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A comparison of laboratory tests for the evaluation of clogging risk in mechanized tunnelling

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A R T I C L E I N F O

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A B S T R A C T

Clogging is one of the most relevant issues in mechanized tunnelling with EPB-TBM in fine-grained soils. This phenomenon, caused by the interaction between soil particles and between soil particles and metallic surfaces of the TBM's cutterhead and working chamber, is influenced by several properties of the soil, mainly grain size distribution, plasticity characteristics and water content. To quantify the clogging effects, and ultimately to provide general indications for proper soil conditioning, classification systems based on laboratory test results were proposed in the last decade. The most adopted systems are based on the pull-out test, developed and used in different versions in several studies, and the mixing test, widespread both in the academia and among chemical suppliers and field engineers. In this work, these two kinds of tests were performed on eight fine-grained natural soils. On one soil, the tests were also performed after its conditioning with four foaming agents of different class and different dosages. The analysis of the results enables to: *i)* highlight the advantages and limitation of each test and provide a general overview of the relationship between clogging phenomena and soil properties; *ii)* find the correlations between the results of the two tests; iii) prove the usefulness of these tests in quantifying the efficacy of soil conditioning in reducing the clogging risk.

1. Introduction and Background

Due to their competitive advantages, the use of Tunnel Boring Machines (TBM) is often the preferred excavation method in most geotechnical scenarios. In the design phase, to optimize the performances and avoid relevant extra costs, all potential risks (i.e. failure, slowness or even blockage) must be thoroughly addressed. When excavating fine-grained soils, TBMs are usually equipped with Earth Pressure Balance (EPB) technology, and major concerns are raised by the risk of clogging.

Clogging leads soil portions to stick to each other and to the metallic parts of the TBM, causing difficulties in the excavation process, obstruction of the screw conveyor, problems in maintaining the desired pressure in the excavation chamber and provoking considerable increases of the required torque up to the blockage of the cutter-head.

The main factors influencing the occurrence of clogging are the so-called adhering and cohering (Fig. 1. Thewes and Burger, 2005). Adhering deals with the interaction between clay particles and metal surfaces and involves the exchange of normal forces and the consequent shear strength at the soil-metal interface. Cohering refers to the same entity but involves the normal forces at the grain-to-grain contact and the shear strength of the soil.

Clogging occurs when the shear stress acting at the soil-metal interface is less than the adhesion shear strength and, as a consequence, the soil remains stuck to the metal and the relative displacement between soil and metal occurs along failure surfaces forming inside the soil.. The phenomenon can evolve with a progressive thickening of the stuck clay until the excavation becomes problematic and, in extreme cases, it is necessary to stop the TBM and operate on the cutterhead or in the excavation chamber to remove the stuck material.

Unfortunately, the consistency of the excavated soil that is optimal for TBM-EPB excavation in order to correctly apply the earth pressure onto the tunnel face, is in similar range of the critical one for clogging risk. Thus, the optimum consistency cannot be achieved by injecting only water and, to reduce this risk, the soil must be treated by injecting chemical agents in the form of foam. The conditioning process consists in the injection of water, foam and/or polymers through the TBM cutterhead during the excavation and their mixing with the soil by its rotation and, within the excavation chamber, by the inner blades. The severity of the clogging phenomenon and the correct dosage of

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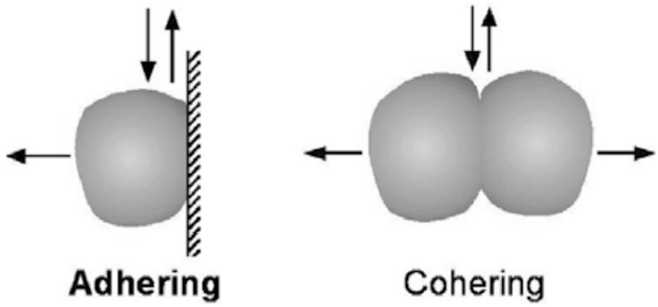


Fig. 1. Main factors influencing clogging (modified after Thewes and Burger, 2005).

conditioning agents necessary to its mitigation strongly depend on the intrinsic properties of the soil and its consistency.

Therefore, it is particularly important to be able to predict the occurrence of this phenomenon, evaluating the clogging risk in relation to the specific soil to be excavated and implement appropriate countermeasures already at the design stage.

Over time, several types of laboratory tests were developed to quantify and predict the risk of clogging and the appropriate dosage of chemical agents required to reduce it. In order to evaluate the effects of the forces that develop between soil particles and between soil particles and metallic surfaces (stickiness behaviour), responsible of the clogging phenomenon, pull-out test and mixing test are most commonly used.

In fact, the results of both tests depend on the two factors influencing clogging. The results of the mixing test, which involves relative displacements between the soil and the tool's metal surface, depend on both adhering and cohering, whereas the pull-out test measurements mainly refer to the minimum between adhering (during the pulling phase failure occurs at the interface and the soil does not remain stuck to the tool) and cohering (failure occurs inside the sample and some amount of soil remains attached to the tool).

The first experimental studies in which fine-grained soils, soil conditioning and tunnelling application are included can be traced back to Thewes (1999). These studies, based on mixing tests and pull-out test results, deeply analyse the relation between consistency and clogging potential in fine grained soils and propose a predictive abacus for the evaluation of potential clogging risk. For the evaluation of clogging risk for slurry shields, Thewes and Burger (2005) proposed a correlation between potential for clogging, consistency index (I_C) and plasticity index (I_P), based on the results of pull-out tests with a plate contact surface (Thewes and Burger, 2004).

In the meantime, other studies were conducted. Feinendegen et al. (2010) proposed the use of a pull-out cone test developed to detect the clogging potential of a soil in the preliminary phase of a project showing a peak in the measured pull-out force for $I_C \cong 0.4$. The same conclusions were reached by Feinendegen et al. (2011), indicating that soft/medium consistencies are to be regarded as critical for the clogging risk.

Zumsteg and Puzrin (2012) proposed the use of mixing test performed with the Hobart mixer for the evaluation the potential clogging risk, suggesting a classification system and a range of consistency index critical for clogging risks based on the results of the mixing test similar to that obtained with pull out test (Zumsteg et al., 2016). An attempt to modify the Hobart mixing test procedure was proposed by de Oliveira et al. (2019) in order to provide "*a qualitative assessment of the clogging and flow of soils to be excavated by an EPB machine*". Attempts like this have the limitation of requiring specific laboratory equipment and make the tests more complex and time-consuming, nonetheless they certainly are an incentive towards more consistent laboratory assessments of the clogging risk.

Hollmann and Thewes (2013) proposed an updated predictive abacus for the clogging potential in several excavation modes (i.e. open mode, slurry and EPB-TBM tunnelling). Among other conclusions, this study affirms that "*a soft consistency of material in the excavation chamber therefore is most critical for clogging*". Instead, when the clayey soil has a stiff consistency, the clogging tendency is comparatively less pronounced.

Over time, several authors (de Oliveira, 2018; Hu and Rostami, 2021; Todaro et al., 2022) have tried to focus on the importance with respect to clogging risk of the presence of chips or lumps in the excavation chamber, i.e., the effects of soil inhomogeneity. This resulted in the development of new tests even at a slightly larger scale.

More recently, other methods to assess the clogging potential were developed. Chen et al. (2022) studied the clogging potential of a natural weathered soil using a laboratory device that simulates shield tunnelling, finding that the risk can be estimated based on the variation of machine parameters such as drops in excavation rates or rises in torque. Fang et al. (2023) developed a study based on modified pullout tests and direct shear tests and proposed a new clogging potential assessment method for conditioned soil based on normal and tangential adhesion.

Further research aimed to correlate physical or mechanical properties of fine-grained soils to the clogging risk was developed by several researchers (Sebastiani et al., 2017; Alberto-Hernandez et al., 2018; Spagnoli et al., 2019; Baghali et al., 2020).

Regarding the conditioning process of clayey soils for the mechanized tunnel excavation employing the EPB technology, an intense experimental activity was developed in recent years by Sebastiani et al. (2019a); Sebastiani et al. (2019b) and, for specific tunnelling projects, by Pirone et al. (2019) for the Rome Metro C Project and Avunduk and Copur (2019) for the Akfirat wastewater tunnel Project.

Even though more than 20 years have passed from the first studies, the general behaviour of fine-grained soils in terms of clogging potential is currently an open research topic. Univocal interpretation of the phenomenon as well as universal accepted procedures (tests and test interpretation) for the risk evaluation are still missing.

Moreover, a complete and detailed description of the correlations between clogging risk and soil characteristics is still missing, as well as a unique way of evaluating the effectiveness of soil conditioning in minimizing the risk.

This work presents the results of a study based on an extensive experimental activity involving two of the main laboratory tests (mixing test and pull-out test) proposed in the literature for the quantification of the clogging risk. Fall cone tests were also carried out on all the samples subjected to mixing and pull-out tests. The tests were performed on eight clayey soils of different grading and plasticity properties.

This article does not have the ambition to cover all the elements that influence the formation and extent of clogging, but rather to provide an understanding of the differences that exist from the assessments regarding clogging that emerge from the results of two of the most common laboratory tests proposed in the literature for the assessment of "potential clogging risk.".

Three main objectives were pursued in this study. The first aim was to investigate the clogging phenomenon quantifying the relationship between its potential intensity and soil properties. To reach this purpose both mixing test and pull-out test on the same soil samples at different values of water content were performed.

A second aim of the study was the evaluation of the beneficial effects of soil conditioning and the effectiveness of the previously mentioned tests in their quantification. To pursuit this aim both mixing test and pull-out test were performed on samples of the same soil before and after its conditioning with four chemical products of different class and different dosages, at different values of water content.

The third aim was to find how the results of mixing and pull-out tests eventually correlate each other. To pursuit this aim, the results obtained on the two kinds of tests were systematically compared.

After the classification of the investigated soils and chemical products and a thorough description of the experimental methodology, the paper presents the results of mixing and pull-out tests performed and the correlations between clogging risk and soil properties (clay fraction, Atterberg limits and water content) are illustrated.

Then the results of the mixing and pull-out tests are compared in order to highlight similarities and differences and the correlations between the two tests are well established.

The same tests were finally performed on one of the selected soils after a conditioning process and the results were compared with the results obtained on the not conditioned samples.

Among others, the main finding of this research is the discovery of strong correlations between mixing and pull-out tests. The correlations confirm that, even though the tests measure different factors, both are related to the clogging phenomenon and can be used to assess risks. The discovered correlations, quantitatively transforming the results obtained with one of the two tests in the results of the other one, permit to compare results and classification obtained in different researches and represent a further step toward the full understanding of the phenomenon and the mitigation of the risk of occurrence.

2. Methodology: Soil samples, soil conditioning process and laboratory tests

In this section the soil samples considered in the study and their characteristics are described, as well as the tests performed and the standard followed including details on the sample preparation, the main precautions used and the issues encountered.

Eight different fine-grained (50 % or more by weight in grains smaller than 0.074 mm in diameter) natural soils from seven real projects of tunnel excavation in Europe were selected. With the aim of investigating clogging potentials ranging from low to high, the chosen soils have different grading and plasticity. In Table 1 the main characteristics of each soil sample are listed, including grain size distribution, Atterberg limits (w_L and w_P are respectively the liquid and plastic limit) and the activity, A. Fig. 2 reports the classification of the samples on the Casagrande plasticity chart. All samples were collected from shafts at the depth of tunnels excavation and reconstituted in the laboratory as detailed below.

Table 1
Main properties of the soils used in the experimental activity.

#	Soil sample	clay (%)	silt (%)	sand (%)	w_L (%)	w_P (%)	I_P (%)	A (−)
S1	Banzi	40	60	0	40	20	20	0.50
S2	Florence	37	43	20	36	21	15	0.41
S3	London	50	42	8	65	25	40	0.80
S4	Bucharest	28	52	20	48	24	24	0.86
S5	Rome ARS	12	38	50	27	19	8	0.67
S6	Rome AR	35	65	0	46	22	24	0.69
S7	Rome AR/ARS	24	51	25	35	20	15	0.63
S8	Naples	30	58	12	48	19	29	0.97

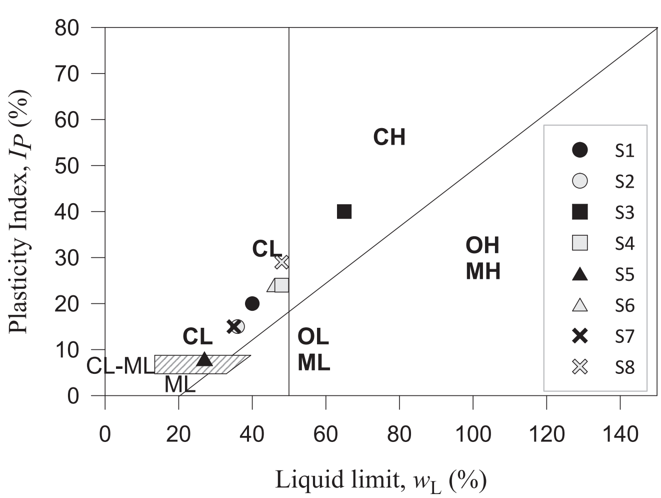


Fig. 2. Classification of the soil samples on the Casagrande plasticity chart.

The soil selection included a silty sand (S5 – Rome ARS) and a silty clay (S3 – London clay). The soil S7 is purposely composed by 50 % of S5 and 50 % of S6 to be representative of a mixed excavation front. All soils are inorganic and have medium–low plasticity, except for S7 and S5 which have respectively high and low plasticity. Therefore, the selected soils cover a relatively wide range of particle size distributions and plasticity index, I_P.

The experimental activities included mixing and pull-out tests, performed at different water contents. Fall-cone tests were also performed in order to fast evaluate the undrained cohesion, c_u, of the tested specimens. For saturated clayey soils, in fact, c_u is univocally related to the clayey soil consistency, a key parameter influencing the stickiness properties (Thewes and Burger, 2004).

For each soil, the tests were carried out on a unique sample of 1.8 kg of soil, obtained by initial quartering and oven dried at 105 °C, mixed carefully with distilled water for at least 30 min and left in an airtight container for at least 48 h, in order to ensure water content homogeneity.

The mixing tests were performed following the methodology proposed by Zumsteg & Puzrin (2012), and the Hobart mixer apparatus suggested in their paper and showed in Fig. 3 employing 1 kg of soil samples.

In some cases, for relatively high values of I_C, it was not possible to perform the Hobart mixing tests because the rotating tool struggled to mix the soil homogeneously and there was a risk of damaging the equipment.

The pull-out tests were performed following a methodology derived, with a slight modification, from the one proposed by Thewes and Burger (2005) and Khabbazi et al. (2019), in which the test is carried out using a tool with a flat surface put in contact with the soil sample before the pulling phase, and from the one proposed by Feinendegen et al. (2010) in which a conic tool is involved. The slight modification is an attempt to reduce the difficulty that has arisen in creating a conical hole in low consistence soil or conditioned soil which is unlikely to maintain the created shape leading to difficulties in the subsequent insertion of the cone for testing.

Preliminary tests were carried out using the tool suggested by Thewes and Burger, with a perfectly flat contact surface (tool diameter = 8.15 cm). The material tested was a fine-grained soil (50 % silt and 50 % clay) with high plasticity (w_L = 65 % and I_P = 36 %, A = 0.72). The results were highly scattered, as reported in Fig. 5. The way the tool is brought into contact with the soil is likely to be the source of the scattering, in fact, for geometrical reasons it is difficult to ensure good contact between soil and flat tool and also some air may remain trapped particularly in soft consistency samples. Recently, Fang et al. (2023) addressed this issue by modifying the soil container and using a new loading method.

In our study, the pull-out tests are performed adopting a tool with a convex contact surface (Fig. 3, curvature radius = 11.04 cm) and slightly modifying the procedure to put in contact the tool and the soil. Fig. 4 shows a picture of the whole pull-out test device. The experimental procedure is described in the following.

The samples are placed in a container (internal diameter = 10 cm, volume = 10^3 cm^3), taking care not to leave gaps or inhomogeneities. The upper soil surface is then regularized using a spatula. The base of the container is firmly connected with a press which is then moved upwards, towards the tool, until the convex part of the tool is no longer visible (Fig. 4). After waiting 1 min, the press is moved downward at a speed of 0.5 mm/s, measuring the displacement and the force every second until the tool is completely separated from the soil. The entire test is carried out quickly and without interruptions in order to avoid the change of water content of the contact surface. Following this procedure, the air cannot remain trapped, and the geometry of the soil-tool contact is always the same independently of the soil relatively low consistency

Fig. 3. Laboratory equipment used in the mixing and pull-out tests.

(while some difficulties in achieving a good soil-plate contact can be encountered at high consistency).

Using the same soil, the tests carried out with the flat tool were repeated adopting the methodology just described. The results (Fig. 5) are clearly less scattered than those obtained with the flat tool and fit better with a gaussian curve ($R^2 = 0.75$ vs 0.40). Furthermore, the pull-out values obtained with the convex tool are more than double respect to the ones obtained with the original procedure. This is another advantage of the new procedure, because a wider range of variation of measured values allows to better discern between low and high clogging risk and a better evaluation of the effects of soil conditioning.

Mixing, pull-out and fall-cone tests were also performed on soil S6 after its conditioning with different chemical products and dosages to evaluate the effects of the treatments. Four different chemical products (P1, P4, P5 and P8) of different class and many combinations of water content and conditioning parameters were tested.

Commercial foaming agents, used for this study, are solutions of water, surfactants (generally anionic, between 10 % and 50 %) and other additives (< 1 %), such as preservatives. The actual composition of the foaming agent is unknown in detail, even though, for all the four products (P1, P4, P5 and P8) used in this study the main anionic surfactant is the *Sodium Lauryl Ether Sulphate* (SLES) and only in the P4 product is also present the *Sodium Dodecyl Sulphate* (SDS). All tests were performed using a concentration factor (*Cf*) of 2 % (the definition of *Cf* is given later on).

Following the classification of chemical products based on the stability of the generated foam proposed by Sebastiani et al. (2019a), products P5 and P8 belong to class IV (the half-life time of the foam generated with these two products is low/moderate), while P4 and P1 products respectively belong to class II and III, being able to generate a more stable foam (Fig. 6).

The foam was generated using a specifically designed laboratory foam generation system available at the Department of Structural and Geotechnical Engineering of Sapienza University of Rome, described in Sebastiani et al. (2019a). The foam generator used is a 1:1 scale equipment taken directly from the injection system of a real TBM consisting of a premixing system and a metal cylinder containing glass spheres. All the main elements and their geometry are identical to the

Fig. 4. Pull-out test device with modified convex tool and detail of the plate-soil contact.

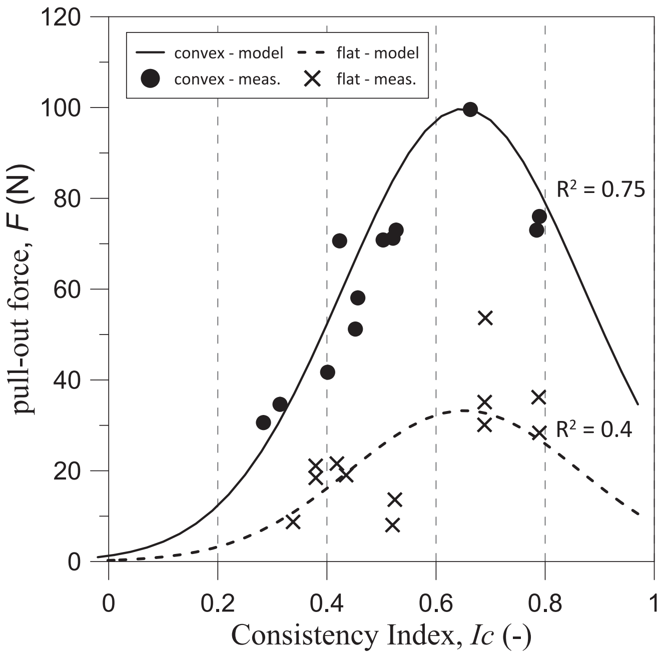


Fig. 5. Comparison of pull-out tests performed using a flat or a convex tool.

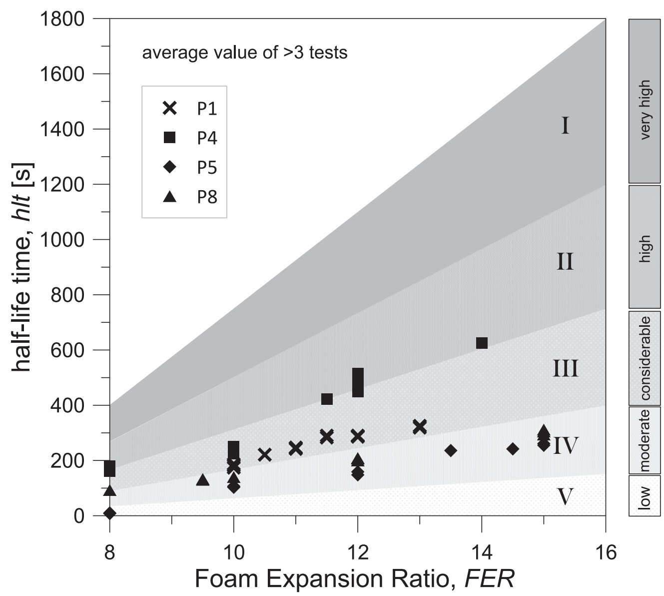


Fig. 6. Classification of the 4 foaming products employed (after Sebastiani et al., 2019a).

real ones, used with constant flow rates of 100 l/min. The details of the system are reported in Sebastiani et al. (2019a). Thus, the properties of the generated foam are essentially the same for all the tests carried out.

The main properties of the foam are described by the concentration factor (*Cf*) and the Foam Expansion Ratio (*FER*), which are defined as:

$$Cf(\%) = \frac{m_{fag}}{m_{sol}} \bullet 100 \quad (1)$$

$$FER = \frac{V_f}{V_{sol}} \quad (2)$$

where, m_{fag} is the mass of the foaming agent in the foaming solution, m_{sol} is the overall mass of the foaming solution, V_f is the volume of generated foam and V_{sol} is the volume of the foaming solution.

The amount of injected foam is quantified by the Foam Injection Ratio (*FIR*), defined as:

$$FIR(\%) = \frac{V_f}{V_{soil}} \bullet 100 \quad (3)$$

where V_f is the volume of injected foam and V_{soil} is the volume of treated soil.

The details of the amount of water and foam (*FIR*) and of the foam properties (*Cf* and *FER*) used are listed in the Table 2 where w_{nat} is the initial natural water content, w_{add} is the water content increment due to the amount of water added during the conditioning process and w_{tot} is the total water content. The last one is obtained adding to w_{nat} and w_{add} the further water content increment introduced with the foam. A comprehensive description of the details of the laboratory soil conditioning process is presented in Pirone et al. (2019) and Sebastiani et al. (2019c).

Table 2
Soil conditioning parameters used on sample S6 for a) product P1, b) product P4, c) product P5 and d) product P8. *Cf* always equal to 2.0% and w_{nat} to 27.0%.

a)

FER	FIR	w_{add}	w_{tot}
(x:1)	(%)	(%)	(%)
10	65	8.5	41.41
10	85	8.5	41.80
10	85	12.0	46.95
10	65	15.0	48.03
10	85	15.0	48.58
10	100	15.0	50.78
10	65	18.0	51.56
8	85	15.0	49.76
8	65	18.0	49.18
12	85	15.0	45.78

b)

FER	FIR	w_{add}	w_{tot}
(x:1)	(%)	(%)	(%)
12	85	15.0	47.05
12	50	15.0	43.91
10	50	12.0	44.49
10	40	10.0	41.99
8	50	12.0	44.95
8	40	10.0	42.81
8	30	10.0	41.50
8	40	8.5	40.16
8	50	8.5	41.65

c)

FER	FIR	w_{add}	w_{tot}
(x:1)	(%)	(%)	(%)
10	50	12.0	44.88
10	40	12.0	44.40
10	40	10.0	42.98
10	65	10.0	43.84
8	50	10.0	45.48
8	40	10.0	44.40
12	50	10.0	42.14

d)

FER	FIR	w_{add}	w_{tot}
(x:1)	(%)	(%)	(%)
8	65	12.5	47.34
8	65	15.0	50.81
8	85	15.0	52.26
10	85	18.0	52.70
12	85	18.0	52.53
8	85	18.0	52.17
10	100	15.0	53.82
10	100	18.0	54.87
10	85	20.0	55.90
6	85	15.0	55.73

In the laboratory, the soil conditioning was performed adding water and foam to the soil samples at its natural water content and mixing until a homogenous paste was obtained for 10 min. To ensure homogeneity and repeatability a mixer equipped with a rotating tool was employed, following a standard procedure described in Di Giulio et al. (2018). Since the foam bubbles could progressively collapse over time, changing the characteristics of the conditioned soil at a rate depending on the chemical composition of the foaming agent and the parameters of the generated foam (Mori et al., 2018; Sebastiani et al., 2019a), the tests were carried out immediately after conditioning the soil.

3. Results and discussion

3.1. Mixing tests

The results of the mixing tests are expressed in terms of adherence, or stickiness ratio, λ, defined in (Eq.4):

$$\lambda(\%) = \frac{G_{MT}}{G_{TOT}} \bullet 100 \tag{4}$$

where G_{MT} is the weight of soil sticking to the mixing tool at the end of the test and G_{TOT} is the total weight of soil used in the mixing process. Thus, the stickiness ratio quantifies the tendency of the soil to remain stuck on a mixing tool after a mixing process in the Hobart mixer.

Fig. 7 shows the results of the mixing test performed on the samples S5, S6 and S7 at several values of water content. For each soil the experimental results are presented together with a Gaussian curve (normal distribution) fitting the experimental results, described by the following Eq. (5):

$$\lambda(w) = \lambda_{pk} e^{-\frac{(w - w_{pk})}{2\sigma^2}} \tag{5}$$

where w is the water content, w_{pk} the value of water content corresponding to the peak of adherence, λ_{pk}, and σ is the standard deviation.

The Gaussian distribution fits well with the experimental data. The peaks of the adherence, for all the soil tested, are in a range between 55 % and 65 %. The S5 curve (Rome ARS, silty sand, low $I_P = 8$ %) shows the lowest λ_{pk}, w_{pk} and σ: the curve has the lowest peak, positioned at the lowest water content, and the lowest standard deviation (narrow curve). On the opposite, the S6 (Rome AR, clayey silt with no sand, medium $I_P = 24$ %) shows higher λ_{pk} and w_{pk} values and a wider curve. The curve of the sample S7, artificially reconstituted mixing the other two in equal parts, shows an intermediate behaviour.

To compare the results of all the experimental tests taking into account the different plasticity properties, in Fig. 8 the adherence measured on all soil samples at several water contents is presented as a function of I_C. In this way, the water content is normalized respect to Atterberg's limits and the abscissa become non-dimensional. As expected, also in this case, the experimental results are well reproduced by a Gaussian curve described by the following Eq. (6):

$$\lambda(I_C) = \lambda_{pk} e^{-\frac{(I_C - I_{Cpk})}{2\sigma^2}} \tag{6}$$

where I_{Cpk} is the consistency index corresponding to the peak value of the adherence. Fig. 8 also includes the classification system of clogging potential proposed by Zumsteg and Puzrin (2012).

All the soils considered in this study show similar behaviour (Fig. 9). The peak values of λ range between 55 % and 75 % and are in a range of I_C between 0.20–0.34.

The values of the three parameters of Eq. (6) obtained from the best fitting process (λ_{pk}, σ, Ic_{pk}) are listed in Table 3. The values of R-squared (R^2), also reported in Table 3, confirm that the experimental data are very well fitted by the Gaussian distribution. Fig. 10 highlights a correlation between these three parameters and the clay fraction of the soils, *CF* (% in weight of grains smaller than 0.002 mm in diameter). In detail, λ_{pk} increases with the clay content (with a quite robust correlation $R^2 > 0.8$) and so does in general Ic_{kp}, even though without a clear correlation ($R^2 = 0.177$), while σ decrease is weakly correlated with the clay fraction ($R^2 = 0.484$). Therefore, as *CF* increases, the curves become thinner and the clogging risks and the critical consistency index increase. Similar correlations exist with the fines fraction (clay + silt), but these are less robust.

3.2. Pull-out tests

As previously done for the mixing test results, Fig. 11 shows a first selection of results of the pull-out tests performed on S5, S6 and S7 soil samples. Usually, when the test was performed on a sample with high I_c the tool was mostly clean (without soil attached) after the pulling phase, meaning that failure occurred at the soil-metal interface and thus the measured force is the normal adhesion between soil and metal. When the tests were performed on low consistency samples, instead, some amount of soil remained attached to the tool, indicating that failure happened inside the soil and thus the force indirectly measures the cohering.

The results were interpolated with the Gaussian curve described by Eq. (7), conceptually identical to Eq. (5).

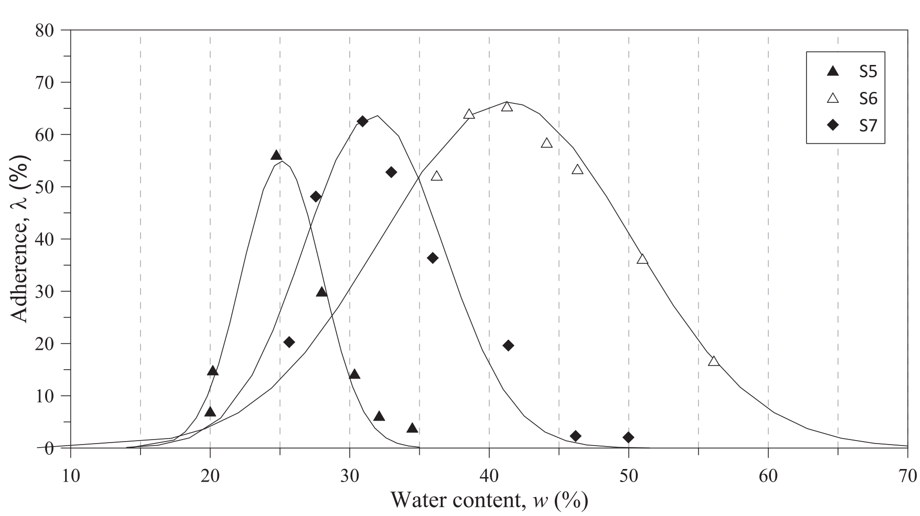


Fig. 7. Results of the mixing tests performed on S5, S6 and S7 soil samples.

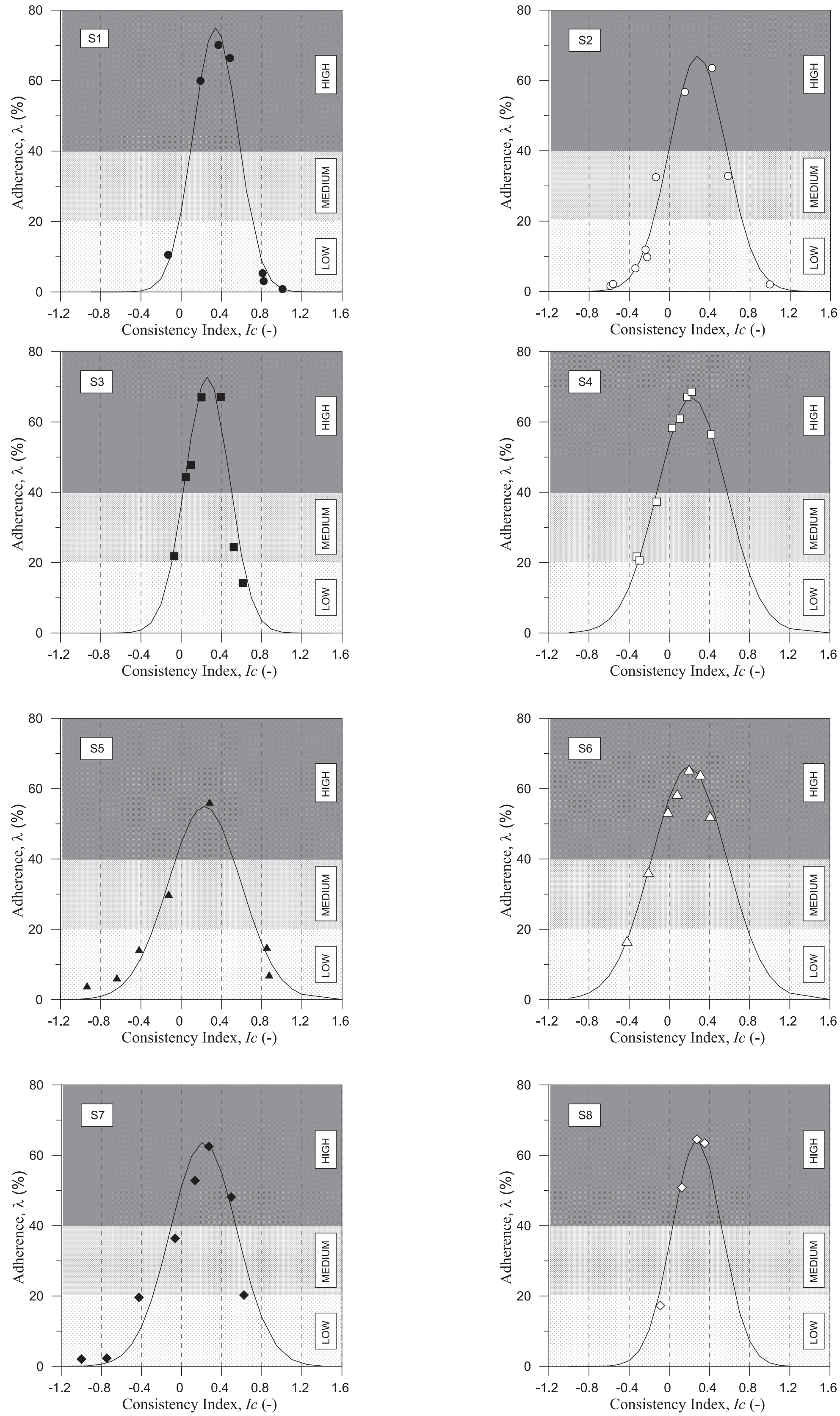


Fig. 8. Results of the mixing tests and fitting Gaussian distributions for all the soils tested (S1 − S8).

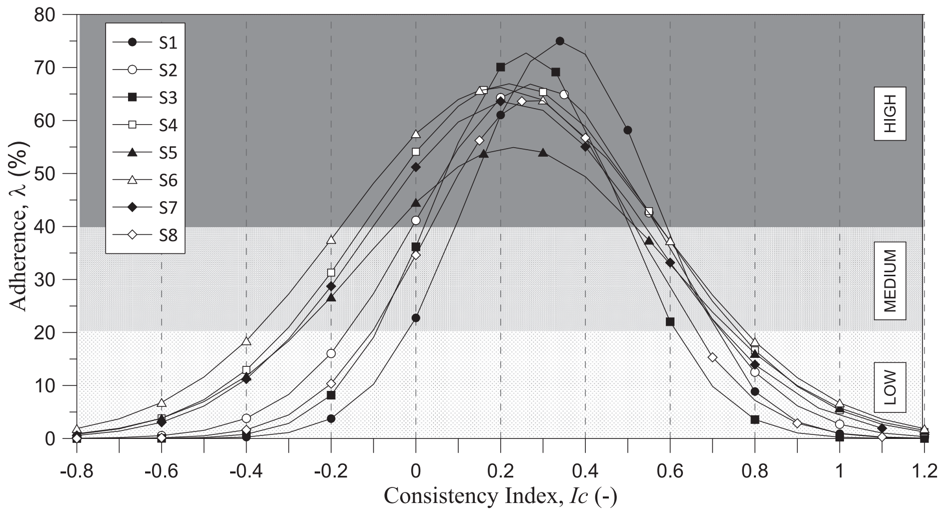


Fig. 9. Comparison of the results of the mixing tests.

Table 3
Best fitting Gaussian distributions parameters (Eq. (6).

#	Soil sample	λ_{pk}	σ	I_{Cpk}	R^2
S1	Banzi	74.79	0.22	0.34	0.99
S2	Florence	66.72	0.28	0.28	0.96
S3	London	72.53	0.22	0.26	0.90
S4	Bucharest	66.76	0.34	0.22	0.99
S5	Rome ARS	54.78	0.36	0.23	0.96
S6	Rome AR	66.05	0.37	0.20	0.97
S7	Rome AR/ARS	63.56	0.33	0.22	0.90
S8	Naples	63.83	0.25	0.28	0.98

$$F(w) = F_{pk} e^{-\frac{(w - w_{pk})}{2\sigma^2}} \quad (7)$$

where F is the pull-out force and F_{pk} is its peak value.

For the pull-out test results too, the Gaussian curves well represent the experimental data. The results also confirm what was observed from the mixing tests. The curve corresponding to the sample S5 (low plasticity silty sand) shows values of F and a ranges of water contents markedly lower than those of the sample S6 (clayey silt with no sand and higher plasticity). Once again, the sample S7 shows an intermediate behaviour.

The results of pull-out tests were also analyzed in terms of I_C and compared with the Gaussian curve described by Eq. (8), conceptually identical to Eq. (6).

$$F(I_C) = F_{pk} e^{-\frac{(I_C - I_{Cpk})}{2\sigma^2}} \quad (8)$$

The results are reported in Fig. 12 and compared in Fig. 13. The peak pull-out forces range between 40 e 200 N. The peaks occur for higher and more spread values of I_{Cpk} (0.25–0.5) than those registered in the mixing tests (0.2–0.34).

Table 4 lists the values of the three parameters of Eq. (8) resulting from the best fitting process.

As showed in Fig. 14, both F_{pk} (good correlation) and I_{Cpk} (weak correlation) increase as the *CF* increases. The standard deviation instead decreases as *CF* increases, but without a clear correlation.

3.3. Comparison of the results of mixing and pull-out tests

The relation between the parameters of the Gaussian curves fitting the experimental data obtained with the two kind of tests was also investigated. A linear relation was found (Eq. (9) between F_{pk} and λ_{pk} (Fig. 15). According to the available data, in the analyzed range, the relation is quite robust ($R^2 = 0.931$). At the peak, a pull-out force of 40 N corresponds to a value of about 55 % of the adherence, and λ_{pk} increases of about 0.114 for each Newton of increment of *Fp*.

$$\lambda_{pk}(\%) = 0.114 F_{pk}(N) + 50.64 \quad (9)$$

A clear correspondence also exists between the other two parameters, σ and I_{Cpk}, obtained with the two kinds of test. These two linear correlations are quite good, although characterized by smaller values of R^2 (Fig. 15). These results confirm the affinity of mixing and pull-out tests and, consequently, that the two test are able to investigate the same physical–chemical interaction between clayey grains and between grains and metallic surface. However, the maximum values of pull-out forces (and then of the clogging potential) are appreciably shifted toward higher values of consistency index than the adherence ones.

It's important to highlight that the peak pull-out forces, ranging between 40 e 200 N (ratio 5), show a greater sensitivity in quantifying the intensity of stickiness of clayey soils respect to the results obtained

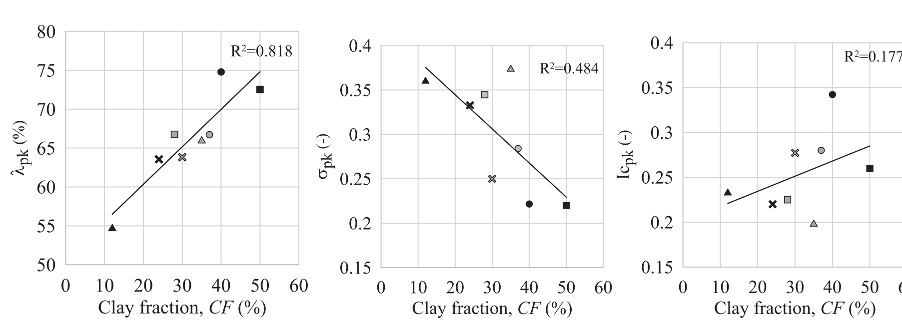


Fig. 10. Relations between key parameters of the Gaussian distributions and clay fraction of the soil samples.

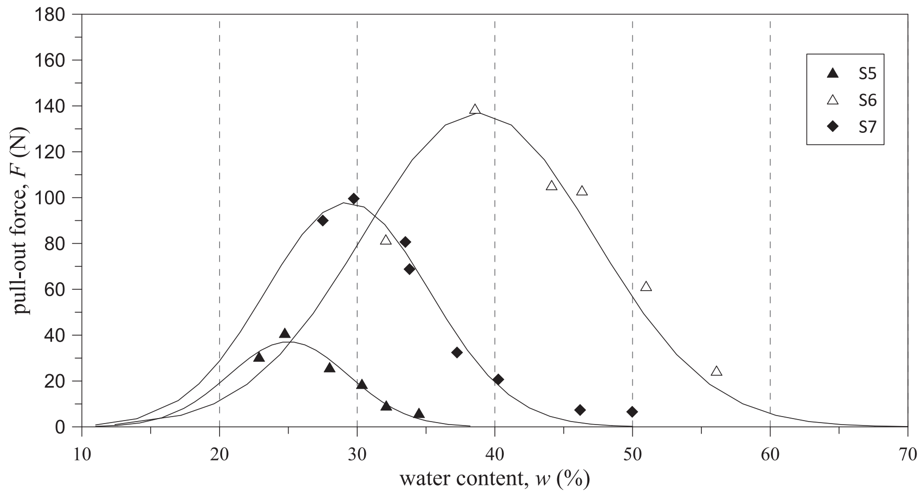


Fig. 11. Results of the pull-out tests performed on S5, S6 and S7 soil samples.

with the mixing test in which the peak adherence ranges between 55 and 75 % (ratio 1.36).

Furthermore, the relatively small value of maximum pull-out force recorded for soil with small clay fraction (i.e. sample S5, $F_{pk} = 40$ N, $CF = 12$ %) is in agreement with the non-occurrence of clogging phenomena in real tunnel excavations in soils with small percentage of clays (Hollmann and Thewes, 2013). This finding was much less evident in the results of the mixing tests, where the minimum and maximum values of peak adherence were much closer to each other and both fall in the range of high potential clogging (Zumsteg et al., 2013). Thus, following Zumsteg and Puzrin classification, also the potential clogging of sample S5 at a consistency index corresponding to F_{pk} is classified as high.

3.4. Soil conditioning

As mentioned before, S6 (Rome AR) soil samples were conditioned with four different commercial chemical products commonly used for mechanized tunnelling with EPB-TBMs, adding water and foam. The foam was generated using a laboratory foam generator specifically designed to faithfully replicate the flow, pressure and geometry of the real scale TBM foam injectors. Further details can be found in Sebastiani et al. (2019a).

The soil was conditioned using a laboratory mixer after being restored to its natural water content ($w_{nat} = 27$ %). The laboratory tests were carried out immediately after the mixing process, avoiding the risk of too much time elapsing, which would cause the foam properties to deteriorate and the characteristics of the conditioned soil to change.

Mixing tests and pull-out tests were then performed obtaining the results presented in Fig. 16.

The changes induced by the soil conditioning process are very much dependent on the product and dosage used. In the case of the products P1 and P8, the effects are generally negligible (except for a few P1 experimental data), leading to adherence and pull-out forces similar to those measured on not conditioned (NC) soil samples.

Specifically, the P8 product did not show particularly satisfactory clogging reduction potential results for any of the tests performed and the P1 product showed extremely dependent behavior on added water. When injected in the form of foam accompanied by a relatively low water volume, it made no positive contribution in reduction of adherence and pull-out force. Conversely, when added to relatively higher water volume it provided minimally positive results. This behavior is not particularly satisfactory because for values of $w > 50$ % even the natural soil without conditioning had shown medium/low clogging risk.

Differently, for the products P4 and P5 relevant beneficial effects were measured for all the combinations of conditioning parameters tested.

The comparison between the results of the two kinds of tests (Fig. 16a and Fig. 16b) highlights the greater sensitivity of the pull-out force in emphasizing the effectiveness of conditioning.

The pull-out test, in the case of the already rather low results obtained on the conditioned soil with the P4 and P5 products gave similar results to each other failing to highlight the differences as the mixing test had made slightly more markedly.

Fig. 17a shows the results of the fall-cone tests performed on all NC soil samples listed in Table 1. All the experimental results, interpreted in term of undrained cohesion, c_u, and reported as a function of the liquidity index, I_L, fall into the range of data collected by Mitchell (1976) on natural soils. This occurrence, being the c_u– I_L relationship very sensitive to the Atterberg limits values, indirectly confirms the accuracy of the Atterberg limits values summarized in Table 1.

Fig. 17b shows the results of the fall-cone tests performed on NC S6 soil samples as well as on samples of the same soil after the conditioning process. Tests carried out on samples treated with P1 and P8 products, in most cases ineffective in reducing the clogging potential, provide results falling into the same range of natural soils. On the opposite, all the results obtained on samples for which the conditioning process produced a marked reduction in adherence and pull-out force (mainly conditioned with P4 and P5 products) fall on the left side of this range. Thus, a well-conditioned soil can be identified comparing the undrained shear strength with the range of values typical of natural soils, evaluated at the current value of I_L of the conditioned sample. It's important to note that, referring to the average value of the range of results collected by Mitchell, for fixed value of I_L, a well-conditioned soil shows a marked reduction in c_u (70–80 % in average).

Even though further studies are necessary to evaluate the mechanical effects associated with the chemical interaction between surfactants and fine-grained soil particles, given the rather similar chemical nature of the basic compounds of the four conditioning agents used, it is likely that the reduction in undrained shear strength, adherence and pull-out force are all three a consequence of the volume of air entrapped into the conditioned soil through the foam. This volume is a function of the amount of air injected through the foam (combination of FER and FIR) and the tendency of the air bubbles to remain stable within the soil without collapsing, resisting the shocks caused by the mixing.

4. Conclusions

In mechanized tunnelling excavation through fine-grained soils the occurrence of the clogging phenomenon is one of the major risk that should be addressed at the design stage to implement appropriate

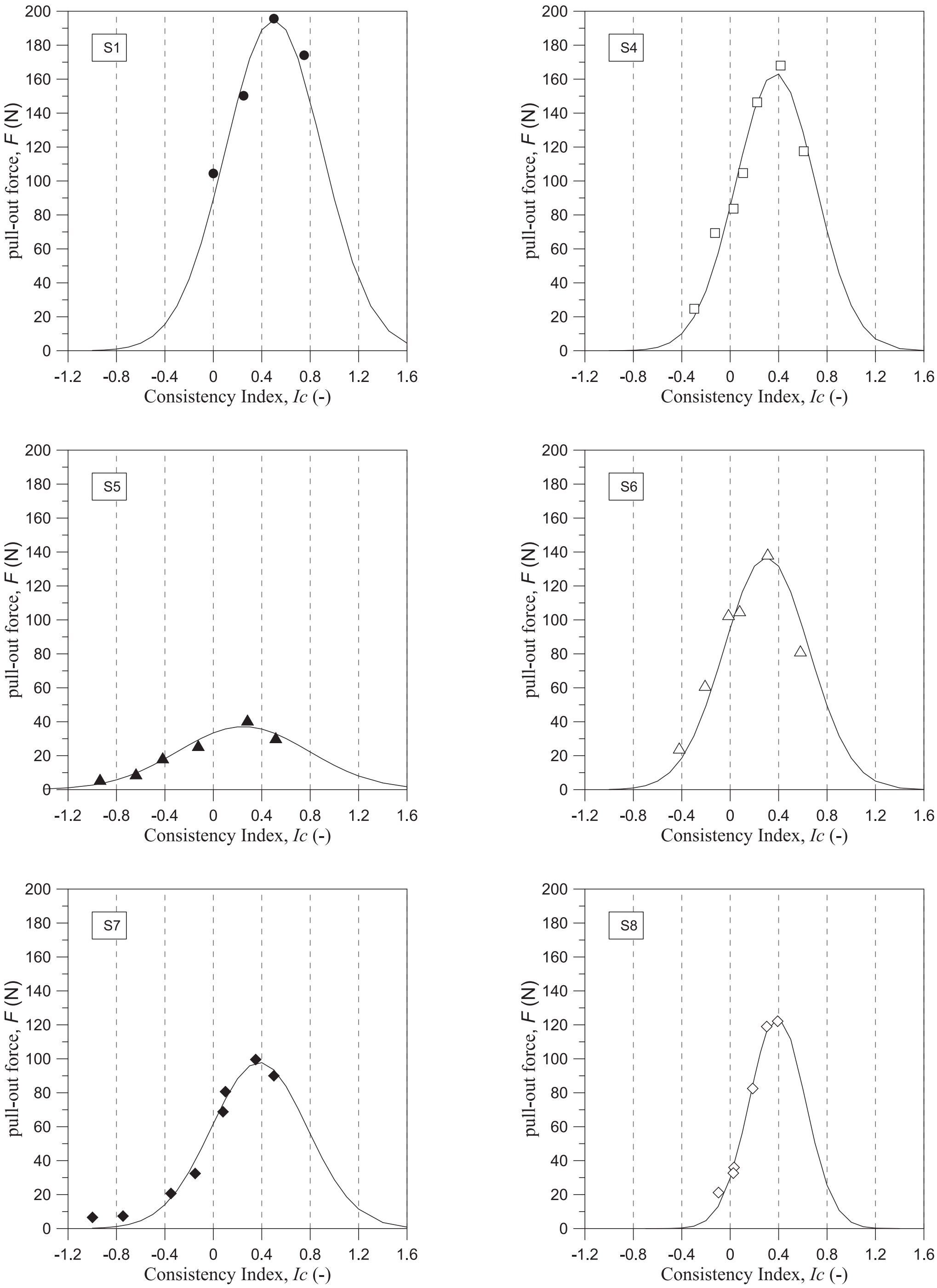


Fig. 12. Results of the pull-out tests and fitting Gaussian distributions.

countermeasures. In this paper, the results of an extensive laboratory experimental program, based on mixing tests and plate pull-out tests were reported and analysed.

Eight different fine-grained natural inorganic clayey soils of different grain size distribution and a wide range of plasticity properties were tested with different water content/consistency index. Some tests were also carried out on a soil also after the conditioning process performed with 4 chemical products of different classes and different dosages, to evaluate the effectiveness of the treatment in reducing the stickiness of the clay and, therefore, the clogging risk.

The main results of this research regarding natural soils are summarized in the following.

1. both laboratory tests explored have relevant limitations in performing the tests for relatively high Ic values; in any case, natural soils with $I_C > 0.6$ are rarely excavated by applying EPB mode, thus this limitation seems of secondary importance for practical tunnelling applications;
2. As the soil plasticity index increases: *i)* the maximum values of adherence and pull-out force increase; *ii)* the values of consistency index at which these maximum values occur increase; iii) the Gaussian curves widen;
3. Consistency index values corresponding to the peak of adhesion fall in a narrow range (0.2–0.34) while, peak values of pull-out force correspond to I_C varying in a wider range (0.25–0.50) and the peak is shifted towards higher values;

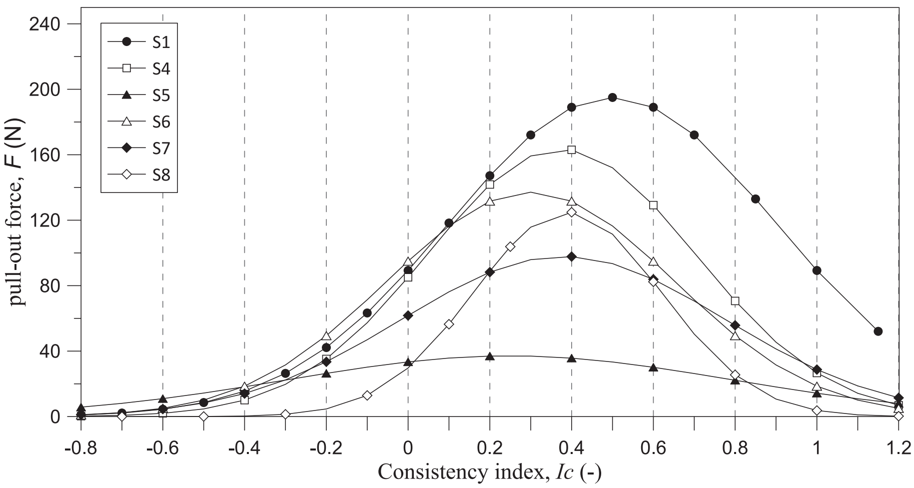


Fig. 13. Comparison of the results of the pull-out tests.

Table 4
Best fitting Gaussian distributions parameters (Eq. (8).

#	Soil sample	F_{pk}	σ	I_{Cpk}	R^2
S1	Banzi	194.48	0.40	0.50	0.89
S4	Bucharest	163.05	0.33	0.37	0.95
S5	Rome ARS	37.03	0.54	0.25	0.95
S6	Rome AR	136.78	0.35	0.30	0.91
S7	Rome AR/ARS	97.62	0.40	0.38	0.98
S8	Naples	124.64	0.23	0.39	0.99

The main conclusions drawn after the analysis of the results of the tests carried out on conditioned soil can be summarized as follows:

1. The effectiveness of the soil conditioning process very much depends on the product and dosage used. For all the combinations of conditioning parameters tested, the measured effects were generally negligible for two chemical products (P1 and P8) irrespective of the dosages (possibly because of their chemical composition), while relevant beneficial effects were observed for the other two products (P4 and P5);
2. The pull-out test is more sensitive than the mixing test to the effectiveness of the conditioning;
3. A further parameter able to describe the stickiness reduction after soil conditioning is the reduction in undrained shear strength (expeditiously evaluated via fall cone test) induced by the
4. The ability of the two tests to quantify the clogging potential was experimentally confirmed; in fact, a robust linear correlation between adhesion and pull-out force was found;
5. The pull-out test is more sensitive to the stickiness of clayey soil than the mixing test;

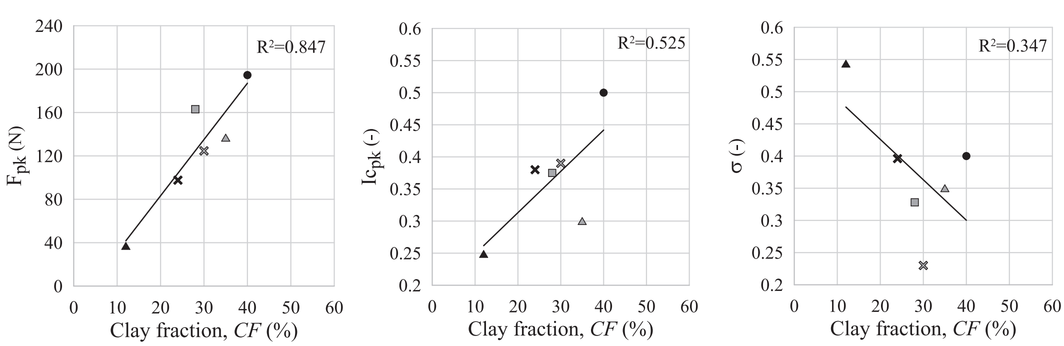


Fig. 14. Relations between key parameters of the Gaussian distributions and clay fraction of the soil samples.

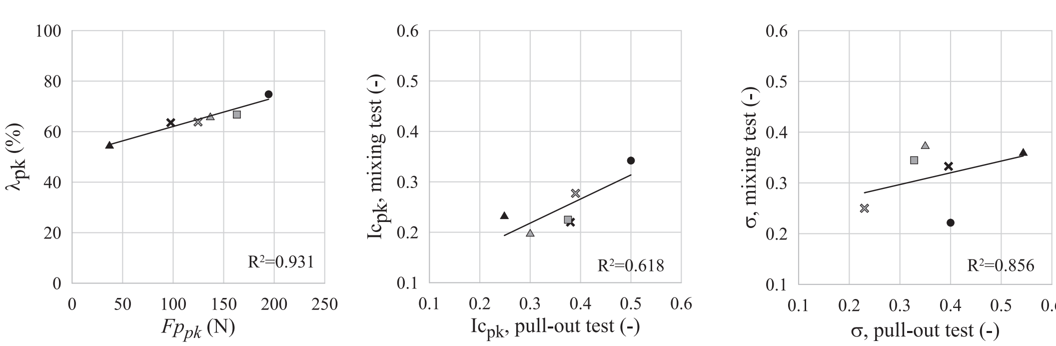
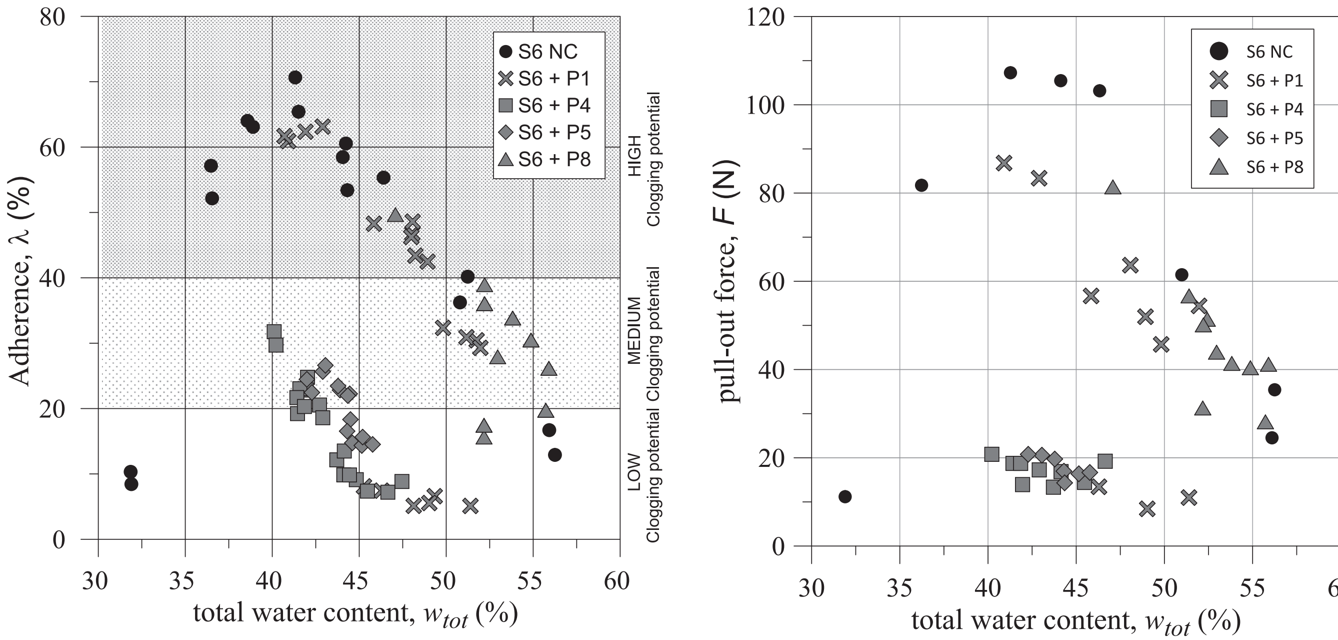
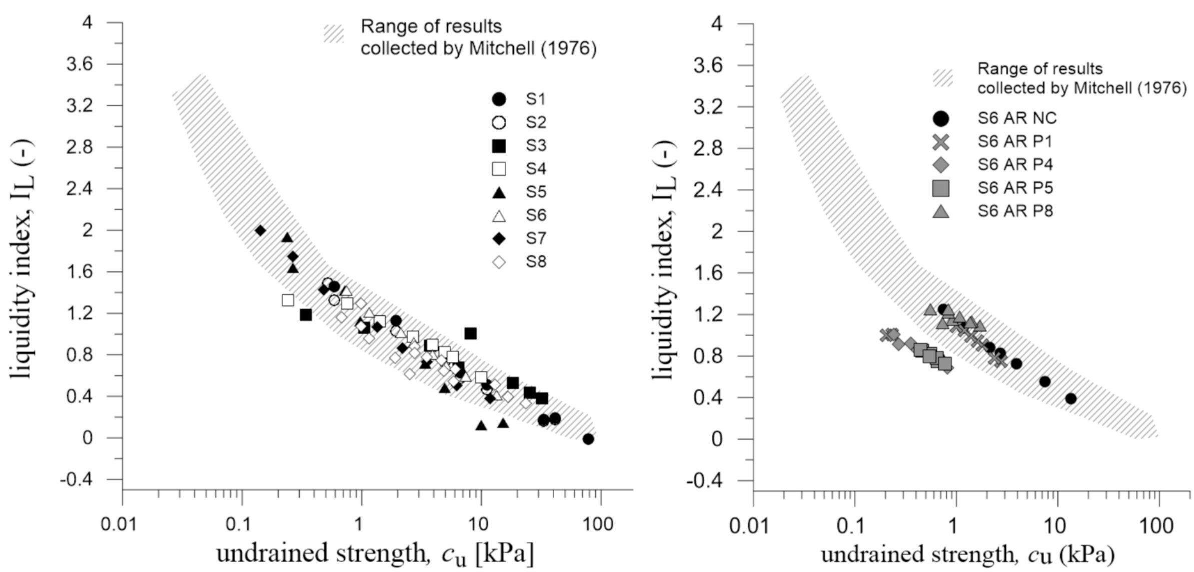


Fig. 15. Relations between key parameters of the Gaussian distributions of mixing and pull-out test.



a) b)

Fig. 16. Results of the a) mixing tests (two tests for each sample) and b) pull-out tests on S6 soil samples conditioned as listed in Table 2 (modified after Pirone et al. 2019).



a) b)

Fig. 17. Results of the fall-cone tests performed on all the soils listed in Table 1 (a) and on S6 soil samples conditioned as listed in Table 2 (b).

conditioning process respect to the value obtained on natural non conditioned soil, assessed at a given I_L.

As a general suggestion, products capable of generating a more stable foam should be preferred. However, foam stability is not the only factor at play. Specific laboratory tests should always be performed to determine the most effective combination of soil, product and dosage.

In conclusion, in addition to the extensive database obtained on different clayey soils, an interesting result of this research is the discovery of strong correlations between the results of mixing and pull-out tests. The two kinds of test can be alternatively used to evaluate the clogging potential risk and the risk mitigation obtainable by properly conditioning the soil.

Finally, the discovery of the departure of the results of well-conditioned clayey soils from the range of c_u– I_L of non-conditioned natural soils, obtainable trough the simple and rapid fall cone test, is another finding very useful to assess the effectiveness of conditioning, especially on-site during TBM-EPB excavation.

The analysis of the state of the art and of the tests results presented herein highlight that universally accepted experimental procedures and quantitative criteria for the evaluation of the clogging risk are still missing, encouraging further research.

CRediT authorship contribution statement

Diego Sebastiani: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Armando de Lillis:** Writing – review & editing, Writing – original draft, Conceptualization. **Salvatore Miliziano:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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