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The management of the soil conditioning process for the excavation of the Rome Metro C line

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ABSTRACT: Tunnel excavations in urban areas are often performed with TBM and Earth Pressure Balance technology which requires the continuous injection of chemicals in the soil conditioning process. Several advantages can be achieved by performing laboratory activities prior to starting the excavation in order to predict risks such as clogging in fine grained soils or severe cutter-head wear in coarse soils and to define an optimal range of values for injection parameters. Since the in-lab reproduction of all the conditions occurring during the excavation is hardly possible, measurement performed directly on site and TBMs monitoring data analysis are relevant tools to improve the knowledge on soil conditioning process and chemicals management. For the project of the Rome Metro C line, laboratory tests and on-site measurement were performed and useful information on excavation were drawn from the analysis of the recorded data. The results provided insights on advantages, limits and differences of results between laboratory-scale and on-site soil conditioning.

1 INTRODUCTION

Starting from the first applications of EPB-TBM in Japan, described by Fujita (1981) and in Europe with the projects of Passante Ferroviario in Milan (Peron & Marcheselli, 1994) and the subway line in Valencia (Herrenknecht & Maidl, 1995), cases of applications of the EPB technology and foaming agents, currently used in most tunnel excavation projects, especially in urban environments, are well known in literature.

Several studies and practical excavation experiences were performed by Nishitake (1990), Babendererde (1998), Babenderende (1991), Jancsecz et al. (1999) and Langmaack (2000) and provide important information and best practices on the management of the soil conditioning process.

Concurrently with said excavation experiences, several studies were developed starting from Bezuijen et al. (1999) and with the joint research activity between Cambridge and Oxford which led to the works by Milligan (2000), Psomas (2001) and Mair et al. (2003).

The evolution of the tunnelling world led us, on one hand, to more audacious projects and more and more complex excavation conditions but, on the other hand, to new, powerful and technologically advanced TBMs, new and more effective chemicals (foaming agents, additives and polymers).

Some general suggestions can even be found in literature, such as EFNARC (2005), illustrating the fast advancements of technology, geotechnical and chemistry and providing precise information which are of a considerable importance to properly manage the conditioning process during the excavation, although specific experimental studies should be performed in specifically equipped laboratories.

This work shows the results of the experimental activity performed at Sapienza University of Rome in cooperation with Astaldi and Metro C, aimed at supporting the soil conditioning process for the excavation of Rome Metro C line, from the selection of products to the management of injection parameters during excavation.

2 THE ROME METRO C PROJECT

2.1 *Metro C line project overview*

Line C is Rome's third subway line. Once completed, it will cross the city from the Northwest to the Southeast, for a total length of 25.6 km and 30 stations, almost doubling the extent of the currently existing underground network. It is also the first fully automated underground line in Rome.

Metro C S.p.A. is the General Contractor, formed of Astaldi (Leader), Vianini Lavori, Ansaldo STS and CMB, entrusted with the construction of Line C in all of its phases: from the design to the archaeological surveys, from building the tunnels to the stations and trains, up to the management of the start-up phase.

The activities started in 2006 with the archaeological surveys and the final design; currently, there are 22 stations and about 19 km of line in service.

For the construction of currently serviceable tunnels, the General Contractor used 4 EPB TBMs, having a cutter head of a diameter of 6.70 m.

Section T3 (Colosseo - San Giovanni), currently under construction, extends across the city's historical centre and very near (sometimes underground crossing) monuments dating back to the age of the ancient Romans, such as the Colosseum, the Aurelian Walls and Basilica of Massenzio. For this reason, extremely effective and innovative technical solutions were devised to reduce settlements.

In order to safeguard all the monuments, Metro C set up a specific Scientific Technical Committee (STC) the members of which include world-famous professors. The purpose of this Committee was to ensure high-quality research methods and to analyze potential interactions between the new line and the historical monumental heritage. The Committee coordinates and supervises the activities of working groups of specialists. The 5 work teams - consisting of university professors and specialists - operate in the following fields: Geology,

Figure 1. General overview of the stretch T3 of the Rome Metro C line.

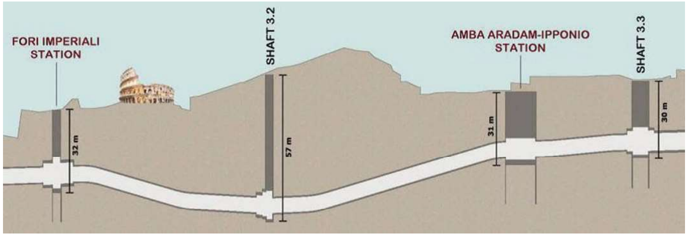


Figure 2. Longitudinal section of the tunnels excavation layout between S. Giovanni shaft and Fori Imperiali stations.

Geotechnical Engineering, Restoration and Preservation, Structural Engineering, Monitoring Systems.

The T3 section starts at San Giovanni station and is about 3 km long. It includes two stations, Amba Aradam station and Fori Imperiali station, and two shafts provided with ventilation systems (TBM shaft 3.3, and shaft 3.2). The T3-section tunnels, excavated by two EPB TBMs, have a variable depth from 30 to 60 m.

The first part of tunnels extends beneath the Aurelian Walls at Porta Metronia, while the other end of the tunnels extends along Via dei Fori Imperiali, very close to the Colosseum and the Basilica of Massenzio.

Due to the context, one of the first requirements is the control of subsidence, in order to prevent any damage to the archaeological structures above ground level. To achieve this goal during the excavation by the TBMs, good soil conditioning is essential but not trivial due to on-site geotechnical conditions.

The excavation layout is characterized by the presence of various litho-stratigraphic units; starting from the surface level downwards, the following formations are expected to be found:

- backfill material (R), with heterometric and heterogeneous elements in a sandy-silty matrix, of varying density and/or consistency;
- recent alluvial deposits of the Tiber river and its tributaries (LSO), consisting of silty clays, clayey and sandy silts, sand and silty sands with variable organic content;
- pre-volcanic fluvial-lacustrine deposits, including two sub-units: an upper unit (AR) formed of clayey silts and silty clays with various sandy interbeddings (ARS), and a lower unit (SG) of medium-coarse grain sands with gravel;
- marine sediments (APL), formed of silty clays and clayey silts of a grey - light blue colour, with alternating fine-grain sand levels.

Moreover, the excavation has to be carried out below groundwater level.

3 THE PRELIMINARY LABORATORY TESTS

3.1 *Generalities*

In a fruitful cooperation between Metro C, Astaldi S.p.A and Sapienza University of Rome, an intense experimental activity, to be developed preliminarily and concurrently with tunnel excavation activities, was planned to deal with the management of soil conditioning.

The general approach includes the division of the excavation layout into three successive phases: the first one characterized by *AR, ARS* and *LSO* lithotypes, the second one by the medium-coarse grain (*SG*) and the last one by the pliocenic grey-light blue clays (*APL*), encountered by the TBM in this sequence.

Before the beginning of the excavation, samples of soil belonging to the various lithotypes were taken from the vertical shaft 3.2 showed in Figure 2 and were examined at Sapienza geotechnical laboratory.

Based on the soil samples, several different products suitable for the excavation were selected from major European suppliers; different samples of the products were placed in white tanks marked with a code, so all the tests performed in the laboratory and described below should be considered as "blind tests", performed without being aware of the commercial products tested.

Laboratory activities included:

- identification and classification tests on the soil samples, including grain size distribution, water content and Atterberg limits;
- tests on each chemical product, including specific weight, viscosity, pH and Total Organic Carbon (TOC);
- stability (half-life) tests of the foam generated by using the different foaming agents;
- clogging measurements (mixing test and pull-out tests) on soil samples before and after the conditioning process performed at the laboratory by using particularly developed apparatuses, described in Di Giulio et al. (2018);
- the same tests during the excavation progress, taking samples at regular intervals and comparing results with those obtained in the preliminary tests.

The aim of the experimental activity was, on one hand, comparing the performance of different products and different dosages in order to provide preliminary indications for the selection and the dosage of the foaming agents to be used during the excavation and, on the other hand, acquiring information on the behavior of the different lithotypes described before conditioning, so as to foresee possible risks, as clogging or uncontrolled wear on the cutter-head. Moreover, the experimental activity allows to create a large database of results of the tests performed on samples taken directly from the jobsite, necessary to fill the gap between the experimental studies performed at the laboratories and actual tunnelling projects.

At present, only the first phase of the excavation has been completed and, consequently, only the preliminary activity data and the results of the samples taken on site belonging to the *AR*/*ARS* and *LSO* lithotypes (whose characteristics are reported in the Table 1) are available.

3.2 *Tests on foam samples*

The most commonly performed test to verify the stability of the foam over time is the half-life test or drainage time measurement. Even if, as suggested by Mori *et al.* (2018), there are significant differences between the laboratory test, carried out at atmospheric pressure and controlled temperature, and the excavation chamber, in which the foam is mixed with the ground under pressure and relevant pressure variations occur, the test results can be an important element for the assessment of the properties of a foam.

The half-life test is one of the tests proposed by the EFNARC guidelines (2005) and is essentially performed by filling a glass cylinder with 80 g of foam and measuring the time necessary to drain 40 ml of liquid into a graduated cylinder placed underneath a funnel, defined half-life time, *hlt* (Figure 3).

The results of the tests carried out on the four tested products at a standard concentration of 2.0% and at different values of *FER* are shown in Figure 4 according to the classification system developed in the Geotechnical Laboratory of Sapienza based on more than 650 tests performed and currently used to provide comparative evaluations on the stability of the foam.

Table 1. Grain size distribution and Atterberg limits of soil samples.

	Grain size distribution				Atterberg limits		
Sample	gravel (%)	sand (%)	silt (%)	clay (%)	LL (%)	LP (%)	IP (%)
LSO	2	21	31	46			
AR	0	4	61	35	45.1	21.4	23.7
ARS	0	40	50	10	24.6	18.6	6.0

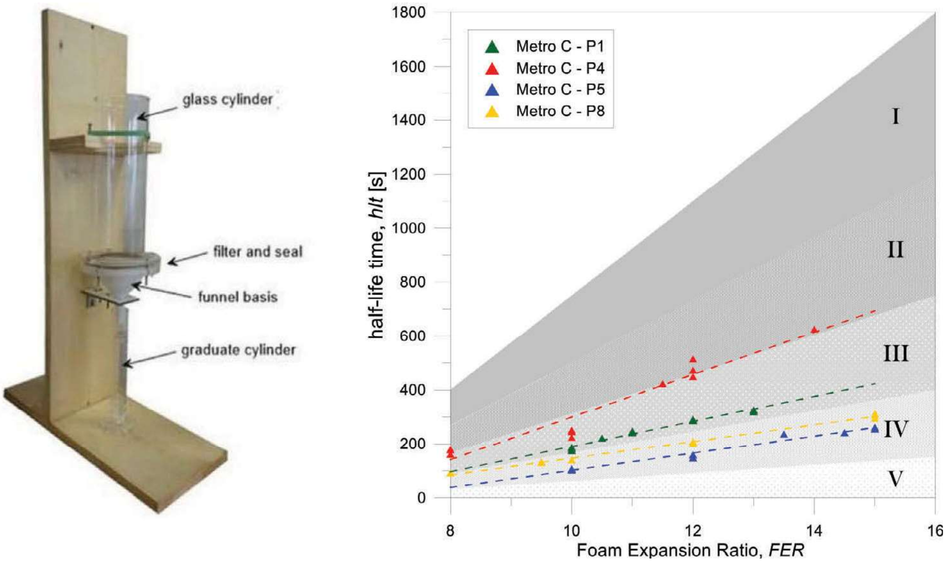


Figure 3. Half-life time test apparatus and half-life times measured.

Appreciable differences were recognized between the stability of the foam generated by the various products at the same concentration and in the range of tested *FER* values: the product P4 is always more stable than the others, positioning in the field of stability II, the product P1 has a stability corresponding to the field III while P5 and P8 have lower stability.

3.3 *Mixing tests*

After the foam characterization, tests were carried out on soil mixed with water and conditioned soil samples using injected water amount and conditioning parameters variable within commonly used ranges for the excavation of fine grained soils.

One of the most commonly performed laboratory tests to verify the achievement of the optimal consistency for the excavation and the reduction of the clogging risk is the mixing test, suggested by Mori *et al.* (2018).

The test consists in letting the soil rotate inside the Hobart mixer (Figure 4a) and in measuring the amount of soil remaining attached to the tool, expressed by the *#x03BB;* parameter, defined as the ratio between the stuck soil and the total amount of soil used for the test.

Tests were initially performed on the soil mixed with only with water w_{nat}, so as to have a basis for comparison with the subsequent tests performed on samples of the same soil mixed with water (the naural water content w_{nat} and the water content added, w_{add}) and foam generated using the four selected products. Figure 4b shows the results of the tests performed on *AR* and *ARS* soil samples; typical behaviors were recorded with curves having low clogging risk for low and high water contents (w_{ant} + w_{add}) and a peak, in the field of high clogging risk, in the middle.

As expected, due to the combined effect of grain size distribution and Atterberg Limits variation, the curves related to *AR* and *ARS* have a peak for very different water content values; tests performed on a soil sample composed of 50% of *AR* and 50% of *ARS* artificially prepared into the laboratory and representative of a mixed excavation section, resulted in a curve between the first two, establishing a relationship between the water content of the sample with an higher clogging risk and the grain size distribution.The same tests were performed on the same soil samples after a soil conditioning process performed by using foam generated at a laboratory foam generator plant equipped with a foam lance taken directly from the TBM actually used for the tunnel excavation. The undrained strength *Cu* on the same soil samples was measured by using a fall-cone test apparatus.

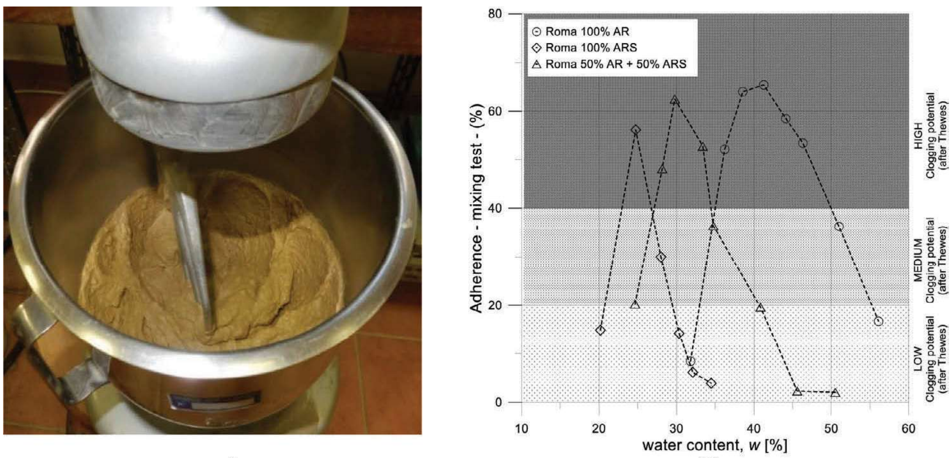
Following the EFNARC standards and on the basis of previous experiences, tests were performed by using a fixed value of *Cf* of 2.0%, variable values of *FER* in the range of 8-12 and variable values of *FIR* and water added apart with the purpose of making the soil reach the proper consistency (measured using standard slump and flow table tests according with EFNARC standards) required for EPB-TBM excavation.

The tested parameter combinations for the four products are listed in Table 2 below. The same Table 2 also sets forth a list of the average values (3 measurements) recorded when performing the mixing tests, as also shown in Figure 5.

The measurement obtained from the mixing tests and the fall-cone test revealed meaningful differences in the use and in the resulting effectiveness of the four tested products. The decrease in #x03BB; values related to the use of the products P4 and P5 if compared to the #x03BB; values recorded for products P1 and P8 is particularly clear. For all the products, relative better results were recorded using *FER* values of 8 and the required *FIR* values are lower for P4 and P5 (between 30% and 50%) than for P1 and P8 (between 60% - 100%). Starting from the natural content of 27%, the amount of water added for the tests was about 10% for products P4 and P5 and about 15% for products P1 and P8. The same effect is visible in the differences in the results obtained from the fall-cone test performed on the same soil samples and represented in terms of undrained strength *Cu*, even if, considering the variation of the saturation of soil samples due to the foam injection, it is not considered, in theory, correct to correlate the differences in results obtained to the undrained strength.

On the basis of the results of the comparative tests on the *AR* soil showed in Figure 6, it is deemed that the Metro C-1 and Metro C-8 products are able to effectively condition the soil only if injected in relatively large quantities and injected together with relatively high amount of water; vice versa, the results of the tests show that the Metro C-4 and Metro C-5 products are much more effective in reducing the natural tendency of the *AR* soil to adhere to metal elements and its undrained strength while achieving, at the same time, the right consistency in the soil.

Finally, it was noted that to obtain slightly better results a lower volume of foam generated with the Metro C-4 product was required to be used if compared with the case of the Metro C-5, which, however, is the most stable, as it appears from the half-life time described in Figure 3 and it was considered the most suitable for the conditioning of the *AR* lithotype.



a) b)

Figure 4. a) Hobart mixer test apparatuses and b) results obtained performing the mixing tests on *AR* and *ARS* soil samples on the classification chart proposed by Thewes.

Table 2. Materials used and features for test tools.

Product 1	Cf (%)	FER (%)	FIR (%)	w_{add} (%)	λ (%)
	2.0	10	65	8.5	61.64
	2.0	10	85	8.5	62.41
	2.0	10	85	12.0	47.54
	2.0	10	65	15.0	47.43
	2.0	10	85	15.0	42.94
	2.0	10	100	15.0	31.39
	2.0	10	65	18.0	30.10
	2.0	8	85	15.0	5.11
	2.0	8	65	18.0	6.07

roduct 4	Cf (%)	FER (%)	FIR (%)	w_{add} (%)	λ (%)
	2.0	12	85	15.0	8.03
	2.0	12	50	15.0	11.01
	2.0	10	50	12.0	11.31
	2.0	10	40	10.0	23.81
	2.0	8	50	12.0	8.61
	2.0	8	40	10.0	19.57
	2.0	8	30	10.0	22.36
	2.0	8	40	8.5	30.74
	2.0	8	50	8.5	19.77

Product 5	Cf (%)	FER (%)	FIR (%)	w_{add} (%)	λ (%)
	2.0	10	65	12.0	14.55
	2.0	10	85	12.0	17.43
	2.0	10	85	10.0	26.13
	2.0	10	65	10.0	23.14
	2.0	8	85	10.0	15.08
	2.0	8	100	10.0	22.12
	2.0	12	50	10.0	23.46

roduct 8	Cf (%)	FER (%)	FIR (%)	w_{add} (%)	λ (%)
	2.0	12	85	18.0	37.49
	2.0	10	85	18.0	25.69
	2.0	10	100	15.0	33.80
	2.0	10	100	18.0	30.50
	2.0	10	85	20.0	26.20
	2.0	8	65	12.5	49.59
	2.0	8	65	15.0	50.42
	2.0	8	85	15.0	42.99
	2.0	8	85	18.0	16.54

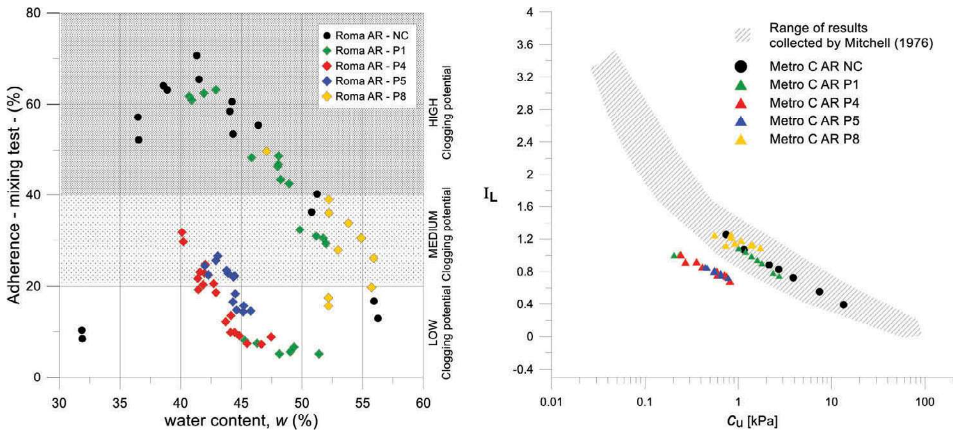


Figure 5. Mixing test and fall-cone tests results on conditioned soil samples.

The results on the *ARS* and *LSO* soil samples, not shown, confirm the relative ease to achieve the optimum consistency due to low plasticity and high percentage of sand (and gravels in the case of *LSO*) and demonstrated the possibility of properly conditioning soil samples with any of the tested products.

All the products turned out to be suitable for conditioning ARS and LSO soils with the addition of water between 2.5 and 5% for ARS and between 8% and 12% for LSO, *FER* values of 8-10 and *FIR* values between 50% and 60% for both the lithotypes.

4 THE MANAGEMENT OF CONDITIONING PROCESS DURING EXCAVATION

4.1 *Generalities*

The results presented in this paper are based on the database of parameters recorded during the excavation of the tunnels of the Metro C line in the section between Shaft 3.3 and Amba Aradam – Ipponio station. The excavation started in March 2018 and was completed in approximately 4 months. The data collected during the excavation of the first of the two tunnels have been processed to obtain the correlations set forth herein. Considering that the TBM launching shaft 3.3 is smaller than the TBM machine, the launching operations has to be executed in a plurality of steps. Moreover, the first excavation steps are generally used to calibrate all the machine's parameters. These are the reasons why, in order to appreciate the overall tendency in the computational phases, the first 9-10 advancements have been neglected.

4.2 *TBM features*

The two TBMs used, Herrenknecht S409 and S410, for the excavation are of an EPB (Earth Pressure Balance) type. The excavation diameter is 6.69 m and the machines are designed to perform excavation through various lithotypes (tuffs, pozzolanic soil, silts and clays). The opening percentage of the machines' face is 40%. They can perform a minimum radius on the alignment of 190m. The lining installed by the machine is a ring consisting of 6 segments +1 key, with a thickness of 30 cm and a length of 1.4 m. The muck can be removed by either a belt conveyor and or a track system.

4.3 *The management of soil conditioning*

During the excavation for the *AR*/*ARS* lithotypes, the *Cf* value used was 2.5% during all the excavation, the average *FER* value was between 6 and 8, and the *FIR* between 70% and 75% as shown in the charts in Figure 6 and Figure 7 for the two TBMs S409 and S410.

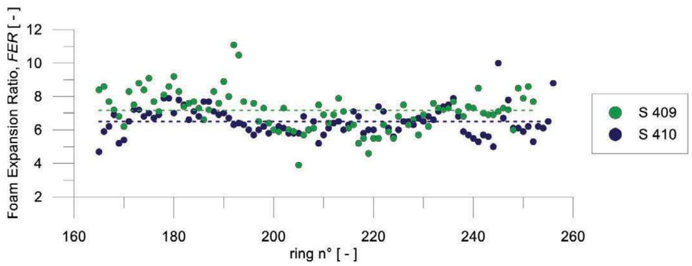


Figure 6. Foam Expansion Ratio (*FER*) values actually used during the excavation.

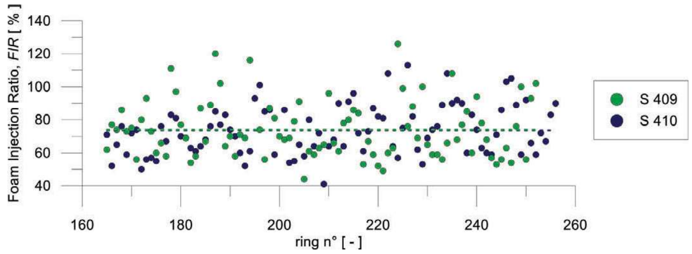


Figure 7. Foam Injection Ratio (*FIR*) values actually used during the excavation.

When compared, the soil conditioning parameter actually used and the results of the preliminary laboratory tests turned out to be generally in agreement and some general remarks can be expressed:

- the *FER* values used were similar to those used for preliminary tests; differences are due to the need, on site, to keep the excavation chamber at 3 bars of pressure at least consequently to the necessity of reducing the risk of dispersed air inside the chamber, reducing the injected air and, finally, reducing the *FER* values;
- the amount of foam injected (*FIR*) was extremely variable during the excavation; the overall average value is slightly higher if compared to the 60% values obtained from preliminary laboratory tests. The reasons therefor are likely attributable to, inter alia, the dispersion of foam during cutter-head rotation and the differences in the mixing process, apparently very effective at the laboratory, while negatively affected by the movement of the cutter-head and by the presence of blades within the excavation chamber when used with the TBM;
- the *Cf* value actually used was 0.5% higher: even in this case, considering that the foam generation is affected by the pressure in the working chamber, probably a higher surfactant concentration could compensate the lower accuracy in foam generation; in any case, it is believed that the recorded differences in *Cf* values do not affect the conditioned soil properties.

5 TESTS DURING THE EXCAVATION PROCESS

During the excavation of the tunnels, performed using Metro C-4 product, conditioned soil samples were taken from the site at regular time intervals. General characterization tests (water content, grain size distribution and Atterberg limits) were performed on this samples and the mixing and fall cone tests were performed in the preliminary tests on untreated soil samples and on soil samples conditioned at the laboratory.

Figure 8 shows the results of the tests performed on samples of soil taken from the site which, according to the grain size distribution, are attributable to a mixed AR/ARS excavation section.

Reportedly, they are samples taken during the first learning (launch) phase, samples of conditioned soil taken thereafter and, as a comparison element, the results of the tests performed on soil conditioned at the laboratory during the preliminary phase with conditioning parameters close to those used on site.

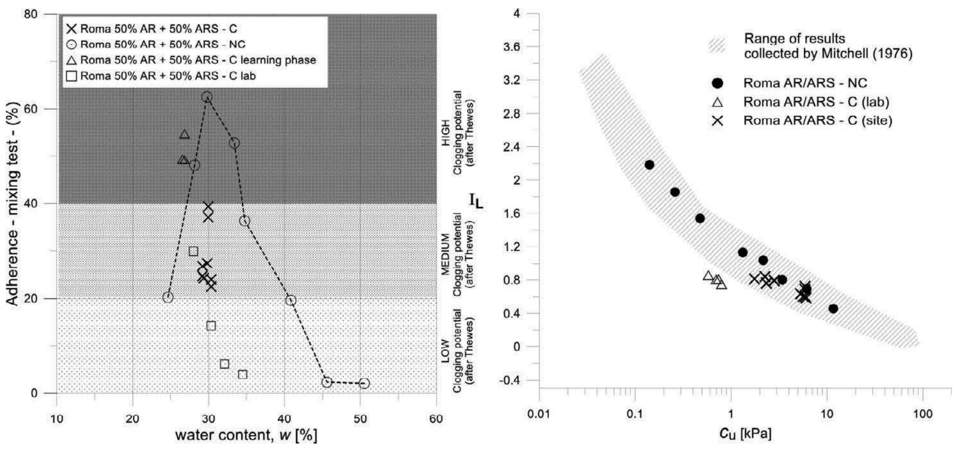


Figure 8. Mixing test and fall-cone tests results on conditioned soil samples taken from the TBM site.

Considering the results of the mixing test performed on the soil samples taken from the construction site relative to the *AR/ARS* sample, we can preliminarily notice a series of issues:

- the samples taken during the "learning phase" in the first 10 rings showed lower values than the maximum values recorded on the not-conditioned soil sample, but still within the field corresponding to an "high clogging risk";
- the samples taken during the further advancement, where the conditioning parameters have been optimized, are positioned in the "medium clogging risk" field;
- the variability in the grain size distribution and in the conditioning process effectiveness provides samples having adherence values of about 25% but also samples having values of 40%;
- in no case, during excavation, has been reached adherence values within the "low clogging risk" field, demonstrating the fact that on site is not as easy to achieve an optimal conditioning as the one obtained in a specific developed laboratory.

Similar conclusions can be obtained by reading the chart in figure 8, in which the undrained strength values are shown in relation to the Liquidity Index; it is clear that:

- the soil samples taken during the learning phase show an undrained resistance coincident with that of the ground conditioned with only water, a clear sign of non-optimal conditioning;
- by setting the conditioning parameters correctly, it has been possible to obtain lower undrained resistance values but still within the range of typical clay values (Mitchell, 1976);
- as in the case of the mixing test, on site, it was never possible to reach the *Cu* reduction values obtained by conditioning the soil in the laboratory.

6 CONCLUSIONS AND FUTURE DEVELOPMENTS

An extensive experimental activity was performed at "Sapienza" University in cooperation with Astaldi and Metro C in order to support the management of soil conditioning prior to and during the excavation of the Metro C line in Rome.

The laboratory tests have proved to be, as a whole, a reliable tool for the optimization of several operations, from the selection of the most suitable conditioning product to the management of the parameters during the excavation. The satisfactory correspondence between the parameters actually used for the excavation and the parameters tuned in the preliminary laboratory phase lead to conclude that, for the future, similar experimental activities can be helpful to predict the proper soil conditioning parameters (FER, FIR and added water).

In no case, the laboratory activities carried out in the preliminary phase will be able to replace the observation of the excavation parameters and the variation of the conditioning during the excavation phases based on the experience and know-how acquired in decades of tunnelling projects.

The ability to foretell the soil conditioning parameters with acceptable accuracy could be an useful instrument to develop projects including soil excavation works based on an "*ahead-of-excavation knowledge*" of the geotechnical and chemical features of the debris.

In the future, since the Metro C line excavation will face sandy gravel (SG) and clay (APL) lithotypes, further preliminary tests will be performed, additional samples will be taken directly from the site and further comparison elements will be recorded to enrich the present work.

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