Tunnelling and Underground Space Technology 157 (2025) 106263

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology incorporating Trenchless Technology Research

journal homepage: www.elsevier.com/locate/tust

Reuse of EPB-tunnelling excavated soil: An approach of logistic constraints estimation through modified Proctor test

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A R T I C L E I N F O

Keywords:
EPB
Tunnelling
Soil conditioning
Reuse
Proctor
Laboratory test

A B S T R A C T

The exponential growth of tunnelling projects worldwide necessitates efficient management of excavated soil, particularly from Earth Pressure Balance Tunnel Boring Machines (EPB-TBMs). This study investigates the temporal evolution of mechanical properties in EPB-excavated soil, focusing on the conditioning process's impact. Through a comprehensive literature review, gaps in understanding the soil's transition from a liquid-like state back to its solid form are identified. Existing studies touch on mechanical property changes over time but lack detailed temporal analyses. Our research addresses this gap by examining the recovery of soil compactability over time, crucial for its reuse. By conducting modified Proctor tests at different time intervals post-conditioning, we elucidate the relationship between soil properties and conditioning parameters. Our findings reveal a direct correlation between recovery time and total water content, influenced by added water and foam injection ratio. We demonstrate that different conditioning parameter combinations yield similar immediate properties but divergent recovery times, which are crucial for logistical planning and environmental suitability. This study offers valuable insights into optimizing EPB-TBM excavation logistics, enhancing soil reuse efficiency, and advancing sustainability in civil engineering projects.

1. Introduction

On a worldwide scale, the number of tunnels is increasing by about 7 % every year, with an estimation of 4700 km of excavated tunnels yearly (Schneider et al., 2019). As more focused examples, Gruber and Östrand (2019) published a summary of the tunnel development in Sweden (Fig. 1a), Kaise et al. (2019) presented the tunnel development in Japan (Fig. 1b) and Baccolini (2022) shown the data relative to Italian major highway concession holder (Fig. 1c). Chen et al. (2018) show how the number of the cities in the world with an underground transport system is sharply increasing (Fig. 1d).

This fast development of underground infrastructures, and the specific volume of soil per excavated meter (ranging from 28 m^3/m for 6 m-diameter tunnels to 200 m^3/m for 16 m-diameter tunnels) is inevitably linked to the production of massive volumes of soil that have to be relocated and reused on the surface. Among the different uses, one of the most common is the reuse as aggregates to build road embankments.

In the execution of civil infrastructural projects, a critical design consideration lies in the interplay between the track and the topographic surface. The relative positioning of these elements along different portions of the infrastructural project, dictates whether the construction of the infrastructure necessitates the addition or removal of a specific volume of soil. Achieving an optimal balance between these volumes is imperative to enhance construction efficiency and minimize the project's impact on the surrounding environment. Striking this equilibrium is essential to ensure that the construction process not only meets its functional requirements but also aligns with sustainability goals, harmonizing with the natural landscape while mitigating adverse effects on the jobsite vicinity.

Hence, it is needed that the soil has properties tailored to meet specific requirements. According to the classification outlined in UNI 11531–1:2014, soils are classified based on their suitability as subgrade and embankment materials for infrastructures. In particular, this suitability depends on the suitability to be compacted. In fact, as a soil gets more compacted, it reduces the sensitivity to loads and water infiltrations, increasing the durability of the embankment. To further understand the suitability of a soil to be compacted, several tests can be conducted. The most diffused one is the Proctor test (e.g. AASHTO T193), that evaluates the dry density after a standardized procedure for its compaction (Connelly et al., 2008; Riviera et al., 2014).

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https://doi.org/10.1016/j.tust.2024.106263
Received 17 August 2024; Received in revised form 21 October 2024; Accepted 21 November 2024
Available online 5 December 2024

To further define if the soil has the potential for reusing, it is necessary to understand how it was produced. According to a report from the European Commission (2018), 55 % of railway tunnels are constructed conventionally, while 43 % involve excavation using Tunnel Boring Machines (TBMs). In the same year, according to Wehrmeyer (2018) 60 % of the total tunneling machines were represented by Earth Pressure Balance (EPB) TBMs.

To excavate soil, the EPB-TBMs relies on the excavated soil itself, properly conditioned, to apply counterpressure, preventing settlements and movements of the excavation face (Herrenknecht et al., 2011). Achieving this goal requires a change in soil behavior, requiring it to temporarily acquire paste-like properties for adequate pressure distribution and extraction through a screw conveyor (Thewes et al., 2012; Todaro, 2016). Moreover, the soil must be highly compressible (Mori et al., 2018). These transient properties are achieved through the addition of water, foam, and, optionally, polymers (Budach and Thewes, 2015). In the view of the reuse of the material, these properties are undesirable for embankment construction.

As foams are susceptible to decay (Carigi et al., 2020; Peila et al., 2022), the entire system is time-dependent, raising the question whether and when the soil is naturally reverting to its original characteristics without muck washing, a resource-intensive treatment process. The critical inquiry is the anticipated timeframe for this reversion and how conditioning parameters influence the process. This temporary shift in behaviour involves a gradual return of the soil to a solid-like state, wherein internal friction increases as conditioning agents decay (Carigi et al., 2020). Despite numerous studies on soil transitioning toward a paste-like mass, scientific literature addressing the inverse transformation is lacking. Existing literature on this topic lacks a comprehensive description of the temporal evolution of conditioned soil behaviour during the initial stages of conditioning decay. This literature review examines the current research, identifies gaps in knowledge, and explores the dynamic changes in conditioned soil properties over time.

The typical Excavated Rock and Soil Management (ERSM) cycle can be divided into various phases (Fig. 2) including (a) removal of material from the excavation front, (b) extraction through screw conveyor and transportation via belt conveyor, (c) preliminary storage on the jobsite, (d) potential transportation to a secondary storage site, and finally, (e) transportation to the ultimate site of use. In particular, the preliminary storage on the jobsite depends both on environmental and mechanical constraints. While the former one is widely studied (Patrolecco et al., 2020; Firouzei et al., 2020), the latter is not well known and investigated.

Riviera et al. (2014) studied the reuse of conditioned soil from EPB tunnel excavation, focusing on compaction methods. Specifically, they employed the modified Proctor method, gyratory method, and rolling compaction method on two samples of soil sourced from EPB tunnels in Turin, Italy. While shedding light on the impact of mechanical excavation on grain size distribution, the study did not delve into the role of time in the recovery of soil mechanical properties. Oggeri et al. (2014) explored the reuse of EPB-excavated soils, introducing quick lime as a modifier. This procedure is efficient from the mechanical point of view but affects the environmental properties, reducing the biodegradation of the chemical products. However, the study lacked details on conditioning parameters during muck production and did not investigate how time influences mechanical properties' evolution. Zumsteg et al. (2018) show that immediate post-conditioning soil is unsuitable for civil engineering purposes due to its high void ratio and viscosity, prompting questions about the process occurring over a certain duration that allows the soil to transition from an unsuitable state to a resource fit for civil applications. Tommasi et al. (2020) contributed by conducting a test campaign on two fine-grained soils. Their study focused on the time-dependent evolution of Atterberg's limits and Proctor test results. These analyses were performed at various time intervals, with a maximum resolution of one test per day, providing valuable insights into how conditioned soil properties change over time. Carigi et al. (2020) proposed a preliminary methodology to assess the time-dependency of mechanical properties in conditioned soil. Their comprehensive analysis encompassed various tests, including the slump test, Proctor test, vane test, direct shear test, and rotational mixing test, conducted at different time points following conditioning. Notably, the findings from the vane test and Proctor test highlighted the need for more frequent time-discretization in studying conditioned soil evolution.

While the literature has begun addressing temporal aspects, significant gaps remain, emphasizing the need for further investigation. The logistical aspects of Excavated Rock and Soil Management (ERSM), particularly for EPB-TBM technology, must consider the temporal evolution of excavated muck properties.

Hence, this paper primarily focuses on topics related to the temporal evolution of the mechanical properties of EPB-excavated rock and soil

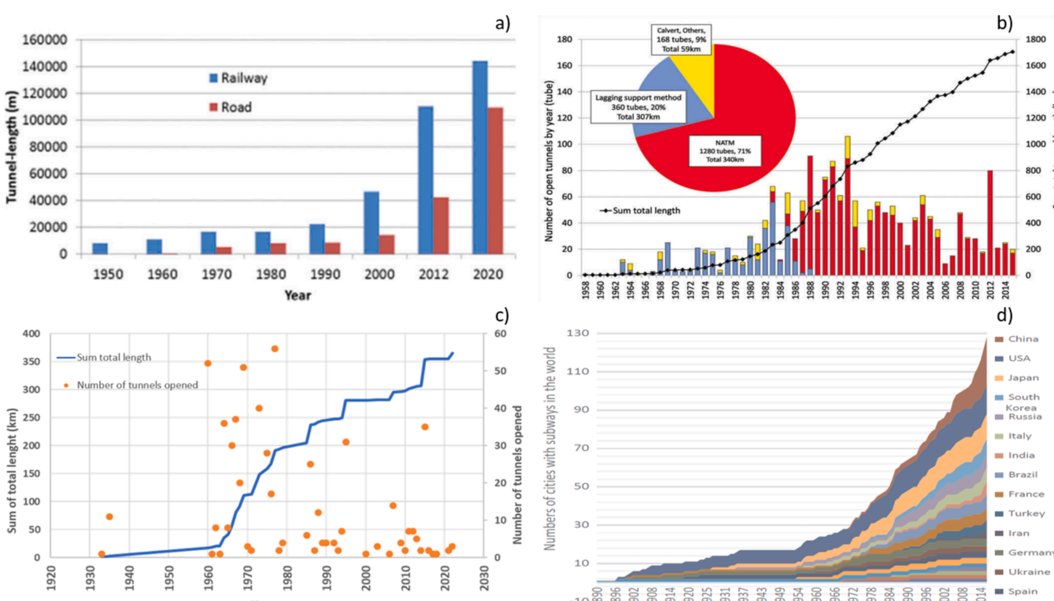


Fig. 1. Historical development of tunnels. A) tunnels in Sweeden (Gruber and Östrand, 2019), B) tunnels in Japan (Kaise et al. (2019), C) motorway tunnels managed by one of the major concession holders in Italy (Baccolini, 2022), D) number of cities with underground transport system divided by country (Chen et al., 2017).

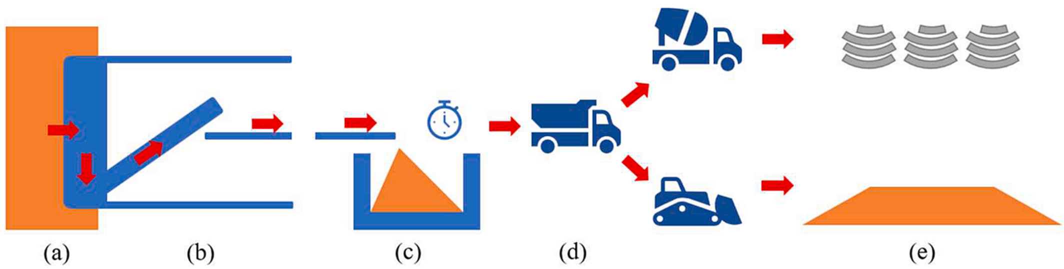


Fig. 2. ERSM phases. a) excavation and conditioning, b) extraction, c) jobsite storage, d) transport, e) final use.

with reference to the conditioning process and specifically to the storage phase.

2. Materials and Methods

For this study, a morainic soil was used. According to UNI 11531–1:2014, this soil falls in category A3 and its granulometric curve falls in the field of applicability of EPB as shown in Fig. 3 (Budach and Thewes, 2015).

For the conditioning, it was used a commercial conditioning agent with the following declared composition:

– Alcohols, C12-14, ethoxylated, sulfates, sodium salts (cc > 10 % – <20 %) CAS: 68891–38-3;
– 5-chloro-2-methyl-2H-isothiazol-3-one and 2-methyl-2H-isothiazol-3-one (cc > 0.0002 % – <0.0015 %) CAS 55965–84-9.

The foam required for soil conditioning was produced using a foam generator referenced in the studies by Vinai et al. (2008), Peila et al. (2013), and Carigi et al. (2020) that has a behaviour close to the ones usually used on the machines (Fig. 4).

When setting up the design of a conditioned soil, the following parameters need to be defined:

– natural water content (w_n) in the soil. It represents the percentage of the mass of total water already present in the soil on the mass of the soil;
– added water content (w_{add}). It represents the percentage of the mass of added water for the conditioning on the mass of the soil;
– total water content (w_{tot}) in the soil. It represents the percentage of the mass of total water on the mass of soil. This amount is obtained by the sum of the natural water content already present in the soil and the added water for conditioning;
– foaming agent concentration (c_f) is the concentration of the foaming agent in the liquid generator, defined as a percentage of volume;
– Foam Expansion Ratio (FER) is the ratio of the volume of foam and the volume of the liquid generator used to produce the foam;
– Foam Injection Ratio (FIR) represents the percentage of foam on the volume of excavated soil;
– Total Water (TW) in the soil. It represents the overall percentage of the water as sum of the w_{tot} and the liquid introduced through foam.

In this research, the foaming agent concentration (c_f) was kept constant at 1.0 % and the Foam Expansion Ratio (FER) was held constant at 15.

For its conditioning, through the procedure described by Peila et al. (2008), it was found that the optimal conditioning set for EPB-TBM excavation are w_{tot} = 9 % and FIR = 30 %. Anyway, to understand how different conditioning parameters influence the recovery in time, several conditioning sets were tried which are listed in Table 1.

To prepare each conditioned soil sample, 40 kg of material were used and placed in a cylinder with a height of 1 m and diameter of 120 mm, featuring drainage at the bottom to simulate the jobsite conditions.

Immediately after the conditioning some tests to verify the quality of the muck with respect of the meaningful parameters for the EPB-TBM management were carried on.

In detail, on each sample were performed 1 slump test, 3 measurements of the scissometric index and 3 measurements of the bulk density. For the slump test it was used the procedure proposed by Peila et al. (2008), for the scissometric index a modified vane test as described by Carigi (2023) was used, and for the bulk density the weight of a standard volume sample was measured.

It should be noted that despite the modified vane test is performed in analogy with the vane test (EN ISO 22476–9) the dimensions of the blades have been increased to 54 mm in diameter and 109 mm in length consider the bigger maximum diameter of the tested soil. Furthermore, being the measured value dependent on a complex behaviour involving the shearing of conditioned soil, the displacement of grains on the surface and viscous resistance of the muck, the authors decided to use the total torque required for the rotation of the blades without dimensions to consider the complexity of the shearing surface.

After this test, a set of tests on each sample at intervals of 0, 1, 2, 3, 4, 7, 9 days, and when necessary, at 11 and 14 days were carried out to measure bulk density, water content, and the Proctor density.

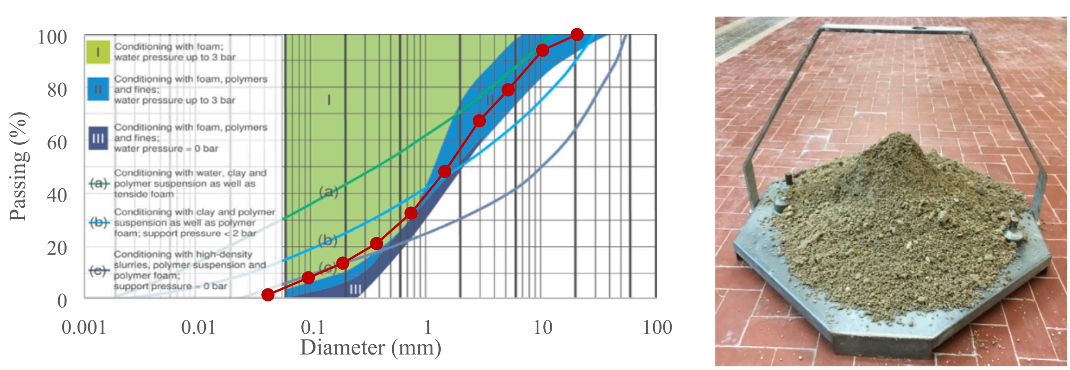


Fig. 3. Grain size distribution curve of the studied soil superimposed to the diagram of Budach and Thewes (2015) (left); Picture of the soil (right).

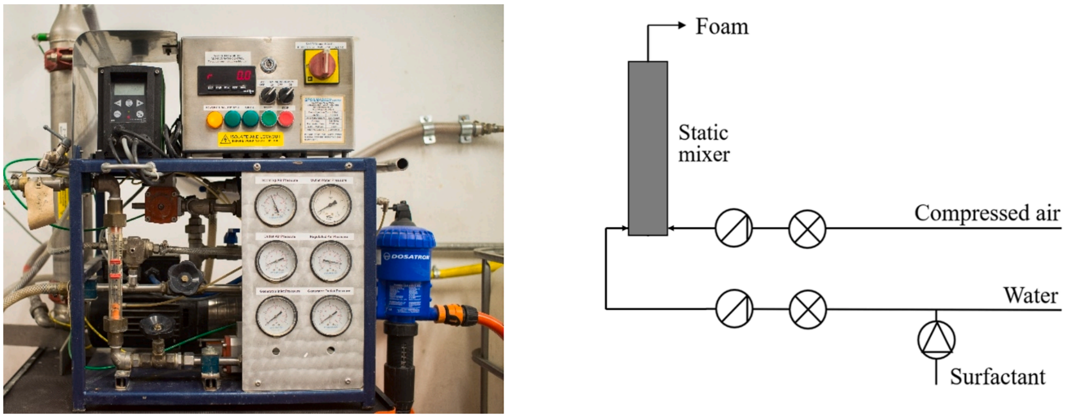


Fig. 4. Left: Foam generator picture. Right: Foam generator scheme. The generator operates with a maximum liquid flow of 11.9 l/min and a maximum air pressure of 4 bar, with both flow rates finely regulated through needle valves. The static mixer with specific dimensions, including an internal diameter (D_i) of 78 mm, a length (L) of 450 mm, and it is filled with glass fragments with a mean diameter of 5 mm. The volumetric pump for surfactant is equipped with a mixing chamber to ensure a correct mixing of water and surfactant.

Table 1
Conditioning set parameters.

ID	w_n (%)	w_{add} (%)	w_{tot} (%)	c_f (%)	FER (−)	FIR (%)
1	4	3	7	1.0	15	30
2	4	3	7	1.0	15	40
3	4	4	8	1.0	15	20
4	4	4	8	1.0	15	30
5	4	4	8	1.0	15	40
6	4	5	9	1.0	15	20
7	4	5	9	1.0	15	30
8	4	5	9	1.0	15	40
9	4	6	10	1.0	15	20
10	4	6	10	1.0	15	30

Each sample was stored in a PVC cylindrical container 1 m high and 120 mm of diameter, open on the top. The average temperature and the relative humidity were 22 °C and 53 %.

Before each test, the material held in the container was poured in a bucket, mixed to obtain a homogeneous sample.

Water content measurement was conducted following the ASTM D4959-16 standard.

The modified Proctor test was performed following the AASHTO T193 standard. The modified Proctor test was initially performed on the non-conditioned soil to establish a reference point. Bulk density was used to monitor the evolution of dry density, particularly when due to conditioning, the soil is not suitable for the Proctor test, as it flows under the applied blows instead of compacting itself (Fig. 5).

Consequently, the dry density was calculated for each specific weight and modified Proctor test using the following formula:

$$\gamma_{dry} = W/[V(1+w)]$$

Where, γ_{dry} represents the dry density in units of g/cm^3, W is the mass of soil in g, V is the volume of the soil in cm^3, and w denotes the water content of the soil in percentage at the moment of the test.

3. Results

The results of the slump test, scissometric index and bulk density on the freshly conditioned material are summarized in Table 2, while the pictures of the carried-out slump tests are given in Table 3, where is possible to observe that ID7 is optimally conditioned and ID5, ID6 and ID9 are well conditioned, while ID8 and ID10 are slightly over-conditioned but anyway suitable for EPB-TBM operation since there is no water or foam loss visible on the slump. On the other side, ID 2 and ID4 are slightly under-conditioned but well within the acceptability conditions. Finally, ID1 and ID3 are not suitable for a well-managed EPB-TBM operation but have been tested anyway to provide a homogeneous test framework. This evaluation is carried on according to the method proposed by Peila et al. (2009) that consider suitable slump cone fall between 14 and 20 cm.

The test results after time are summarized in Table 4 the results of the tests are given. In italic are given the bulk densities and in bold the ones after Proctor test.

In describing Proctor test results, a conventional approach for evaluation and representation involves illustrating the Zero Air Void Curve (ZAVC), (Connelly et al., 2008). This curve is a standard means of

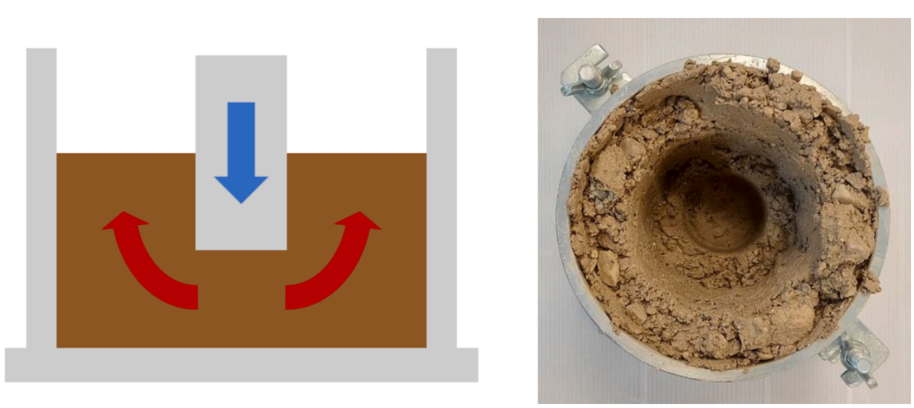


Fig. 5. Scheme of the soil flow under the blow of the Proctor ramming weight (left); Instance of failure of the Proctor test (right).

Table 2
Properties of freshly conditioned samples.

	ID		1	2	3	4	5	6	7	8	9	10
Conditioning sets	w_{tot} (%)		7.0	7.0	8.0	8.0	8.0	9.0	9.0	9.0	10.0	10.0
	FIR (%)		30	40	20	30	40	20	30	40	20	30
	TW (%)		8.09	8.45	8.72	9.09	9.45	9.72	10.08	10.45	10.72	11.09
Test results	Slump (cm)		5	14	2	13	18	15	20	22	17	22
	Scissometric index	$I_{sc,1}$ (–)	5.9	3.1	7.4	6.2	2.1	3.2	1.6	1.3	1.6	1.2
		$I_{sc,2}$ (–)	6.3	3.6	9.2	5.0	1.9	3.2	1.6	1.1	2.1	1.5
		$I_{sc,3}$ (–)	7	4.9	9.8	7.0	2.0	3.8	1.6	0.8	2.1	1.2
		$I_{sc,avg}$ (–)	6.4	3.9	8.8	6.1	2.0	3.4	1.6	1.1	1.9	1.3
	Bulk density	γ_1 (g/cm^3)	1.78	1.62	1.95	1.80	1.58	1.80	1.65	1.49	1.73	1.63
		γ_2 (g/cm^3)	1.86	1.64	1.98	1.77	1.61	1.81	1.65	1.44	1.77	1.62
		γ_3 (g/cm^3)	1.91	1.66	1.97	1.86	1.59	1.82	1.65	1.39	1.76	1.62
		γ_{avg} (g/cm^3)	1.85	1.66	1.97	1.81	1.59	1.81	1.65	1.44	1.75	1.62

Table 3
Pictures of slumps of freshly conditioned muck.

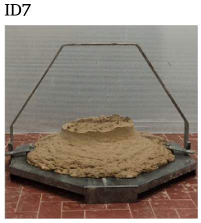
ID1	ID2	ID3	ID4	ID5
				
ID6	ID7	ID8	ID9	ID10
				

Table 4
Summary of modified Proctor test and dry density results (B: Bulk density; P: Proctor density): values in g/cm$^{3.}$

Conditioning sets	ID	1	2	3	4	5	6	7	8	9	10
	w_{tot} (%)	7.0	7.0	8.0	8.0	8.0	9.0	9.0	9.0	10.0	10.0
	FIR (%)	30	40	20	30	40	20	30	40	20	30
	TW (%)	8.09	8.45	8.72	9.09	9.45	9.72	10.08	10.45	10.72	11.09
0 days	B	*1.85*	*1.66*	*1.97*	*1.81*	*1.59*	*1.81*	*1.65*	*1.44*	*1.75*	*1.62*
	P	–	–	–	–	–	–	–	–	–	–
1 day	B	*2.18*	*2.18*	*2.18*	*2.21*	*2.12*	*2.15*	*2.11*	*2.07*	*2.10*	*2.04*
	P	–	–	–	–	–	–	–	–	–	–
2 days	B	*2.22*	*2.23*	*2.22*	*2.23*	*2.22*	*2.21*	*2.17*	*2.15*	*2.16*	*2.13*
	P	**2.18**	**2.19**	–	–	–	–	–	–	–	–
3 days	B	*2.17*	*2.18*	*2.24*	*2.25*	*2.24*	*2.23*	*2.19*	*2.20*	*2.21*	*2.20*
	P	**2.21**	**2.22**	–	–	–	–	–	–	–	–
4 days	B	*2.16*	*2.17*	*2.25*	*2.27*	*2.25*	*2.27*	*2.23*	*2.23*	*2.21*	*2.22*
	P	**2.17**	**2.22**	**2.20**	–	–	–	–	–	–	–
7 days	B	*2.14*	*2.16*	*2.19*	*2.24*	*2.24*	*2.25*	*2.25*	*2.24*	*2.25*	*2.25*
	P	**2.21**	**2.21**	**2.19**	**2.22**	**2.18**	**2.21**	–	–	–	–
9 days	B	*2.01*	*2.05*	*2.12*	*2.21*	*2.28*	*2.26*	*2.27*	*2.26*	*2.26*	*2.25*
	P	**2.21**	**2.21**	**2.19**	**2.22**	**2.19**	**2.14**	**2.21**	**2.19**	–	–
11 days	B						*2.25*	*2.20*	*2.23*	*2.26*	*2.26*
	P						**2.21**	**2.18**	**2.17**	**2.17**	**2.20**
14 days	B						*2.17*	*2.09*	*2.19*	*2.24*	*2.23*
	P						**2.25**	**2.20**	**2.23**	**2.25**	**2.18**

representing the theoretical correlation between dry density and water content if voids contain no air. The evaluation process required the determination of solid grain density using the ASTM D854-14 standard. Then, the values of the ZAVC are calculated according to the following equation:

$$\gamma_b = [\gamma_s \cdot \gamma_w (1 + w)]/(\gamma_w + \gamma_s \cdot w)$$

Where, γ_b denotes the bulk density in g/cm^3, γ_s represents the grain density in g/cm^3, γ_w represents the water density in g/cm^3, and w signifies the water content in percentage.

Hence, the outcomes of the abovementioned tests are summarized in Fig. 6, where it is possible to see that although a maximum dry density similar to that of unconditioned soil was achieved, the position of this maximum density is slightly shifted to the right. Moreover, it is evident that at 0 days from conditioning, the range of obtained density values is wide and highly sensitive to the employed conditioning parameters.

Based on these results it was measured that, as shown in Fig. 7, in the range of suitable to borderline soil conditioning sets, the total water content (TW) is linearly dependent on the number of days required to achieve success in performing the modified Proctor test. It is notable that the relationship is based on the total water content, computed as the sum of the natural water content, added water, and water introduced through the addition of foam, while there is no dependency with the form in which this water is added.

On the contrary, as shown in Fig. 8 and Fig. 9, the Scissometric index and the bulk density show a more complex behavior that depends both on the w_{tot} and FIR. It is possible to observe that the values of Isc and bulk density are influenced both by w_{tot} and FIR in a combined way that is dependent on the modalities of addition. This behavior is observable also with reference to the slump value as pointed out in Table 2.

4. Discussion

From the results obtained in this research, it is possible to observe that the soil approaches the no void curve (ZAVC) within a few days, indicating that the air introduced through soil conditioning is removed in few days from conditioning due to the natural foam degradation and helped by the necessary manual operation of mixing required to carry out the tests. Subsequently, the gradual drying process facilitates the achievement of higher dry density.

Based on the carried-out tests, it can be stated that the density values obtained at 0 days after conditioning exhibit a broad range and are greatly influenced by the conditioning parameters employed. Conversely, it is evident that the conditioning process does not have a significant impact on the maximum dry density of the soil. However, despite the limited impact on the maximum dry density of the soil, the conditioning process demonstrates a slight influence on modifying the optimal water content. Hence, the tests needed to define the optimal water content should be performed on a soil that experienced a history of soil conditioning.

The obtained results highlight the relevance of TW in the forecast of soil residence time in the jobsite before being suitable for embankment construction. In the studied case (i.e. combination of soil, conditioning set and curing procedure) the relationship was found to be linear (Fig. 7). On the opposite side, it was found that the TW is not directly linked to flowability, bulk density and scissometric index (Fig. 8 and Fig. 9). Being these last parameters functions of both w_{tot} and FIR, it is possible to find sets of these values with resulting constant TW that lead

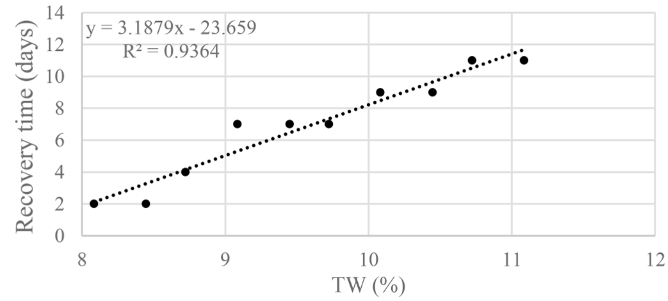


Fig. 7. Relationship between Total water (sum of w_{tot} and water introduced through foam) content and required time to successfully perform the Proctor test (recovery time).

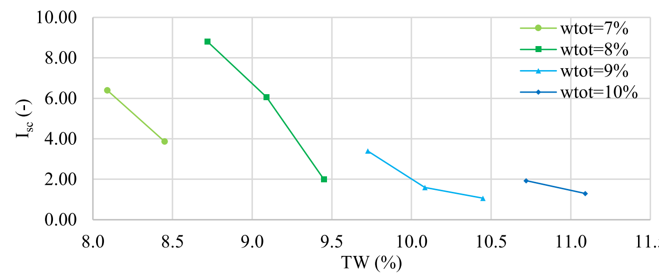


Fig. 8. Total water content vs Scissometric index.

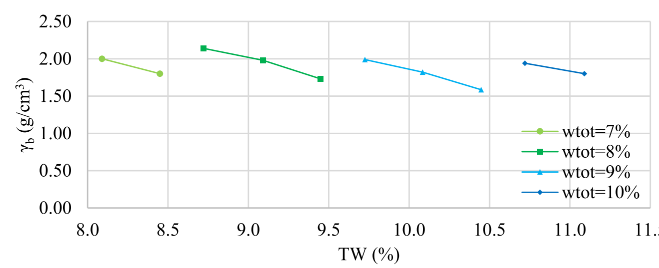


Fig. 9. Total water content vs Bulk density.

to different properties of the conditioned soil but to the same recovery time.

5. Conclusions

In the studied case, it was found that the time needed for the recovery of compactability of soil is directly linked to the total water (TW) in it. This parameter is a function of both added water, w_{add}, and FIR, two

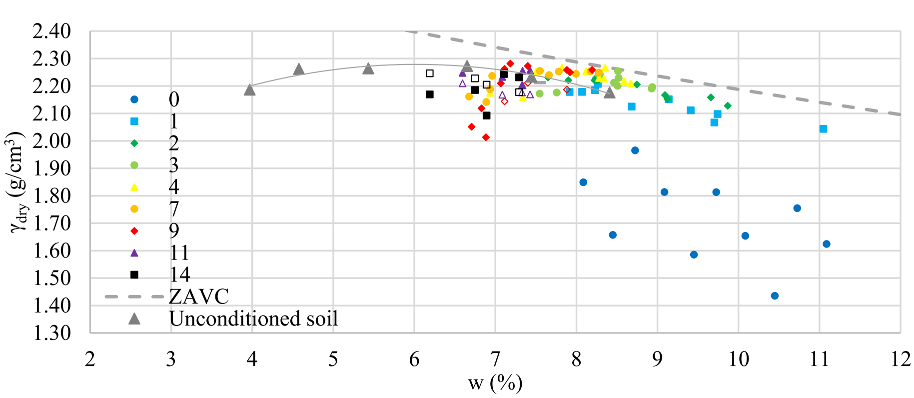


Fig. 6. Summary of results of dry density (solid markers for bulk density and void markers for Proctor test) versus measured water content at the moment of the test.

parameters that influence differently the properties of conditioned soil.

In fact, using different combinations of added water and FIR, it is possible to have similar results in terms of flowability, scissometric index and bulk density, while, due to different TW, having different recovery times. Considering that the use of different combinations of w_{add} and FIR has effect also in the time required to be environmentally suitable for uses external to the jobsite, an optimization of the two aspects is needed.

Hence, a knowledge of the link between conditioning sets used during the excavation process and the time required for the reuse of soil is fundamental to correctly manage the jobsite logistics and optimize the used spaces, the used conditioning agents' quantities, and the planning for reuse of soil in a more integrated and sustainable way.

This study describes a first approach to the problem and, despite being limited to a single type of soil and conditioning agent, has shown promising results and insights on the link between soil conditioning and soil recovery time.

CRediT authorship contribution statement

Andrea Carigi: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carmine Todaro:** Writing – review & editing, Funding acquisition.

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.

Acknowledgments

We would like to express our gratitude to Prof. Daniele Peila for his guidance and support throughout this research project. His expertise and encouragement have been instrumental in shaping this work.

This research was funded through contract 473/2023 of Department of Environment, Land and Infrastructure Engineering of Politecnico di Torino and by Dipartimento di Eccellenza 2023–2027 (15659 – 28 December 2022).

Data availability

Data will be made available on request.

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