

These results can be used during the design stage, to have a first estimation of the workability of the conditioned soil, and during construction, as a simple and real-time estimation of the water content of the conditioned soil produced by TBM tunnelling.

It can also be seen that for soils with relatively low PI, the effect of the different soil conditioning processes is modest and mainly limited to the effect of the resulting water content; on the contrary, the results obtained on soil samples with higher PI are much more dispersed, a symptom of the fact that, in that case, not only the water content but also the conditioning process affects the value of D15.

Future developments will involve an extensive comparison between the results of this laboratory investigation, carried out during the design phase, and the results of the same tests performed on site during the actual TBM excavation phase. This systematic comparison will produce interesting evidence and enable us to further improve our predictions of conditioned soil behaviour at the design stage and will be a valuable support for the TBM team in calibrating the optimal conditioning parameters in the machine.

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