

Soil conditioning process of Pliocene formation for Rome Metro C EPB-TBM tunnelling

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ABSTRACT: The overall project of the Rome Metro C line includes the realization of more than 50 km of tunnels and 30 underground stations. The T3 stretch, in particular, involves the realization of underground operations under the Rome city centre, one of the richest areas of historical and archaeological buildings included in the UNESCO World Heritage. In the central part of section T3 the excavation involved the Pliocene clay formation, particularly subject to the risk of clogging and for the first time affected in Rome by the mechanized excavation. Being the interaction between the mechanized excavation and the surface particularly sensitive, specific measures have been taken to manage the conditioning process during the excavation. Specific laboratory tests were therefore carried out at Sapienza University of Rome to verify the potential clogging risk associated with this formation and the effectiveness in minimizing this risk through a careful selection of conditioning chemicals and parameters. This paper presents the results of the research activity developed to describe the peculiarities of the behaviour of the Pliocene clay and the beneficial effects of soil conditioning process. Moreover, interesting insights will be shown by comparing the results obtained in the laboratory and the evidences recorded on site during the excavation.

KEYWORDS: TBM, soil conditioning, mechanized tunnelling, Research, laboratory.

1. INTRODUCTION

The mechanized excavation of tunnels represents a solution increasingly used to cope with the growing need to increase urban mobility through an increasingly complex network (Babendererde, 1998; Nishitake, 1990; Miliziano et al., 2016).

In densely urbanized contexts often rich of pre-existing structures and an artistic and archaeological heritage, the interaction between the excavation of tunnels and the effects induced on the surface becomes particularly delicate (Fujita, 1981; Mair et al. 2003). In the panorama of tunnels built around the world, Line C of the Rome Metro certainly represents one of the most complex and articulated projects.

As part of the study and research activities aimed at better managing the implementation of the project, in this document are collected some results of a part of the experimental activities performed at Sapienza University of Rome in cooperation with Metro C for the study of the soil conditioning process for the excavation of tunnels with Tunnel Boring Machines (TBM) and Earth Pressure Balance (EPB) excavation technology. In the following will be described the study and research activities developed from the selection of products to the management of soil conditioning parameters during excavation with specific reference to the Pliocene clay (APL) formation. The APL formation, in fact, was a formation never faced in previous tunnel excavation projects in Rome and, given the nature of the clay, particularly subject to the risk of clogging.

The results shown have allowed an easier management of the excavation phases and a deeper understanding of the specific characteristics of this formation.

2. THE ROME METRO C PROJECT

2.1 Generalities

The route of the Rome Metro C Line was conceived to link the city's eastern quadrant with its northwest quadrant. Starting from the Pantano terminus in the Municipality of Montecompatri, the line stretches for about 25.6 Km, approximately 9 of which on the surface and 16.5 underground, traversing such historic city neighbourhoods as Centocelle, Alessandrino, Pigneto, Appio, and the historic centre before reaching the Prati neighbourhood in the vicinity of Piazzale Clodio.



Figure 1 Rome Metro C line (modified after Pirone et al., 2020).



Figure 2 aerial view of the Metro C – Fori Imperiali job-site.

The most sophisticated technologies presently known in matters of tunnelling are being exploited. The tunnel design requested the use of 4 Earth Pressure Balance (EPB) Tunnel Boring Machines (TBM), manufactured by Herrenknecht and owned by Metro C, to excavate two parallel tunnels with an excavation diameter of 6.71 m. The tunnel lining is constituted by precast reinforced concrete segments with a thickness of 30 cm – an internal diameter of 5.80 m and

external diameter of 6.40 m. Each precast ring is 1.40 m long and is constituted by 6 main segments and 1 key segment.

The T3 stretch runs over a length of about 2.8 km right underneath the historic centre of Rome. It includes 2 stations - Amba Aradam and Fori Imperiali - and 2 ventilation shafts – shaft 3.2 located in Piazza Celimontana and shaft 3.3 located in via Sannio. The tunnels run at a depth ranging from 30 to 60 m in difficult and frequently changing soils. The job sites are located in an area containing several historical buildings: as a consequence, technical and operative choices were imposed in order to minimise the job site dimensions.

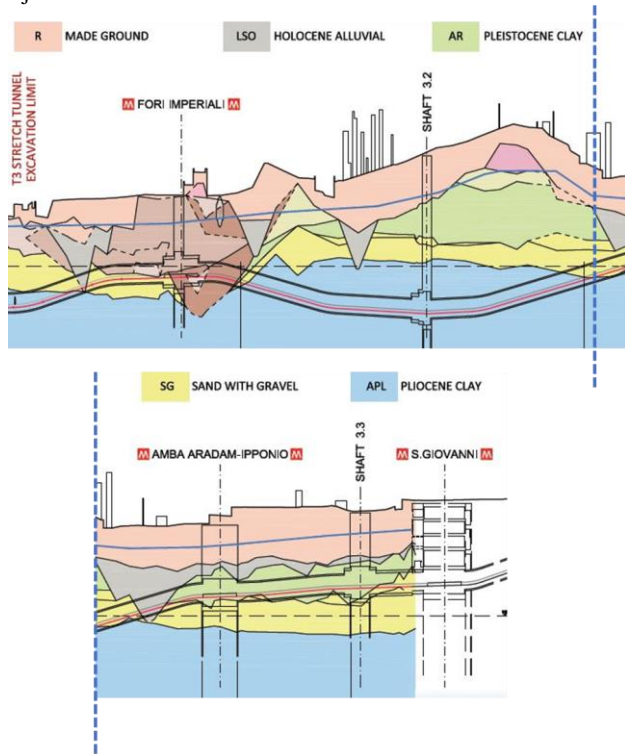


Figure 3 Overall geological section of the Metro C T3 stretch.

The tunnels in the first section between shaft 3.3 and Amba Aradam station – for a length of about 400 m – have been excavated with 2 EPB TBMs.

2.1 The Pliocene clay (APL) formation

The APL unit is made up of consistent silty clays interspersed with thin layers of thickened fine silty sands prevalent between 46 and 48 meters deep. From the analyses from geotechnical laboratory on samples taken from site, an average volume weight of 20.7 kN/m³ was obtained, with an average water content of 21.3%; furthermore, from literature and preliminary evaluation analyses the material is commonly characterised by an high plasticity; the liquid limit is on average between 37 ÷ 48% with an average plasticity index of 21%.

The following Table 1 shows the results of the laboratory tests carried out which substantially confirmed the expected soil characteristics.

Table 1 APL average values of grain size distribution and Atterberg's limits.

gravel (%)	sand (%)	silt (%)	clay (%)	LL (%)	LP (%)	I _p (%)
0	25	50	25	38	18	20

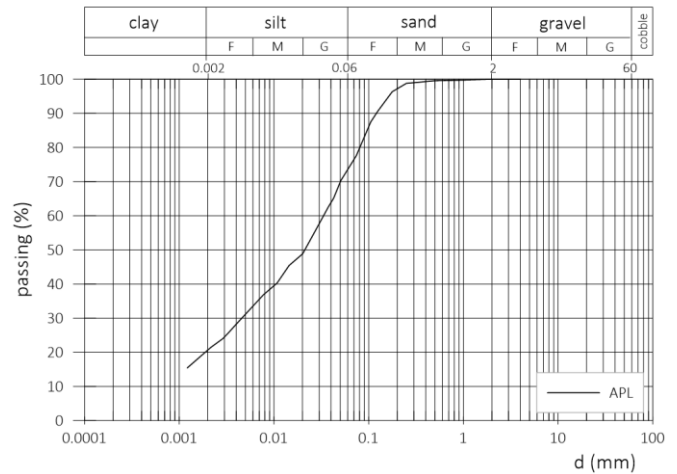


Figure 4 grain size distribution of APL samples.

3. THE EXPERIMENTAL ACTIVITY

The APL lithotype corresponds to a fine-grained soil characterized by a high presence of silt with secondary components of clay and sand.

Fine-grained soils having these characteristics usually require high volumes of water necessary to modify the consistency of the material and transform it into that “homogeneous paste” useful for correctly transmitting the pressure to the excavation face (Bezuijen, 1999; Mair et al., 2003; Di Giulio et al., 2018). These soils are closely linked to the development of clogging phenomena, understood as adhesion of the finest soil particles to the metal parts of the TBM excavation head (Thewes and Burger, 2004), with a consequent increase in the efforts required to proceed with the excavation.

For these reasons, laboratory tests were carried out using 4 different conditioning agents and checking in parallel the achievement of the right consistency, by means of a shaking table and measurement of the undrained resistance, and reduction of the natural risk of clogging, median mixing and pull tests. out.

3.1 Generalities

To study the effects of conditioning in tunnel excavation, to select the most suitable products for the specific formations involved in the project and to define the dosages necessary to optimize the excavation process, Metro C and Sapienza, University of Rome have developed a joint research activity on this topic.

The activity involved taking representative samples of the formations involved in the excavation during the construction of a ventilation shaft and carrying out experimental activities at the Sapienza geotechnical laboratory.

3.2 Laboratory tests

The performed laboratory tests can be briefly described as follows:

- 1) characterization of soil samples (particle size distribution, liquid and plastic Atterberg's Limits, soil particles specific gravity);
- 2) fall cone test, for the determination of undrained strength of soils before and after the soil conditioning process;
- 3) mixing test and pull-out test for the measurement of the clogging tendency on soil samples at different water content and on similar soil samples after each soil conditioning process.



Figure 5 Hobart mixing apparatus and mixing tool (modified after Sebastiani et al., 2017).

In the Hobart mixing test, used to empirically quantify the potential clogging of soft clayey soil mixtures, the soil sticking to the mixing tool after a fixed time of mixing can be weighted: the potential clogging increases as this weight increases. The adherence quantifies the tendency of the soil to remain stuck on a mixing tool after a mixing process in a mortar mixer and is defined as:

$$\lambda = \frac{G_{MT}}{G_{TOT}} \quad (1)$$

where G_{MT} is the weight of soil sticking to the mixing tool and G_{TOT} is the total weight of soil involved in the mixing process, usually about 1000 g.

By comparing the results of tests performed on natural and conditioned soil samples, it is possible to individuate the optimum treatment to reduce the clogging risk.

The pull-out test is a widespread system for measuring the adhesion between a metallic element and the soil. Different authors, with different approaches, used this test to measure the clogging tendency of a soil and, by comparison, the beneficial effect obtained by injecting chemicals into the soil.

The test is performed by placing a metal tool in contact with the soil sample and then measuring the force necessary to separate the tool from the soil, extracting it vertically.

The fall cone test measures the penetration of a cone dropped under its own weight after being released from the standardized support. The resulting values, together with the weight and shape of the cone, are correlated with Atterberg's limits and with the undrained shear strength of fine-grained soils, providing a fast, simple and accurate method to determine these parameters.

3.3 Soil conditioning process

The soil conditioning process was performed in the laboratory with the support of equipment specifically designed to replicate the generation of foam in the laboratory with characteristics similar to what happens on site during excavation (Sebastiani et al., 2018). As is well known in the literature (Langmaack, 2000; Milligan, 2000; Psomas, 2001; Sebastiani et al. 2020), the characteristics of the foam depend significantly on the generation system and these characteristics in turn influence the effects of the conditioning process. The dosages of conditioning agent, water and air used in the soil conditioning process are commonly defined by means of some characteristic parameters. The most commonly used are listed below.

Concentration Factor of the conditioning product in the solution

$$Cf = 100 \cdot \frac{m_{f.ag.}}{m_{sol.}} \quad (2)$$

Foam Expansion Ratio of the foam

$$FER = \frac{V_f}{V_{sol.}} \quad (3)$$

Foam Injection Ratio of the foam into the soil

$$FIR = 100 \cdot \frac{V_f}{V_s} \quad (4)$$

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

The laboratory tests were carried out on soil samples from the site conditioned with foaming agents from 4 different suppliers. The conditioning parameters used and the estimated and measured water content values are shown in the following Tables for each of the products used and each test performed.

Table 2 Soil conditioning parameters for tests with P1 product.

w_{nat} (%)	w_{agg} (%)	Cf (%)	FER (x:1)	FIR (%)	w exp (%)	w meas (%)
17	10	2	9	75	35.17	35.29
17	10	2	9	100	37.89	36.62
17	6.5	2	9	75	31.67	31.81
17	10	2	9	60	33.53	33.74
17	6.5	2	11	65	29.29	30.6
17	14	2	11	35	34.12	34.71
17	10	2	12	58	31.74	31.14
17	2.5	2	12	100	27.67	28.31
17	15	2	12	65	37.31	37.59

Table 3 Soil conditioning parameters for tests with P1 product.

w_{nat} (%)	w_{agg} (%)	Cf (%)	FER (x:1)	FIR (%)	w exp (%)	w meas (%)
17	10	2	10	70	33.86	34.25
17	10	2	10	35	30.43	33.76
17	6	2	10	70	29.86	29.98
17	10	2	9	70	34.62	34.76
17	12.5	2	9	70	37.12	36.11
17	6	2	9	70	30.62	31.17
17	15	2	12	70	37.72	36.89
17	4	2	12	100	29.17	28.2
17	10	2	12	60	31.9	33.12

Table 4 Soil conditioning parameters for tests with P1 product.

w_{nat} (%)	w_{agg} (%)	Cf (%)	FER (x:1)	FIR (%)	w exp (%)	w meas (%)
17	10	2	9	70	34.62	36.69
17	12.5	2	9	70	37.12	37.63
17	12.5	2	9	100	40.39	39.98
17	10	2	10.5	90	35.4	35.17
17	15	2	10.5	85	39.93	38.31
17	17	2	10.5	85	41.93	42.19
17	10	2	12	95	34.76	34.51
17	12.5	2	12	95	37.26	36.19
17	17	2	12	70	61.94	39.22

Table 5 Soil conditioning parameters for tests with P1 product.

w_{nat}	w_{agg}	C_f	FER	FIR	w_{exp}	w_{meas}
(%)	(%)	(%)	(x:1)	(%)	(%)	(%)
17	12.5	2	9.5	80	37.75	36.12
17	15	2	9.5	80	40.25	38.54
17	18	2	9.5	65	41.71	40.04
17	8	2	11	100	33.91	32.7
17	17	2	11	65	39.79	40.35
17	14	2	11	65	36.79	37.67
17	10	2	13	85	33.41	33.57
17	12.5	2	13	85	35.91	34.68
17	20	2	13	30	39.26	38.83

4. RESULTS AND DISCUSSION

The graphs in the following Fig. 6 and 7 show the results of the mixing and pull-out tests as a function of the consistency index for the APL samples and, for comparison, with the samples of the AR and ARS soils subject to the previous experimental activity (Pirone et al., 2020).

The results were superimposed with a Gaussian curve calibrated according to a best fitting process, minimizing the mean square deviation with respect to the experimental data.

As already shown in different experimental activities carried out (Sebastiani et al., 2019) the results are well approximated by the typical trend of the Gaussian curve even if, especially in the case of samples with high I_c values, difficulties in the execution and dispersion of results.

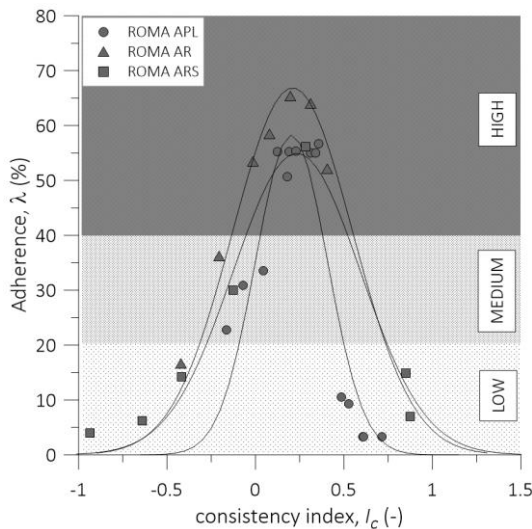


Figure 6 Results of the mixing test performed on APL soil samples and, as a comparison, on AR and ARS soil samples.

The results highlighted relevant differences between the results provided by the mixing test and the pull-out test. In particular, it is clear that the mixing test leads to very similar results in terms of maximum clogging risk, between 55% and 65%. On the other hand, the pull-out test leads to different results with a very limited maximum pull-out force for the ARS sample and very accentuated for the APL sample with a much higher clay content.

The position in terms of I_c of the peak is also different in the case of the two tests: in the mixing test the peak of the three Gaussian curves is substantially superimposed for values of $I_c=0.25-0.3$; on the opposite, in the case of the pull-out test, the peak for the three soil samples is different and, in the case of the APL sample, it is obtained for I_c values higher than 0.5.

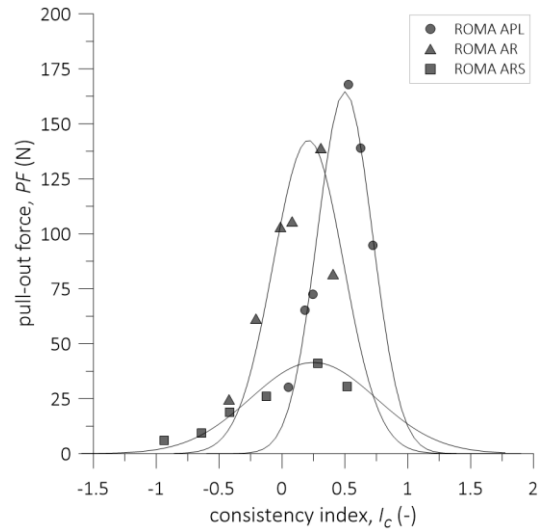


Figure 7 Results of the pull-out test performed on APL soil samples and, as a comparison, on AR and ARS soil samples.

This apparent inconsistency of the results of the two laboratory tests had already been found in previous laboratory activities described by Sebastiani et al. 2017 and 2019. In this regard, one of the critical points on the studies on conditioning repeatedly found by various authors is the absence of shared standards on the execution of laboratory tests. Considering the differences of the APL clays from the other fine-grained media shown (AR and ARS) it is believed that the results provided by the pull-out test are more reliable and reasonable than those produced by the mixing test.

In the following figures 8 the results of the mixing tests on different samples of APL clay formation before (NC) and after the soil conditioning process with the four different chemical products and the dosage described in Tables 2, 3, 4 and 5 are shown.

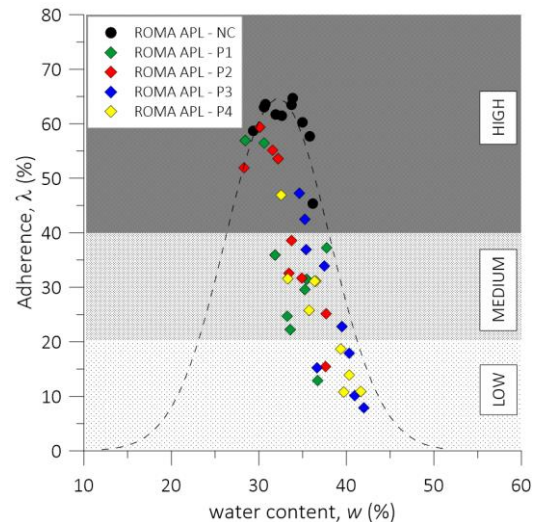


Figure 8 Results of the mixing test performed on APL soil samples before (NC) and after the soil conditioning process.

As can be seen, different results were obtained for each product depending on the soil conditioning characteristic parameters used. In general, however, it is possible to note how there are two products, P1 and P2, which for different I_c considered, provide lower adherence values than those measured on the “not conditioned” samples (NC).

The ability to reduce the risk of clogging without an excessive injection of water is one of the elements of an effective soil conditioning.

From this point of view it seems evident that the results of the mixing tests provide substantially coherent results for samples of conditioned soil, demonstrating that that test is able to provide reliable and consistent results on the effectiveness of a given conditioning in reducing clogging risk.

Confirmation of the validity of these claims comes from the results of the fall-cone tests presented in the following figure 9.

It is possible to note, in fact, as the same products that had shown positive signals of an effective reduction of the clogging risk from mixing and pull-out tests are related to an higher reduction in undrained strength for relatively low values of water content.

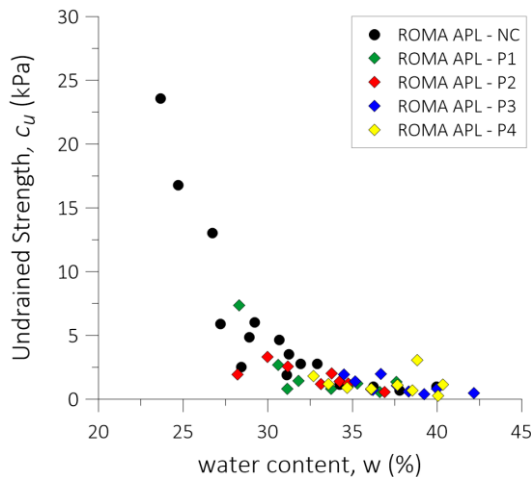


Figure 9 Results of the fall cone test performed on APL soil samples before (NC) and after the soil conditioning process.

5. CONCLUSION

The mechanized excavation of the tunnels for the construction of Metro C in Rome provided for the crossing of the Plionece clay formation; this formation, never affected by the excavation of the tunnels of the previous underground lines, presented a series of possible complexities linked to the greater plasticity and greater presence of clayey fraction.

A study specifically developed by Metro C and Sapienza, University of Rome was developed in order to investigate the characteristics of this fraction with specific reference to the clogging risk and verify the differences between the performance of four different conditioning chemicals.

The parallel execution of mixing tests and pull-out tests allowed to verify the limits and advantages of each test and to compare the results. In particular, for the tests on the untreated soil samples, the mixing test, together with several limitations related to the difficult execution of the test for high I_c , provided very similar results for the APL formation and for other formations involved in the excavation having physical and mineralogical characteristics. On the other hand, the pull-out test proved to be able to highlight the peculiarities of each formation with respect to the clogging risk.

The results of the mixing test on conditioned soil samples highlighted how the P1 and P2 products showed the best results in terms of clogging risk reduction, particularly in the range of the critical water content/consistency for the development of this phenomenon.

These statements are confirmed by the results of the fall-cone test elaborated in terms of undrained strength which have shown how this test can be a useful confirmation tool (to be used also on site) for the definition of the effectiveness of a soil conditioning process.

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