POLITECNICO DI TORINO

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Master Thesis:

Soil conditioning in the application of EPB shield machine

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1 Introduction

The advancement of mechanized tunneling technology has significantly transformed the construction of underground infrastructure, particularly with the widespread application of Earth Pressure Balance (EPB) shield machines. The EPB machines are widely used due to their ability to maintain consistency and to control the pressure at the face of the tunnel. This type of machine can guarantee the ground stability, minimize the risk of subsidence and avoid the inflow of the water and soil particularly in the soft ground conditions. Moreover, it is adaptive with the various types of soil allowing for precise adjustments while excavating, make it well-suited to be opted in tunnel projects in urban area.

These machines rely on the controlled manipulation of excavated soil at the tunnel face to maintain stability and ensure efficient progress through a variety of ground conditions. Central to the performance of EPB tunneling is the process of soil conditioning, which involves the treatment of in-situ soil using additives to modify its properties for optimal pressure transfer and spoil handling.

Soil conditioning enhances the plasticity, flowability, and cohesiveness of the excavated material, enabling it to behave like a pressurized fluid within the working chamber. This modified soil acts as a supporting medium, counterbalancing the earth and water pressures at the tunnel face while also facilitating smoother transportation through the screw and belt conveyors system. The choice of conditioning agents—whether foams, polymers, bentonite, or combinations thereof—plays a critical role in adapting the soil behavior to the operational requirements of EPB tunneling.

In the choice of conditioning agents, it is fundamental to choice them correctly and assess effectiveness of various soil conditioning agents used in EPB shield machines. Drawing from the insights provided in the reviewed literature, the tests aim to assess the advantages and limitations of each conditioning method in relation to different soil types and conditions in which will be excavated the tunnel. Understanding these conditioning techniques is essential not only for achieving efficient excavation but also for minimizing environmental impact, reducing mechanical wear, and improving overall tunnel stability.

By examining the principles and practical applications of soil conditioning, this work contributes to the ongoing efforts in optimizing EPB tunneling technology—especially in projects where soil variability presents significant engineering challenges. In particular, it was performed an extensive campaign test on materials obtained from a real case study, from which three soils were obtained: two as different geological formations and one as a mixed face condition. Due to the limited quantities of soil available, a first test campaign was performed using miniflow cone test. Then each of these soils were conditioned using foam, bentonite slurry and/or water absorbing polymer and then tested for slump test, the most common and known tool for conditioned soil properties assessment. The study also integrates experimental investigations using a modified vane test and bulk density measurement, offering a deeper insight into the behavior of conditioned soils under controlled settings. Finally, it has been performed a screw conveyor extraction test to assess the behaviour of conditioned soil under pressurized conditions. The purpose was to determine the optimal combination of foam, water, slurry, and polymer to reach the soil consistency which provides the proper pressure control at tunnel face, smooth flow via the screw conveyor beside reducing the mechanical wear while utilizing the EPB machine.

2 Earth Pressure Balance Tunnel Boring Machines

1 - Tunnel Boring Machine

Tunnel Boring Machines (TBMs) are used to construct different kind of infrastructure, from superhighway to water transportation systems. The opt for TBMs comes from the geological, economic, and social conditions.

One specific type of TBM, the Earth Pressure Balance (EPB) is particularly effective in soft ground since it is based on the use of the excavated ground as supporting medium in the excavation chamber. In other words, the machine maintains face stability by using excavated soil to create a counterpressure using conditioned soil.

To get optimal results the soil should fall in precise grain size distribution classes and for each one a recommended approach in terms of conditioning agents should be followed.

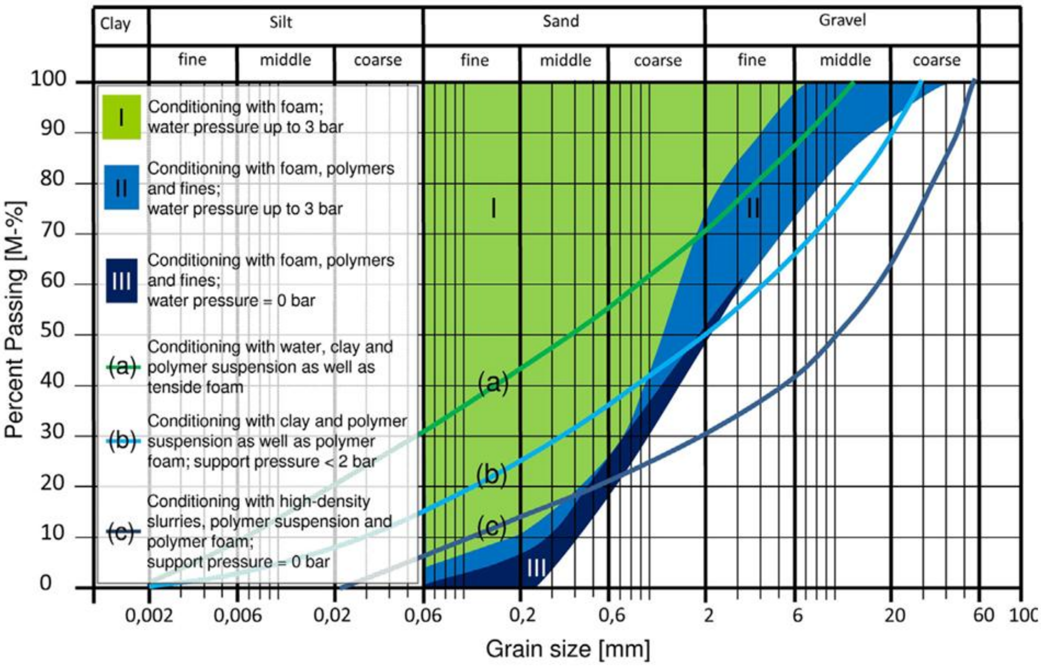


*Figure*2_the range of application for EPB-technology [Budach,M.Thewes/TunnellingandUndergroundSpaceTechnology50(2015)296–304]

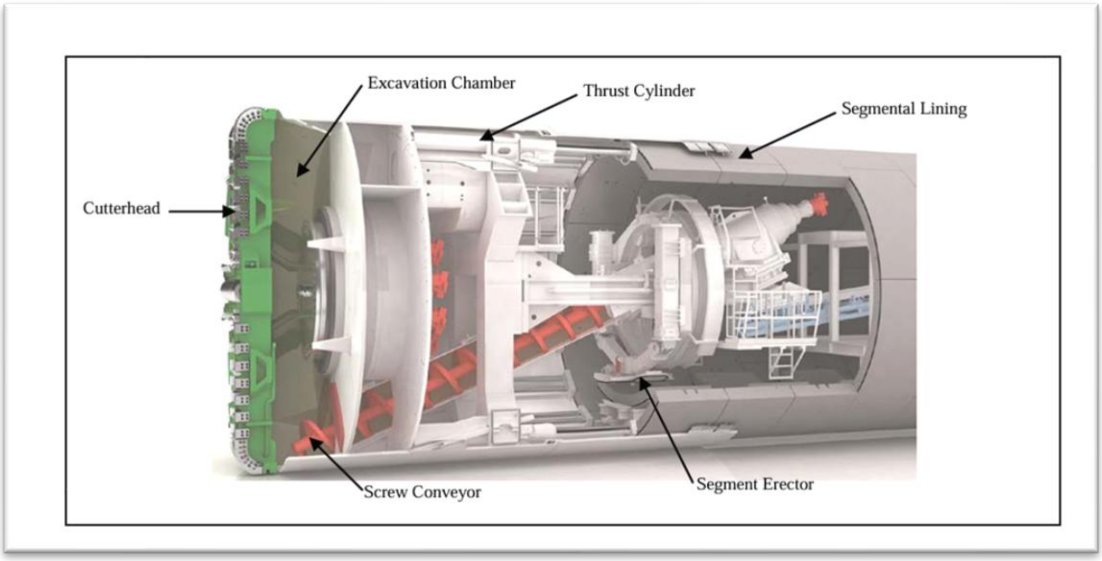


Figure 3 - Schematic of an EPB TBM Showing Some of the Major Features (Courtesy of Herrenknecht AG)

The capability to ensure face stability and ground settlements control enabled this machine to be widely adopted in case of urban tunneling function, adaptability to different geologies which means the performance can be improved with soil conditioning.

The main parts of the EPB machine are described in the following chapters.

2.1 Cutterhead and Excavation

The frontmost rotating section of EPB, the cutterhead, is equipped by cutters and scraps which are the primary excavation tool responsible for cutting and breaking soil or rock depending on the medium as the machine advances through the tunnel, Figure1. In other words, with its rotating cutterhead the tunneling machine breaks the material from tunnel face. The material is then transferred to the belt conveyor system in the rear of the shield via a screw conveyor while the hydraulic cylinders push the machine forward continuously, Figure3.

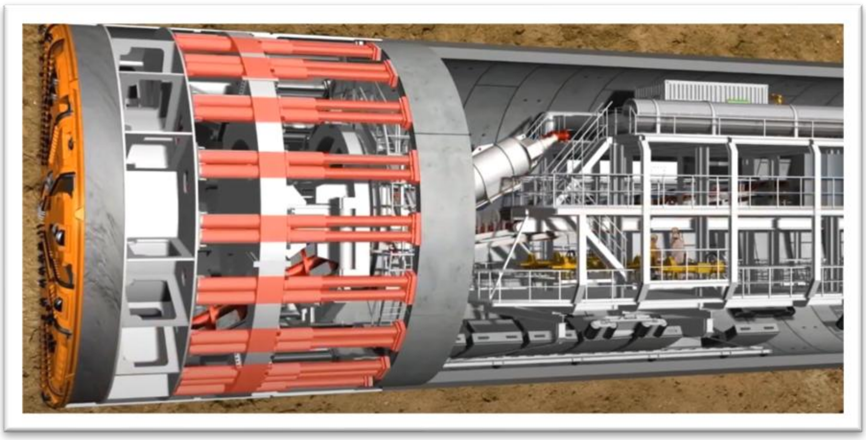


Figure 4_the hydraulic cylinders press the machine forward in the tunnel

The primary function of the cutterhead is to perform the excavation at the tunnel face with different kinds of cutting tools like pick, scrapers and disc cutters which are dependent on the condition of the ground. These tools by cutting and fragmenting the soil or weak rock at the tunnel face, allow the materials to be entered into the pressurized chamber behind the cutterhead. The opening on the cutterhead permits the excavated materials to entered pressurized chamber. The volume and rate of the material entry is impacted by the rotation speed and advancement, while the design of the cutterhead is aimed to guarantee and maintain the counterbalance pressure at the tunnel face. The third function can be addressed as initial mixing the conditioned of soil. The conditioning agents such as bentonite slurries, foams, and polymers are normally injected at the cutterhead. as the cutterhead rotates and facilitates the mixing of the soil with the conditioning agents, it improves the workability and mechanical properties such as plasticity, low-friction, and homogeneity of spoil in the pressurized chamber. Then the mix can then be efficiently transported by the screw conveyor.

2.2 Excavation Chamber and Face Support

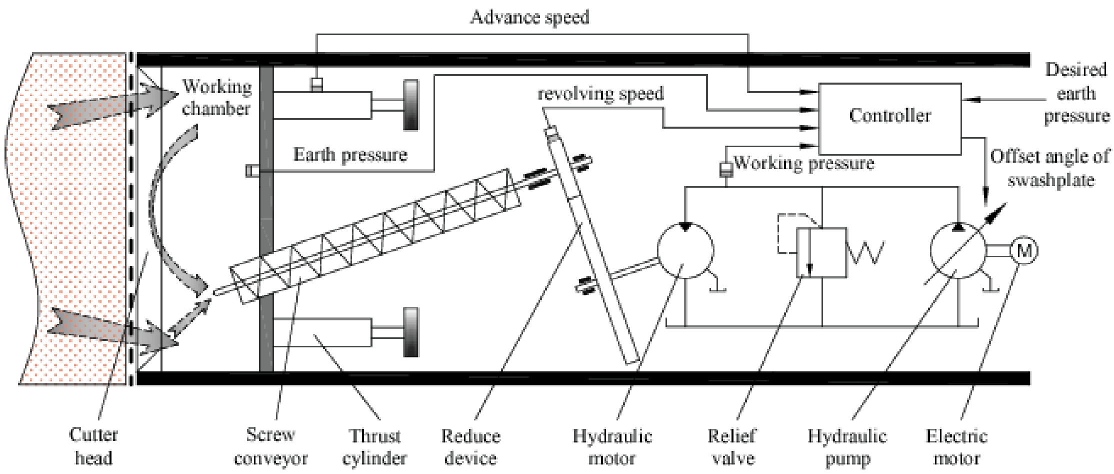


Figure 5_The lateral scheme of EPB machines

The Excavation Chamber is a critical part of an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM), located directly behind the cutterhead. It plays a key role in maintaining tunnel face stability by counter-balancing the pressure of the soil and the groundwater pressure with the pressure of the conditioned soil while excavation takes place. As the EPB technology is used for soft or mixed ground condition, the risk of soil collapse due to the vibration, ground-water pressure, and over-excavation is always a threat while tunneling. By adjusting the volume of the excavated materials inside the chamber as well as controlling the rate of the soil discharge on the screw conveyor, it is possible to achieve the wanted pressure inside the chamber.

If the pressure inside of the chamber is too low, it results the collapse of the soil from tunnel face into the tunnel, instability of the face, and potential ground subsidence. On the contrary, if the pressure is relatively too high it causes deformation at the surface as it pushes the periphery soil outward. Hence, it is crucial to create a balance between internal and external soil pressure to prevent any probability of having a damage while tunneling.

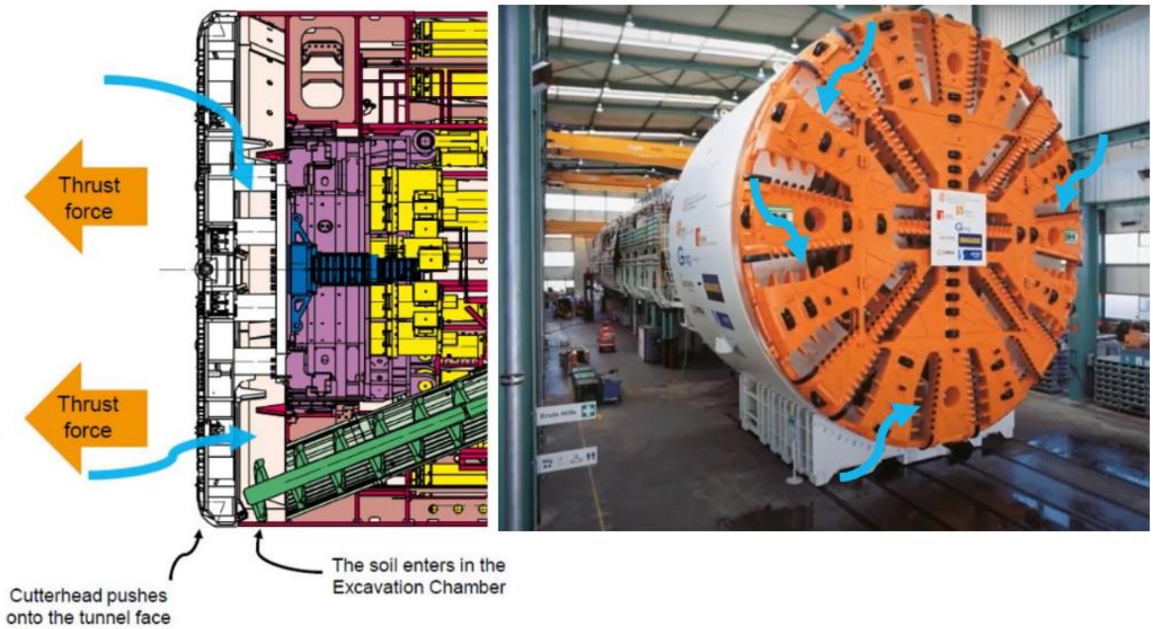


Figure 6_ excavation chamber inside an EPB TBM, showing how it maintains tunnel face stability with pressurized Conditioned Soil through the Cutterhead.

2.2.1 Regulation of Soil Flow and Conditioning

Due to the required of smooth extraction of the soil outside of the tunnel the soil conditioning plays a significant role to modify the properties of the excavated soil. The excavation chamber is the first zone where the conditioned soil is stored, mixed, and regulated before being transported through the screw conveyor. In the excavation chamber the soil interacts with conditioning agents like foam, water, and polymer to guarantee the favourable condition such as workability, plasticity, and consistency of the soil for the optimal excavation process.

The principle of the EPB machine is based on the excavated soil itself acting like a supporting medium to maintain the pressure at the face of the tunnel. The machine, by keeping the excavated materials inside the excavation chamber under controlled pressure, ensures the face stability and prevents the collapse of the tunnel face. As this pressure inside the excavation chamber is equal to the applied external load, it avoids the excessive deformation and reduces the probability of the collapse inward the tunnel section. The design face support pressure is affected by soil pressure at the face, groundwater pressure, while the operative face support pressure depends on the rate of the machine advancement with the rate of soil extraction, and screw conveyor operation.

2.2.2 Factors Influencing Face Support in EPB Machines

There are several critical factors to be considered that impact on the effectiveness of the face support in EPB tunneling technology. These factors can be categorized as follows.

1. Soil properties

The different types of the soil such as cohesive soil (clay, silt), granular soil (sand, gravel), mixed and variable soil provide specific situations to be faced. For instance, clay or silt are easier to maintain face stability as they are naturally cohesive. On the contrary, sand or gravel can be more challenging to maintain the face support as they are not cohesive. So that generally, it is essential to have soil conditioning with foam to improve pressure transmission into these kinds of soils.

2. Groundwater conditions

While tunneling under water table condition, it is necessary to provide adequate pressure inside the excavation chamber to prevent the water inflow in the tunnel. Appropriate conditioning of the soil contributes to control the water content and promote the soil mechanical properties.

2.2.3 Screw Conveyor: Controlling Material Flow

To regulate this counterpressure, the quantity of material in the excavation chamber must be balanced. The pressure increases if the quantity of material that enters the excavation chamber, due to excavation, is higher than the quantity of material that is extracted with the screw conveyor. Conversely, the pressure decreases if the opposite happens.
Through the screw conveyor the pressure is regulated thanks to the viscosity of the conditioned soil extracted from the excavation chamber to the discharge point. The pressure differential between chamber and screw conveyor draws the conditioned soil into the screw conveyor. **Figure7,** as this happens the conditioned soil pressure decreased from excavation chamber pressure to atmospheric pressure. The excavation chamber pressure is determined by water level above the tunnel and the depth of the tunnel.

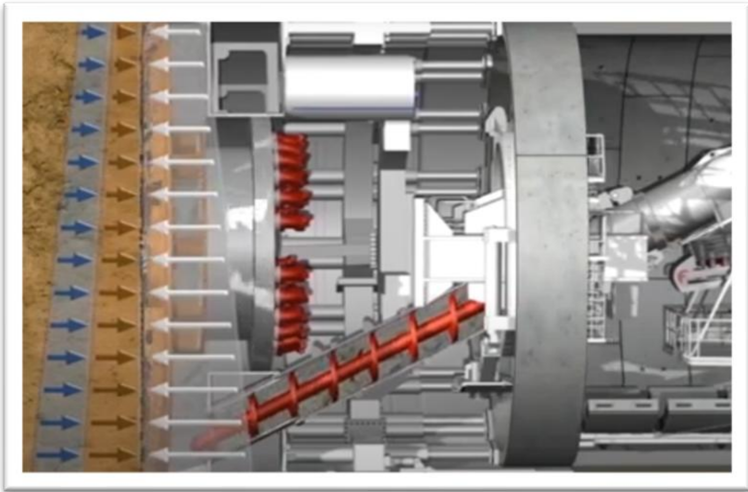


Figure 7 - Balancing of pressure between chamber and ground plus water pressure.

2.3 Segment Erection and Tunnel Lining

In (EPB) machines in tunneling the segment erection and tunnel lining are crucial processes to ensure that the excavated tunnel can structurally stays stable while excavating the tunnel. These processes include assembling precast concrete segments, Figure 8, to create a continuous lining which can support the pressure applied by the surrounding soil and avoid the collapse of the tunnel. Besides, the waterproofing is one of the duties done by an element of the segments, the gaskets. The followings are the main aspects of segment erection and tunnel lining, especially in the context of soil conditioning for EPB tunneling.

2.3.1 Goals of tunnel lining for EPB tunneling technology.

The purpose of tunnel lining can be noted as:

Goals	Definition
Ground support	Prevent the collapse of the surrounding soil and maintain the tunnel stable.
Load distribution	To distribute the pressure of the soil and water equally around the tunnel.
Sealing and waterproofing	One of the problems being faced while tunneling especially being below the water table is the presence of the water into the tunnel. Therefore, waterproofing could be achieved with the segments and tunnel lining.
Long-term stability	Act as the final structure in the tunnel to guarantee the durability of the tunnel.

Figure8_Segment

2.3.2 Interaction Between Tunnel Lining and Backfilling

The interaction between tunnel lining and backfilling plays a crucial role in EPB tunneling, particularly in reducing segment overloading by filling the gap between excavated ground and the outer surface of the lining segment after the segments are installed.

The purpose of backfilling in the tunnel lining can be stabilizing the tunnel lining, preventing movement or deformation of the segment, avoiding ground subsidence, distributing the periphery loads, waterproofing, and sealing the tunnel.

2.3.3 Design Parameters of Segmental Lining

The structural and functional design of the tunnel lining considers several key parameters, including:

- Gasket System
  Rubber gaskets are installed at the joints between segments to ensure watertight connections, preventing groundwater infiltration into the tunnel (waterproofing);
- Segment Jointing Methods
  Segments can be connected using bolted joints or dowel systems. The method selected influences the alignment precision and structural integrity of the ring. Therefore, the choice of connection system is an important design consideration;
- Segment Thickness and Reinforcement
  Both the thickness of the segments and the amount of reinforcement are determined based on tunnel diameter and ground conditions. Soil conditioning indirectly affects these parameters by influencing the load distribution around the lining during and after installation.

2.3.4 Mechanized Segment Erection Process

Segment installation in EPB machines is a process carried out within the TBM shield. The key steps in this process include:

- Segment Handling and Transportation
  Segments are transported from the storage area to the TBM using a rail-mounted system installed within the tunnel. This system ensures continuous and efficient delivery of segments to the assembly zone;
- Segment Lifting and Placement
  Inside the TBM, segments are lifted and positioned using either a vacuum lifting device or a mechanical gripper, depending on the equipment setup. These tools allow for precise and safe handling of the heavy concrete segments;
- Ring Completion and TBM Thrust
  Once the ring is fully assembled, including the key segment, it forms a rigid structural unit. This completed ring then acts as a reaction surface for the TBM's hydraulic jacks, enabling the machine to push itself forward toward the tunnel face as excavation continues.

Soil conditioning impacts the last step by ensuring that the consistency of the excavated material is sufficiently stable to avoid excessive ring deformation.

2.4 Muck Removal and Transport

The excavated material, the soil mixed with foam, polymer or other soil conditioning agents, with plastic and flowable consistency used to support the tunnel face and allow a well-controlled extraction, is called muck.

During the EPB tunnelling process, muck removal and transport is an important process which ensures the continuous excavation with no disruption and the correct balance of the counterpressure at the excavation face. Working principle of EPB: the pressure is regulated by balancing the amount of soil coming inside the excavation chamber and the one extracted. The moment that the muck exit from screw conveyor, it can be transported via conveyor belt, muck car or rail.

In this phase control of the material flow, clogging of the screw conveyor, wear and tear of the equipment like abrasion from coarse materials can be challenges to be faced during the process.

In case the material is not enough viscous due to the limitation of soil conditioning in specific types of soil, it may be needed to add polymers in the screw conveyor to better the properties of the muck.

In these cases, to regulate the muck extraction and maintain the face pressure stability, to improve the efficiency of the screw conveyor the polymer may not be injected in the excavation chamber to avoid the problem of clogging. The followings points address the key consideration for the correct choice of the polymer and its use.

1. Analysing the soil properties: according to the soil condition, for example, in cohesive clays or in abrasive sands we can adopt different types of polymers.
2. Dosage evaluation of the polymer: The use of polymer impacts the soil to make it suitable for excavation at the expense of major costs and environmental impact. On the other hand, if the amount of polymer is too low, it may not be effective for the challenge to be resolved.
3. Environmental Impact: To reduce the environmental impact, the selected polymer must be biodegradable and environmentally safe to comply with regulations. In other words, the type of the polymer being used to conditioning the soil is not allowed to contaminate the soil, to cause environmental damage, or to have side effects on ground water.

In the most challenging situations, the adoption of polymers may be essential for a controlled muck removal and face pressure stability. Proper control and optimization of polymer use can significantly enhance TBM performance.

2.5 Soil conditioning

The application of full face mechanised tunneling specifically with EPB shielded machine has increased recently. Besides, it can be considered as key technology while tunneling in the soil both above and below water table. The applicability of EPB has widened due to both mechanical and technological progress and the research and production of new and more performing conditioning products. It is noted that there are no ISO standards to be referred to soil conditioning laboratory tests and each research centre follows its procedure with small differences in the approach between them. In this chapter, the procedure and methods used at the Politecnico di Torino, discussed in the following, were applied to the soil conditioning assessment.

In cohesionless soils, the conditioning process is the base of the correct excavation process with an Earth Pressure Balance tunnel boring machine. The excavated soil detached by the excavation tools enters through the opening of the cutterhead itself in the pressure chamber from where it is extracted using the screw conveyor. The screw conveyor discharges the muck on the conveyor belt that transport the muck outside the tunnel. Moreover, in the excavation chamber the soil is pressurized to counterbalance the pressure of both natural soil and water. It is noted that in the screw conveyor there should be a gradual reduction of the pressure down to zero at the outlet of the screw conveyor itself. To guarantee an optimal working process, it is essential that excavated volume which enters in the chamber is always equal to the volume extracted from the screw conveyor Figure 9. To correctly manage this process, it is fundamental that the soil in the pressure chamber has a plastic behaviour with a pulpy consistency that means, semi-fluid, thick soil which is paste-like during the excavation.

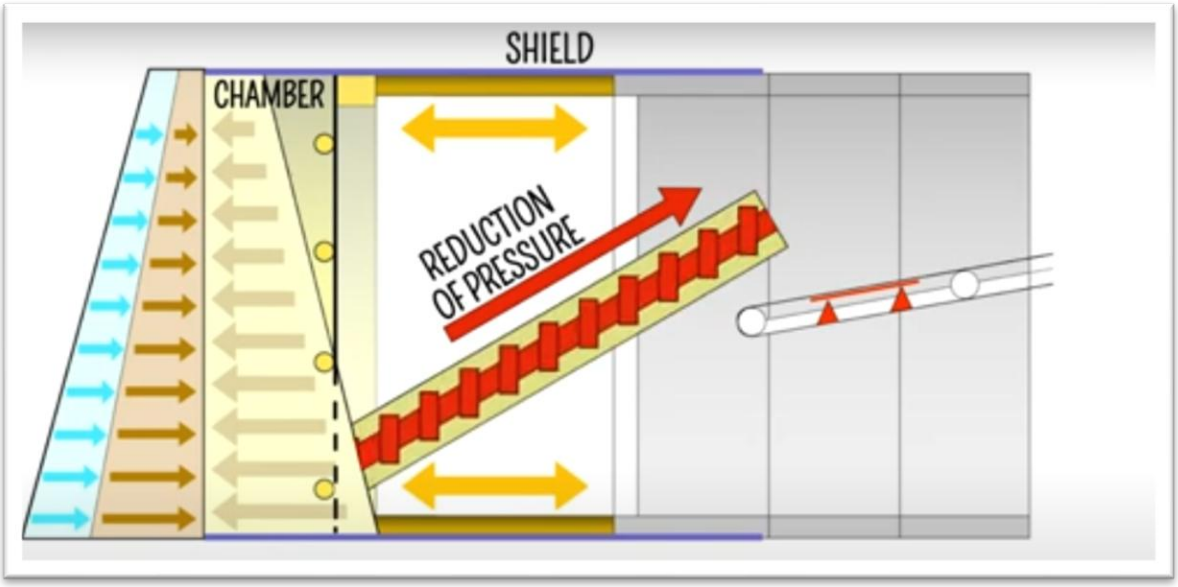


Figure 9_The material in the pressure chamber must have a plastic characteristic with a pulpy consistency.

The pulpy consistency is obtained by conditioning the soil by adding water, foam, bentonite slurry and/or polymers which can interact with soil grains to change the overall soil properties. The conditioning agents can be injected ahead of the cutterhead, in the pressure chamber and along the screw conveyor.

The main purposes of soil conditioning in EPB tunneling are to guarantee a uniform distribution of the pressure at the excavation face, to control the flow of the excavated material through the cutterhead and in the screw conveyor, to reduce the friction forces in the bulk chamber, to control the water in-flow through the reduction of the soil permeability, to create a plug in the screw conveyor, to reduce wear of the mechanical parts of the machine that are in contact with the soil, to allow easy spoiling handling and, if tunneling is in clay, to prevent the stickiness of the clay on mechanical parts of the TBM.

This change of behaviour depends on the foam that fills the intergranular voids as can be seen in the Figure 10.

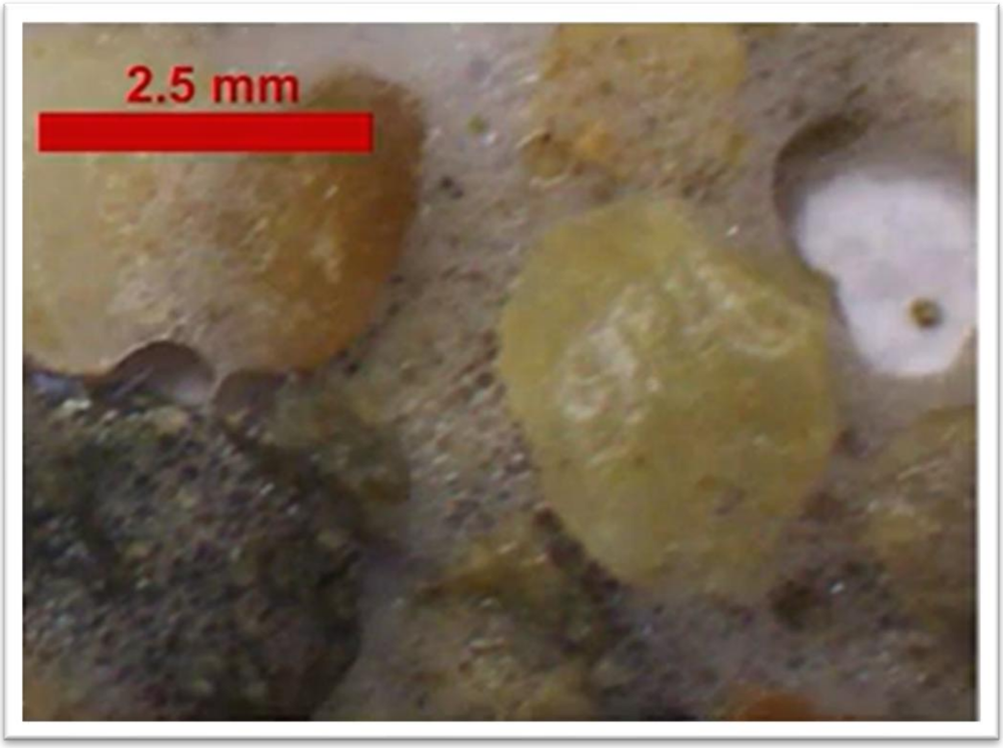


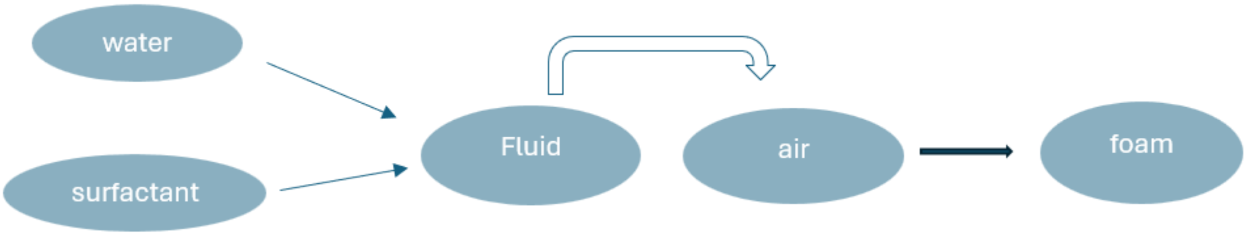
Figure10_The presence of the bubbles between the voids existed among the grains.

The most frequent product used for soil conditioning are as following:

1. **Foam:** which is the key product, and it is always used in soil conditioning;
2. **Long chain polymers** are used to improve the stability of foam bubbles and enhance the quality of the conditioned soil especially in the case of presenting water in the mass of excavated soil.
3. **Anti-clogging and lubricating agents** which adopted to avoid amalgamation and stiffness of the clay;
4. **Abrasion-preventers** which is used to reduce the wear of the metallic parts of the TBM;
5. **Bentonite slurry;**
6. **Fillers** to change the soil grain size distribution;
7. **Water** to change natural content of the soil to have better combination with the foam.

2.5.1 Foam

Foam is generated by firstly mixing the surfactant with the water (generation fluid). Then the fluid is mixed with air in a static mixer which allows to generate a high turbulence; so that as the result the foam can be obtained.



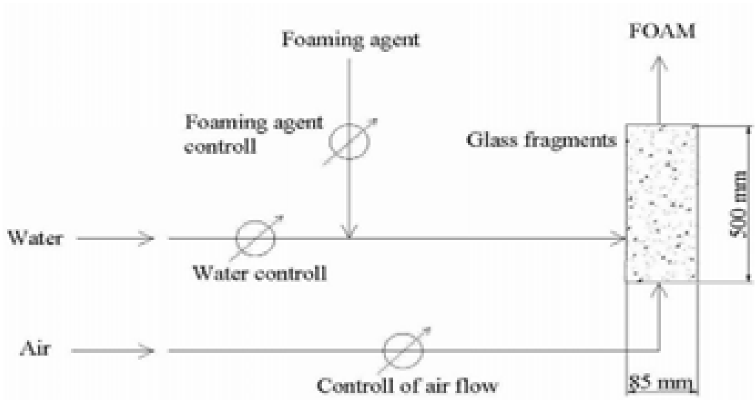


Figure 11_Left: the foam generator used for the foam production; Right: scheme of the foam generation process

The average range composition of a standard foam is water ranging from 5-10% of the foam. The surfactant agent percentage of the generation fluid is ranging between (0.8-5%) depending on the type of adopted product and the environmental limits allowed in each country. Eventually the remaining part is air which is (90-95%) of the foam.

2.5.2 Bentonite slurry

The slurry was formulated by mixing water and bentonite in a precise ratio, in this thesis has been used a ratio with 6417 (g) of water combined with 1082 (g) of bentonite to achieve a slurry unit weight of $\gamma_{slurry} = 1.1(\frac{kg}{l})$.

The procedure to make the slurry is shown in Figure 12 where the impeller was adopted and rotated at the constant speed of 2000 (rpm) for 7 minutes.

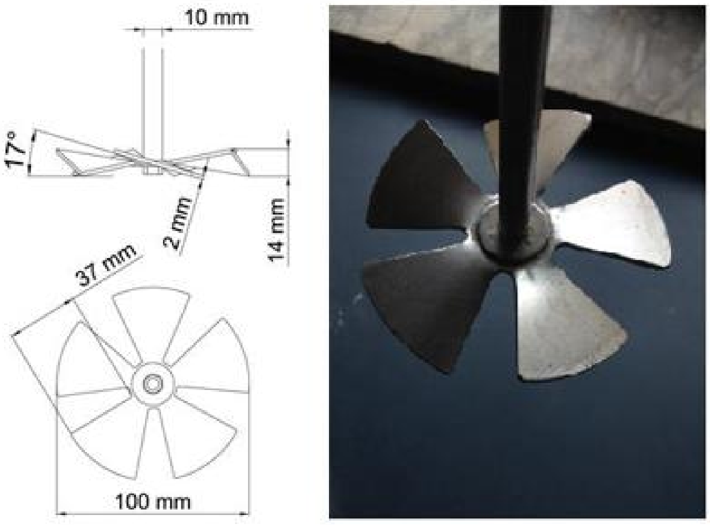


Figure 12_scheme and photo of the used impeller.

2.5.3 The design parameters of the soil conditioning

1. Concentration of the generation liquid: represents the volumetric ratio between surfactant and water in the generation liquid (Equation 1)

$$c_f = \frac{V_{surfactant}}{V_{water}} \tag{1}$$

2. Foam Expansion Ratio (FER): represents the expansion of the foam with reference to generation fluid volume (Equation 2).

$$FER = \frac{V_{foam}}{V_{generation\_liquid}} \text{ (-)} \tag{2}$$

Where:

V_{foam}: volume of the foam;
$V_{generation\_liquid}$: volume of the generation fluid at atmospheric pressure.

FER values typically range from 5 to 25 in tunneling applications. If FER is low, it means that the foam is wet which means that a lot of generation fluid is present in the foam; on the other side, if this value is high, the produced foam is dry which means there is more air in the foam. Depending on the type soil and its water content we can opt either for wet or dry foam, Figure13.

Figure 13_Foam sample produced at Politecnico di Torino

3. Foam Injection Ratio (FIR): FIR represents the percentage ratio between the volume of the foam injected in the soil during the excavation and the volume of the soil itself. Equation2)

$$FIR = \frac{V_{foam}}{V_{excavated\_soil}} \cdot 100\ (\%) \tag{2}$$

Where:

V_{foam} is volume of the foam injected;

$V_{excavated\_soil}$ is the volume of the excavated soil.

Typical values range from 20% to 80%, depending on soil conditions.

4. Slurry Injection Ratio (SIR): SIR is a significant parameter to determine the volume of slurry injected relative to the volume of excavated soil. It can be calculated by the Equation 3 and be expressed as a percentage:

Equation 3:

$$SIR = \left(\frac{V_f}{V_s}\right) \cdot 100(\%) \tag{3}$$

Where:

- V_f : Volume of injected foam;
- V_s : Volume of the excavated soil.

The interpretation of the SIR is practical to choose the optimal amount of the slurry which means higher SIR causes soil plasticity and workability, prevents clogging, and enhances flowability in EPB chamber. However, it is notable that the injection of an exaggerated amount of slurry can have reversed result like reducing the cohesion and leading difficulties into create the plug in the screw conveyor. On the other hand, lower SIR may lead to insufficient conditioning, causing the soil to be too dry and the slump test to show the low number which interprets as dryness and unworkable of the conditioned soil.

These three parameters should be evaluated and analysed before starting the excavation with proper laboratory study.

2.5.4 The design process of the soil conditioning

The design process of soil conditioning is composed of three different steps: the first phase starts with the geomechanical and geotechnical characterization of the soil properties and the following laboratory test to assess the required amount of conditioning agents. Based on the Figure 2 it is reported a scientific literature summary of possible conditioning products that can be utilized with different grain size distribution of the soil.

The second phase requires the environmental characterization of the muck. It needs to be environmentally compatible with the laws and regulation in force. Both conditioning agents as pure product and the conditioned soil must be tested, in other words, the goal of this step is to assess that the used conditioning agents are environmentally friendly; plus, the utilized agents are compatible with the environmental threshold values.

Finally, the last phase will be carried out during the tunneling excavation. It is always necessary to carry out a control of the muck properties during the excavation. Due to the natural variability of soil properties these changes can affect the effectiveness of the conditioning process carried out in the laboratory. This aspect is particularly important when mixing faces are to be met during tunneling process.

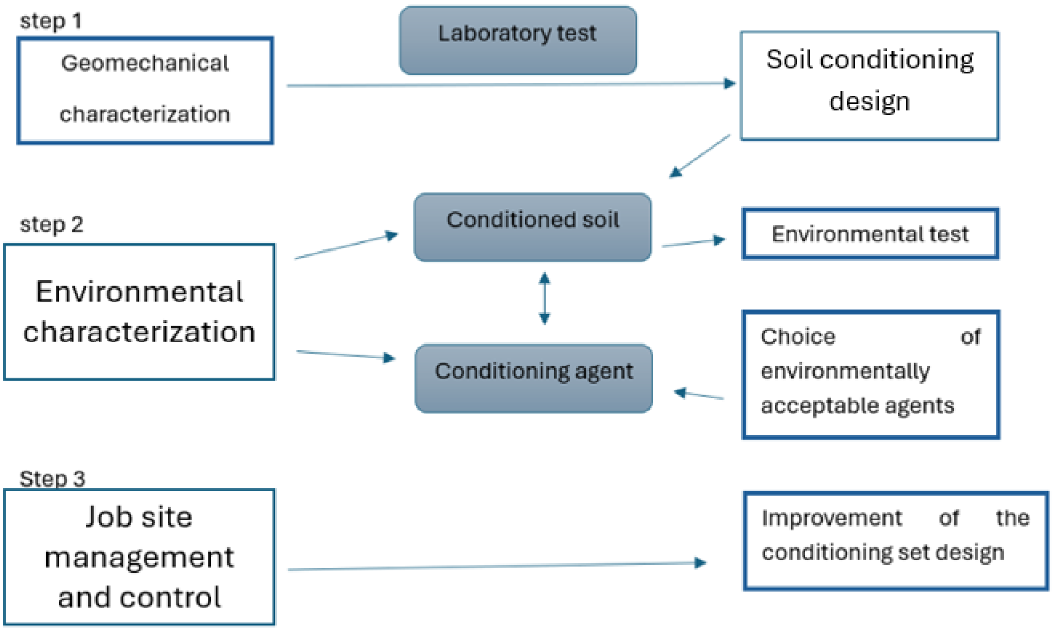


Figure 14_The design process of the soil conditioning

2.5.5 Laboratory test on soil conditioning

Once all the conditioning agents are ready, they were added into the soil A, using a concrete mixer. Prior to testing, the concrete mixer was carefully cleaned to prevent contamination and ensure consistent results. During the mixing process, foam was incorporated into the material in two distinct stages to closely replicate the soil conditioning process within an Earth Pressure Balance (EPB) machine. This stepwise addition of foam aimed to achieve uniform distribution and enhance the sand's mechanical properties, facilitating optimal workability and flow behavior under simulated tunneling conditions. Furthermore, to achieve the desired Foam Expansion Ratio (FER), the prepared foam must be accurately weighed. One of the most frequently used tests on soil conditioning assessment is slump test, Figure 15. This test is popular thanks to its simplicity which allows to be used in both laboratory test as well as in the jobsite. The soil sample mixed with the soil conditioners was added in the mixer with the speed of 8 rpm. The slump cone has the dimension of hight 30 cm, bottom diameter of 20 cm and top diameter of 10cm. once the cone is filled with the soil the cone can be lifted vertically then the soil is able to collapse under its weight; as the result the slump value can be measured as the vertical distance between the height of the cone and the highest point of the slumped soil.

Figure 15_ The process of soil conditioning with foam to have the slump test

The slump test procedure is summarised as follows:

1. a sample of 10 kg of soil is inserted into a standard concrete mixing device with a capacity of ¼ m^3;
2. foam is generated according to the required FER;
3. water, foam and slurry (potentially with polymer) are added to the soil sample in the required order and quantity, and then mixed by rotating the drum;
4. the conditioned soil is then poured into a standard slump cone (UNI EN 12350-2:2019) and the cone is lifted up;
5. the slump of the material is recorded and the conditioned soil unit weight, scissometric index, and general characteristics of the material are noted and compared with the reference table.

It is crucial to realize that for the same soil the well-suited conditioning depends not only on the foam content but also on the water present in the soil. In other words, if there is too much water and foam in the conditioned soil, the soil as the result would be too fluid. On the other hand, if the present foam is too much and water amount is not enough, the result would be the material which is not properly conditioned. It is noticeable that only a good combination of water and foam content give an acceptable result, Figure 16.

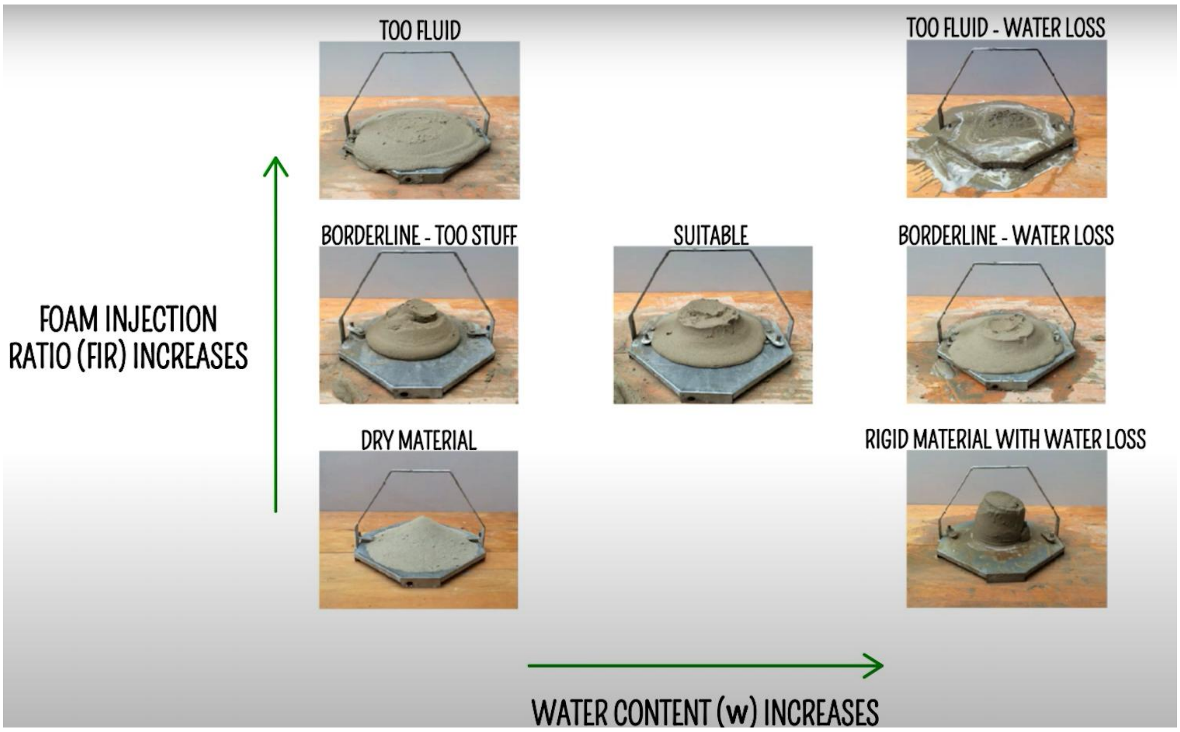


Figure 16_Illustrates the impact of the water and foam content on soil conditioning.

As it is shown in the Figure 17, it is possible to see an assessment chart for the slump test to recognize the different behaviour between too dry soil and too wet soil. For a correct assessment it is essential to define a suitable behaviour which means materials should have both good plastic and pulpy behaviour. The slump value within the range of 12-20 cm is acceptable for the soil conditioning.

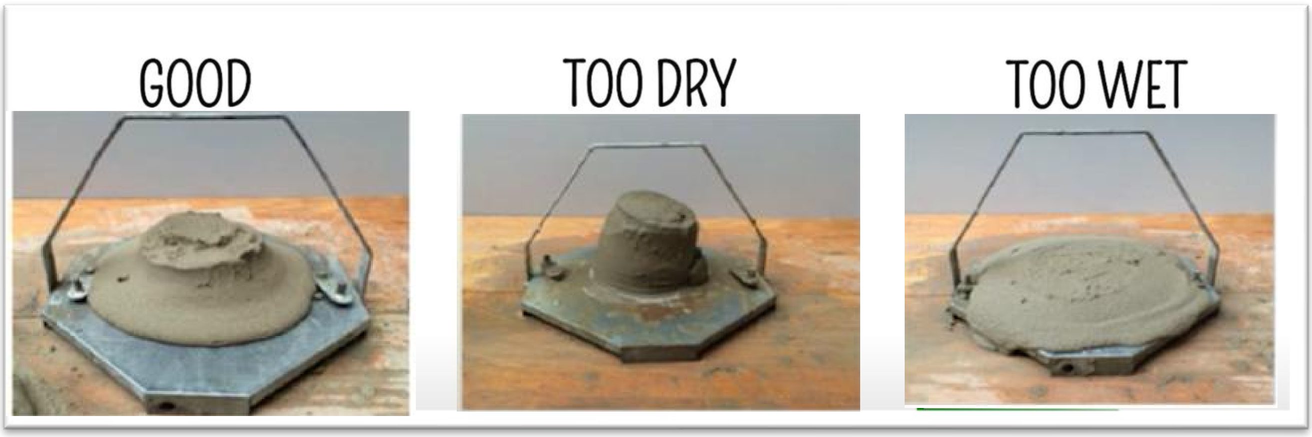


Figure 17_The result of water combination with foam agent in soil conditioning

2.6 Laboratory assessment tests

2.6.1 Mini flow test

It is important to recognize that laboratory tests are conducted at a reduced scale compared to the actual conditions in which an EPB-TBM operates. Consequently, these tests are subject to inherent scale effects, influenced by factors such as the TBM diameter and cutterhead characteristics, as well as operational variables like excavation time and chamber temperature.

Initial testing involved a series of mini flow trials aimed at evaluating soil behavior in response to water and foam conditioning. A mini flow cone—measuring 66 mm in height, 44 mm in lower base diameter, 20 mm in upper base diameter, and with a volume of 55.6 cm^3—was employed to gain early insights while minimizing soil consumption. Final evaluations were then performed using the standard slump test method.

The following steps shows the methods of mini flow tests:

1) a sample of 0.120 kg of soil is inserted into a container with a capacity of 0.4 L;
2) foam is generated according to the required FER using the foam generator;
3) water, foam and slurry (prepared in advance and potentially with polymer) are added to the soil sample in the required order and quantity, and mixed;
4) the obtained material (the conditioned soil) is poured into a mini flow cone, and the cone is lifted-up;
5) the slump of the material is recorded, and the conditioned soil unit weight and general characteristics of the material are noted;
6) steps 1 to 5 are repeated, but this time, before lifting the mini-cone, a light pressure is applied to the surface of the material. The data recorded in this way are called post-compaction, while the data without pressure are called pre-compaction.

2.6.2 Bulk density test

Bulk density test is essential in case of realizing the mechanical behaviour of the soil particularly in tunneling, where soil density influences pressure counterbalance, muck transportation, and efficiency of soil conditioning.

Bulk density (ρ_b) can be defined as the ratio between the total mass of the soil on its total volume, which represents both solids and voids. It will be expressed in unit of $g/_{cm^3}$, equation 4:

$$\rho_b = \frac{M_t}{V_t} \tag{4}$$

Where:

M_t: total mass of the soil comprehensive of water and conditioning agents in grams that has to be measured;

V_t: total volume of soil sample, (2014 cm^3).

2.6.3 Modified vane test

In the laboratory to control the quality of the conditioned soil a modified version of vane test was developed.

This version is different from the standard test (Figure 18) due to the different size of the blades (the vane dimension has been raised to a diameter of 54 mm and a hight of 109 mm to be more sensible in measuring while the large-size grains are presented).

This test is performed by pushing the blades vertically into the soil sample and rotate the handle till a cylindrical shear surface is formed and the value of measured torque is registered and divided by the lateral area of the cylinder.

Figure 18_Modified vane test device

2.6.4 Screw Conveyor Extraction Test

To verify the suitability of conditioned soil for extraction using an EPB-TBM screw conveyor and to simulate material behavior during the excavation phase, a custom-designed experimental device has been developed and is operational at the Tunnelling and Underground Space Laboratory & Research Center (TUSC) of the Department of Environment, Land and Infrastructure Engineering (DIATI) at the Polytechnic University of Turin. The extraction procedure utilizing this apparatus is thoroughly described in the works of Martinelli et al. (2019) and Vinai et al. (2008), as detailed in Chapter 7. Experimental results obtained from tests on various conditioned soils using this setup are also summarized therein and have been widely published.

The screw conveyor extraction device consists of a cylindrical steel tank with a nominal diameter of 600 mm, connected to a screw conveyor with an external diameter of 168 mm and a length of 1500 mm. The screw operates at a constant rotational speed of 8 rpm. To monitor extraction behavior and operational parameters, the setup includes four pressure gauges positioned along the screw conveyor and a torque meter that records the applied torque. An additional pressure gauge, installed at the base of the tank, allows for the evaluation of stress transmission through the conditioned soil—providing key insights into the homogeneity and rheological behavior of the material under pressurized conditions.

Materials conditioned with FER values of 16 and FIR of 30%, C: 2%, w_{tot}: 12%. The foam was produced using a commercial foaming agent.

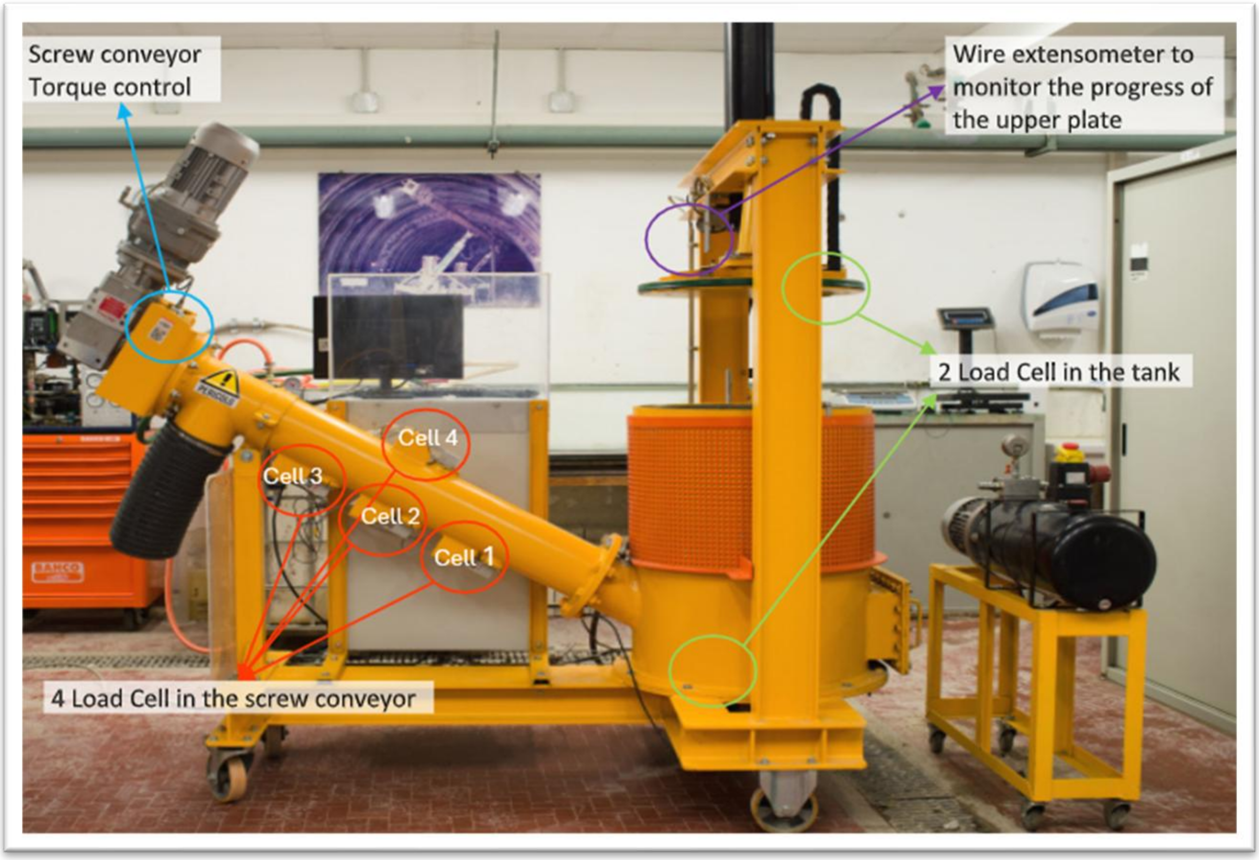


Figure 19_Screw Conveyor extraction test device.

To perform the tests the procedure is articulated as follows:

1) Data acquisition unit is set to acquire data;

2) The material to be conditioned is inserted into a standard concrete mixing device with a capacity of ¼ m^3;

3) Foam is generated according to the required FER. Water, foam and slurry (potentially with polymer) are added to the soil sample in the required order, quantity, and mixed;

4) The prepared conditioned soil is inserted into the tank of the experimental machine. Steps 2 to 3 are repeated till the tank is fill with conditioned soil;

5) The tank cap is greased to reduce the friction between its edge and the inner surface of the tank;

6) The cap is pushed inside the tank using the hydraulic cylinder till the working pressure of 1 bar is reached;

7) The screw conveyor is turned on to extract the conditioned material and at the same time keeping the pressure inside the tank to 1 bar;

8) The extracted material is regularly collected to undergo the standard slump test;

9) The test ends when the hydraulic cylinder reaches its end of stroke.

Figure 20_Materials being extracting from screw conveyor.

2.6.5 Time consideration for better simulating the application of EPB machine under-ground regarding bubble lifespan

One of the key factors in soil conditioning using foam is time, as it influences foam stability over time. Foam enhances the workability and plasticity of the soil; however, it is unstable due to bubble coalescence, collapse and liquid drainage over time which can affect the soil properties. After mixing foam with soil, the foam bubbles merge over time, growing bubble size which leads to a decrease overall foam volume. In addition, loss of uniformity in air dispersion causes a reduction in soil homogeneity. Also, liquid drainage over time reduces foam stability and makes soil stiffer and less plastic, which has influence on the performance of the EPB machine.

3 Case Study

In this study, three different types of cohesionless sand, collected from the northern part of Europe, have been examined to evaluate their suitability for Earth Pressure Balance Tunnel Boring Machine (EPB-TBM) applications. The assessment was based on the results of the carried-out tests.

By conditioning the sands and performing the slump test, the modified vane test and the bulk density evaluation it was assessed if the chosen parameters were optimal for EPB applications.

To further assess the effectiveness of the conditioning process and verify its suitability also in pressurized conditions, a screw conveyor extraction test has been performed. This allowed to evaluate whether the conditioned sand met the functional requirements for use in an Earth Pressure Balance (EPB) machine.

The following sections provide a detailed description of the laboratory experiments conducted in this study.

3.1 Characteristic of the sands under the assessment

The soil which is going to be excavated in the Northern-Europe jobsite is made of two main formations where the second one lays on the bottom 4 meters of the excavation section as shown in Figure 21.

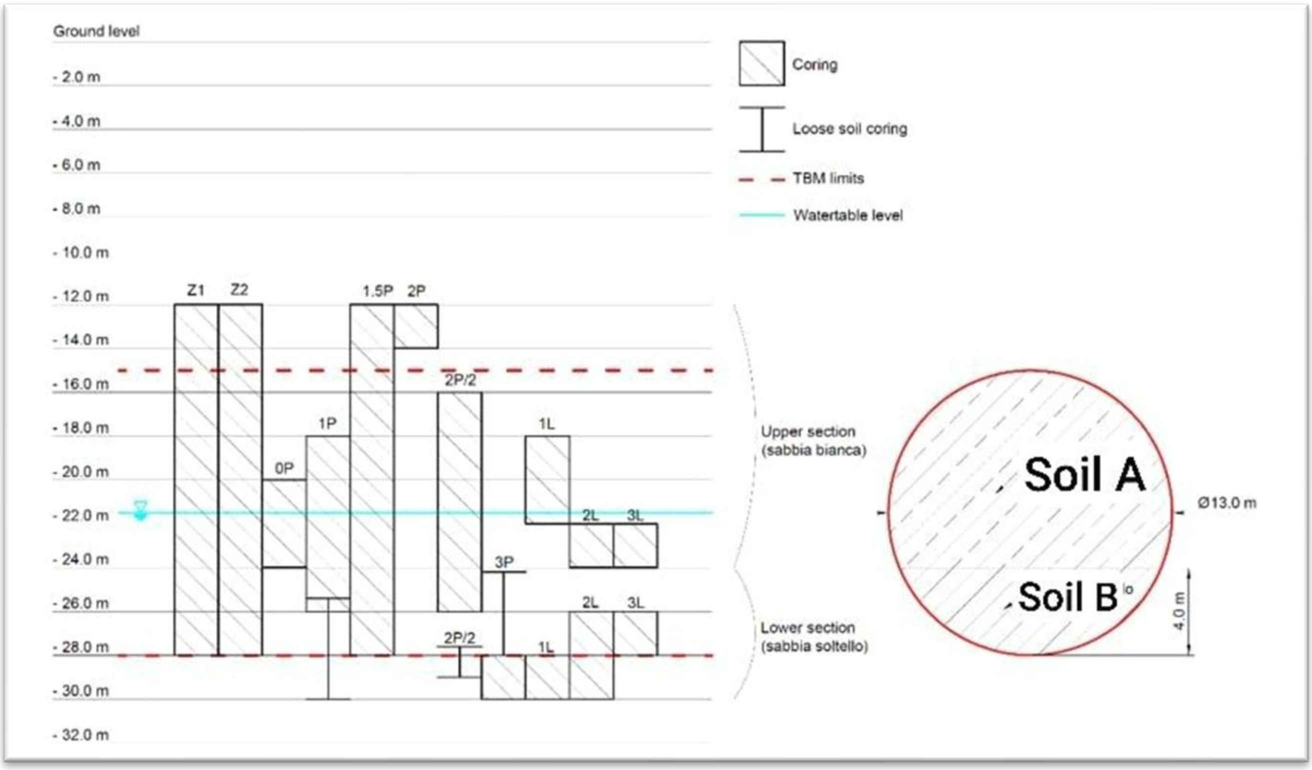


Figure 21_Core sampling distribution along the vertical and highlight of the two types of sand area.

The Soil A is characterised by a bulk unit weight of 1560 (kg/m^3) and a natural water content of 8.0%.

The soil B is characterised by a bulk unit weight of 1610 (kg/m^3) and a natural water content of 19.5%.

The third soil used for the tests is the mixture of 75% of Soil A and 25% of soil B and is called Soil **C**. Soil C is characterised by a bulk unit weight of 1570 (kg/m^3) and a natural water content of 10.7%.

3.1.1 Soil classification

The tasted soil can be classified according to the organized classification system such as Unified Soil Classification System (USCS) to assess if the soil is appropriate for the application of the Earth Pressure Balance (EPB) Tunnel Boring Machine.

The three types of soil were analysed in terms of grain size distribution and composition. Cohesionless Soil, especially sand, plays a significant role in TBM performance due to its effect on the wear on cutting tools, face stability, and material flow through the screw conveyor. By assessing the classification of the soil, it is possible to recognized if the soil is well-graded (SW) or poorly graded (SP) under (USCS).

The classification moreover analyses if the soil is compatible for the application of EPM, in which ideal soil should have some level of cohesion to be able to sustain the pressure and maintain the stability under applied pressure. In the case of pure cohesionless soil, taking into action the conditioning using foam and polymer is critical to improve mechanical properties such as plasticity, cohesion and flow properties.

3.1.2 Grain Size Distribution (D10, D30, D60)

To assess the mechanical properties of tested soil the grain size distribution curves were performed and are shown in Figure 22.

They were also analysed to determine if the tested soil is applicable for the function of EPB. Hence the following parameters are included:

- D_{10}: The particle diameter indicates that only 10% of the total mass can pass the sieve. Furthermore, D_{10} is effective size as it determines permeability as well as drainage characteristics;
- D_{30}: The particle diameter indicates that only 30% of the total mass can pass the sieve that is used for the uniformity and gradation calculation;
- D_{60}: The particle diameter indicates that only 60% of the total mass can pass the sieve which is practical in soil stability evaluation.

The introduced parameters D_{10}, D_{30}, and D_{60} are functioned to calculate Uniformity Coefficient (C_u) and Coefficient of Gradation (C_c).

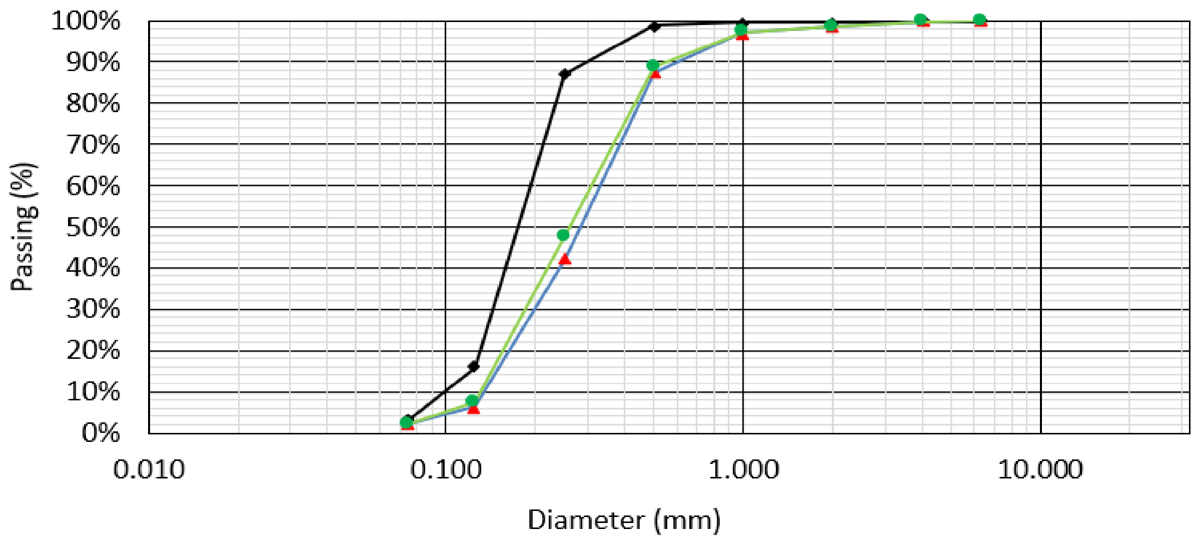


figure 22_Grain size distribution and coefficient of uniformity (Cu) for: "soil A", "soil B" and "soil C".

The Uniformity Coefficient is defined as:

$$C_u = \frac{D_{60}}{D_{10}} \tag{5}$$

- If $C_u > 4$ (for sands), the soil has a not uniform particle size distribution;
- If $C_u < 4$ (for sands), the soil has a uniform particle size distribution.

The Coefficient of Gradation is defined as:

$$C_c = \frac{(D_{30})^2}{(D_{10}) \times (D_{60})} \tag{6}$$

- If $1 < C_c < 3$, means the soil has a well-graded distribution;
- On the contrary, the values out of the given range interpreters as gap-graded or poorly graded soil.

In this study C_u and C_c were determined for each of the three soil samples to evaluate their granular structure and permeability before and after the conditioning process. The soil with high permeability and low cohesion generally requires foam or polymer additives to promote their capability such as plasticity, maintaining face pressure, controlled flow, reduced permeability, and creation of more homogeneous mixture for the function of EPB technology.

To calculate the Uniformity Coefficient (C_u) and Coefficient of Gradation (C_c) for the three soil samples, we need the values of D10, D30, and D60 from the grain size distribution curves. The Table 1 below by considering the Equation 5 and 6 illustrates the result on the tasted soil sample:

Soil B	Soil A	Soil C
C_u = 2	C_u = 2.46	C_u = 2.31
C_c= 1.03	C_c= 1.12	C_c = 1.09

Table 1_ Cu and Cc value for soil A, B, and C

While $C_u < 3$, the soil samples are not well-graded. Besides $1 < C_c < 3$ suggests a well-graded sand suitable for the application of the Earth Pressure Balance EPB machine compering to the Standard Grain Size Distribution Curve for EPB machine.

3.2 Results of the tests

In the results tables, the following nomenclature has been used:

Symbol	Defination
c (%)	foaming agent concentration, expressed as the ratio between the volume of the used foaming agent and the volume on the liquid generator; it is expressed in percentage.
FER (-)	– foam expansion ratio, computed as the volume of the foam on the volume of the generator liquid.
FIR (%)	foam injection ratio, computed as the ratio between the volume of the used foam on the volume of the soil.
I_{sc} (kPa)	scissometric index, obtained through the Shear Vane Test (Carigi at al., 2020, ASTM D2573/D2573M-18).
TR (L/m^3)	treatment ratio, it is the quantity of used foaming agent, computed as L on cubic meter of soil.
SIR (%)	slurry injection ratio, computed as the ratio between the volume of the used slurry on the volume of the soil.
$w_{natural}$ (%)	natural water content, expressed in percentage and computed on the solid mass.
w_{add} (%)	– added water content, expressed in percentage and computed on the solid mass
w_{tot} (%)	total water content, expressed in percentage and computed on the solid mass; it is the sum of $w_{natural}$ and w_{add};
γ_{soil} (kg/L)	it is the bulk unit weight of the soil intended to be conditioned
$\gamma_{conditioned\ soil}$ (kg/L)	it is the bulk unit weight of the conditioned soil
γ_{slurry} (kg/L)	it is the bulk unit weight of the slurry. Use a table

3.2.1 Mini flow Results

The results of the mini flow tests performed on *Soil A*, *Soil B*, and *Soil C* are reported in the following tables.

Soil A	**-**	**Picture**
TEST	**1a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	65	
TR (L/m^3)	1.30	
$w_{natural}$ (%)	8.0	
w_{add} (%)	2.0	
w_{tot} (%)	10.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	8	
γ_{slurry} (kg/L)	1.20	
Pre-compaction. (collected data without applying compression) The material flows out of the cone with difficulty.		

Soil A	**-**	**Picture**
TEST	**1b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	65	
TR (L/m^3)	1.30	
$w_{natural}$ (%)	8.0	
w_{add} (%)	2.0	
w_{tot} (%)	10.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	8	
γ_{slurry} (kg/L)	1.20	
Post-compaction, with a small compression on the upper side. Fluid leakage when the pressure is applied.		

Soil A	-	Picture
TEST	**2a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	80	
TR (L/m^3)	1.60	
$w_{natural}$ (%)	8.0	
w_{add} (%)	7.0	
w_{tot} (%)	15.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	16	
γ_{slurry} (kg/L)	1.20	
Pre-compaction. Foam leakage.		

Soil A	-	Picture
TEST	**2b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	80	
TR (L/m^3)	1.60	
$w_{natural}$ (%)	8.0	
w_{add} (%)	7.0	
w_{tot} (%)	15.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	16	
γ_{slurry} (kg/L)	1.20	
Post-compaction, with a small compression on the upper side. Average slump. Fluid leakage from the bottom of the mini-cone when the pressure is applied. The material flows out from the mini-cone with difficulty.		

Soil A	-	Picture
TEST	**3a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	65	
TR (L/m^3)	1.30	
$w_{natural}$ (%)	8.0	
w_{add} (%)	7.0	
w_{tot} (%)	15.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	16	
γ_{slurry} (kg/L)	1.20	
Pre-compaction. The material flows out easily from the mini-cone.		

Soil A	-	Picture
TEST	**3b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	65	
TR (L/m^3)	1.30	
$w_{natural}$ (%)	8.0	
w_{add} (%)	7.0	
w_{tot} (%)	15.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	16	
γ_{slurry} (kg/L)	1.20	
Post-compaction, with a small compression on the upper side. Fluid leakage when the pressure is applied. The material flows out easily from the mini-cone.		

Soil A	-	Picture
TEST	**4a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	65	
TR (L/m^3)	1.30	
$w_{natural}$ (%)	8.0	
w_{add} (%)	4.0	
w_{tot} (%)	12.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	20	
γ_{slurry} (kg/L)	1.10	
Pre-compaction. The material is fluid.		

Soil A	-	Picture
TEST	**4b (post-comp)**	not assessed (excessively fluid observed) N/A
foaming agent concentration C (%)	2.0	
FER (-)	10	
FIR (%)	65	
TR (L/m^3)	1.30	
$w_{natural}$ (%)	8.0	
w_{add} (%)	4.0	
w_{tot} (%)	12.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	20	
γ_{slurry} (kg/L)	1.10	
Post-compaction, with a small compression on the upper side. The material is too fluid.		

Soil A	-	Picture
TEST	**5a (pre-comp)**	
foaming agent	n/a	
c (%)	0.0	
FER (-)	-	
FIR (%)	0	
TR (L/m^3)	0	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	35	
γ_{slurry} (kg/L)	1.10	
Pre-compaction. The material flows out from the mini-cone with difficulty. The material is sticky.		

Soil A	-	Picture
TEST	**5b (post-comp)**	
foaming agent	n/a	
c (%)	0.0	
FER (-)	-	
FIR (%)	0	
TR (L/m^3)	0	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	35	
γ_{slurry} (kg/L)	1.10	
Post-compaction, with a small compression on the upper side. No fluid leakage when the pressure is applied. The material flows out from the mini-cone with difficulty.		

Soil A	**-**	**Picture**
TEST	**6a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	32 + 24	
TR (L/m^3)	0.75	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
Pre-compaction. Good slump.		

Soil A	**-**	**Picture**
TEST	**6b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	32 + 24	
TR (L/m^3)	0.75	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
Post-compaction, with a small compression on the upper side. Good slump. Some soil leakage with water when the pressure is applied. The material flows out easily from the mini-cone.		

Soil A	-	Picture
TEST	**7a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	32 + 24	
TR (L/m^3)	0.75	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
$\gamma_{conditioned\ soil}$ (kg/L)	1.44	
Pre-compaction. Good slump. The material flows out easily from the mini-cone.		

Soil A	-	Picture
TEST	**7b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	32 + 24	
TR (L/m^3)	0.75	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
$\gamma_{conditioned\ soil}$ (kg/L)	1.44	
Post-compaction, with a small compression on the upper side. Good slump.		

Soil A	-	Picture
TEST	**8a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
$\gamma_{conditioned\ soil}$ (kg/L)	1.44	
Pre-compaction. Foam added before the addition of the slurry. Good slump.		

Soil A	-	Picture
TEST	**8b (post-comp)**	
foaming agent concentration	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
$\gamma_{conditioned\ soil}$ (kg/L)	1.44	
Post-compaction, with a small compression on the upper side. Foam added before the addition of the slurry. Fluid leakage when the pressure is applied.		

Soil A	-	Picture
TEST	**9a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
$\gamma_{conditioned\ soil}$ (kg/L)	1.32	
Pre-compaction. Foam added after the addition of the slurry. Adhesion of the material on the inner surface of the mini-cone. Foam is absorbed by the material with difficulty.		

Soil A	-	Picture
TEST	**9b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
$\gamma_{conditioned\ soil}$ (kg/L)	1.32	
Post-compaction, with a small compression on the upper side. Foam added after the addition of the slurry. Good slump. Some fluid leakage when the pressure is applied.		

Soil A	**-**	**Picture**
TEST	**10a (pre-comp)**	
foaming agent concentration	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
$\gamma_{conditioned\ soil}$ (kg/L)	1.57	
Pre-compaction. Foam added before the addition of the slurry. The material is fluid.		

Soil A	**-**	**Picture**
TEST	**10b (post-comp)**	
foaming agent concentration	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
$\gamma_{conditioned\ soil}$ (kg/L)	1.57	
Post-compaction, with a small compression on the upper side. Foam added before the addition of the slurry. Fluid leakage when the pressure is applied. The material is sticky.		

Soil A	-	Picture
TEST	**11a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m3 of slurry)	0.71	
$\gamma_{conditioned\ soil}$ (kg/L)	1.56	
Pre-compaction. Foam added before the addition of the slurry. The material is viscous but fluid.		

Soil A	-	Picture
TEST	**11b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
$\gamma_{conditioned\ soil}$ (kg/L)	1.56	
Post-compaction, with a small compression on the upper side. Foam added before the addition of the slurry. The material is viscous but fluid.		

Soil A	-	Picture
TEST	**12a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
$\gamma_{conditioned\ soil}$ (kg/L)	1.57	
Pre-compaction. Foam added before the addition of the slurry. Water leakage. The material flows out easily from the mini-cone.		

Soil A	-	Picture
TEST	**12b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
$\gamma_{conditioned\ soil}$ (kg/L)	1.57	
Post-compaction, with a small compression on the upper side. Foam added before the addition of the slurry. Fluid leakage when the pressure is applied.		

Soil A	**-**	**Picture**
TEST	**13a (pre-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	1.42	
$\gamma_{conditioned\ soil}$ (kg/L)	1.68	
Pre-compaction. Foam added before the addition of the slurry. The material flows out easily from the mini-cone.		

Soil A	**-**	**Picture**
TEST	**13b (post-comp)**	
foaming agent concentration C (%)	2.0	
FER (-)	15	
FIR (%)	55	
TR (L/m^3)	0.73	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	1.42	
$\gamma_{conditioned\ soil}$ (kg/L)	1.68	
Post-compaction, with a small compression on the upper side. Foam added before the addition of the slurry. Fluid leakage when the pressure is applied. The material flows out easily from the mini-cone. The material is viscous and pasty.		

3.2.2 Results on slump tests, bulk density tests and modified vane test for optimal soil conditioning determination

The results and the pictures obtained after carrying the slump test is reported in the following tables, together with the results obtained from bulk density tests, modified vane test, and the parameters used for the soil conditioning.

In the relevant cases some tests were performed also after certain amount of time after the soil conditioning to verify the stability in time of the conditioning.

Moreover, some relevant notes are attached to each table.

Soil A	**-**	**Picture**
TEST	**1**	
foaming agent C (%)	2.0	
FER (-)	15	
FIR (%)	32 + 24	
TR (L/m^3)	0.75	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
slump at t_0 (cm)	24	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.43	
I_{sc} at t_0 (kPa)	0.7	

slump at 1h (cm)	24	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.48	
I_{sc} at 1h (kPa)	0.9	
t_0: no fluid or foam leakage. The material is fluid. t_{1h}: no fluid or foam leakage. The material is fluid. FIR (%) 32+24: means the foam was injected twice during the process once with 32% and then with 24%.		

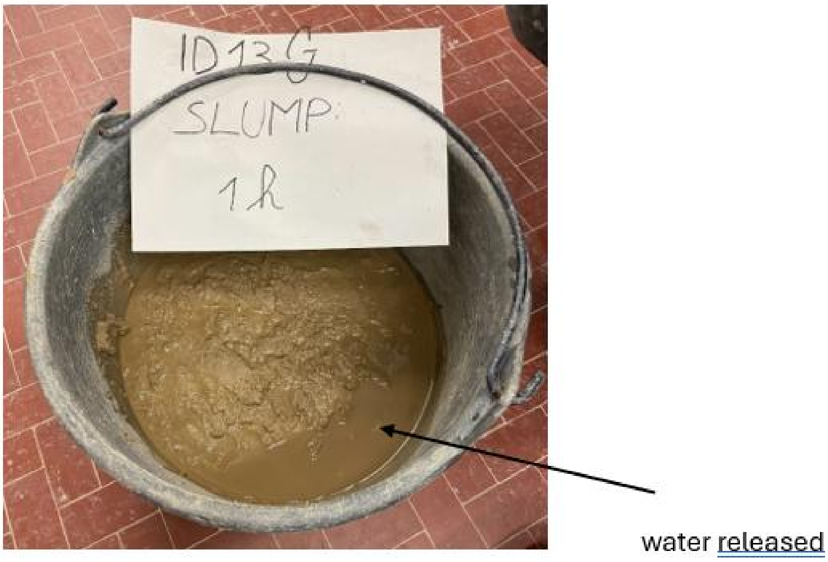


figure 23_material of test 13G at 1 h before to perform the slump test. It is noticeable the water leakage on the surface of the conditioned soil.*

Soil A	**-**	**Picture**
TEST	**2**	
foaming agent C (%)	2.0.	
FER (-)	15	
FIR (%)	40	
TR (L/m^3)	0.53	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
slump at t_0 (cm)	23	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.56	
I_{sc} at t_0 (kPa)	1.6	
slump at 1h (cm)	22	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.58	
I_{sc} at 1h (kPa)	1.4	
t_0: no fluid or foam leakage. The material is fluid and sticky. t_{1h}: no fluid or foam leakage. The material is fluid and sticky.		

Soil A	-	Picture
TEST	**3**	
foaming agent C (%)	2.0	
FER (-)	15	
FIR (%)	24	
TR (L/m^3)	0.32	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.10	
slump at t_0 (cm)	19	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.67	
I_{sc} at t_0 (kPa)	1.9	
slump at 1h (cm)	16	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.70	
I_{sc} at 1h (kPa)	2.3	
t_0: good slump. Some foam and water leakage. The material is homogenous and sticky. t_{1h}: the material is sticky.		

Soil A	**-**	**Picture**
TEST	**4**	
foaming agent C (%)	2.0	
FER (-)	15	
FIR (%)	25	
TR (L/m^3)	0.33	
$w_{natural}$ (%)	10.7	
w_{add} (%)	0.0	
w_{tot} (%)	10.7	
γ_{soil} (kg/L)	1.57	
SIR (%)	32	
γ_{slurry} (kg/L)	1.1	
slump at t_0 (cm)	22	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.66	
I_{sc} at t_0 (kPa)	1.9	
slump at 1h (cm)	19	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.7	
I_{sc} at 1h (kPa)	1.9	
t_0: no fluid or foam leakage. The material is homogenous and sticky. t_{1h}: good slump. No water leakage. The material is sticky.		

Soil A	**-**	**Picture**
TEST	**5**	
foaming agent C (%)	2.0	
FER (-)	15	
FIR (%)	24	
TR (L/m^3)	0.32	
$w_{natural}$ (%)	8.0	
w_{add} (%)	0.0	
w_{tot} (%)	8.0	
γ_{soil} (kg/L)	1.56	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
slump at t_0 (cm)	13	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.69	
I_{sc} at t_0 (kPa)	3.1	
slump at 1h (cm)	15	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.72	
I_{sc} at 1h (kPa)	3.5	

t_0: average slump. Few water and foam release.
t_{1h}: Few water and foam release.

Soil A	-	Picture
TEST	**6**	
foaming agent C (%)	2.0	
FER (-)	15	
FIR (%)	25	
TR (L/m^3)	0.33	
$w_{natural}$ (%)	10.7	
w_{add} (%)	0.0	
w_{tot} (%)	10.7	
γ_{soil} (kg/L)	1.57	
SIR (%)	32	
γ_{slurry} (kg/L)	1.027	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
slump at t_0 (cm)	18	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.67	
I_{sc} at t_0 (kPa)	2.3	
slump at 1h (cm)	23	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.72	
I_{sc} at 1h (kPa)	1.2	
t_0: good slump. Few fluid and water leakage. The material is homogenous, pasty, and not sticky. t_{1h}: fluid and water leakage. If the material is remixed, it reabsorbs the lost water but then it loses again.		

Soil A	**-**	**Picture**
TEST	**7**	
foaming agent C (%)	2.0.	
FER (-)	15	
FIR (%)	25	
TR (L/m^3)	0.33	
$w_{natural}$ (%)	10.7	
w_{add} (%)	0.0	
w_{tot} (%)	10.7	
γ_{soil} (kg/L)	1.57	
SIR (%)	32	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
slump at t_0 (cm)	22	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.69	
I_{sc} at t_0 (kPa)	1.7	
slump at 1h (cm)	22	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	1.71	
I_{sc} at 1h (kPa)	2.1	
t_0: good slump. No fluid or foam leakage. The material is fluid, homogenous and pasty. t_{1h}: no fluid or foam leakage.		

Soil A	**-**	**Picture**
TEST	**8**	
foaming agent C (%)	2.0	
FER (-)	14	
FIR (%)	30	
TR (L/m^3)	0.43	
$w_{natural}$ (%)	10.7	
w_{add} (%)	0.0	
w_{tot} (%)	10.7	
γ_{soil} (kg/L)	1.57	
SIR (%)	23	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	0.71	
slump at t_0 (cm)	9	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.69	
I_{sc} at t_0 (kPa)	4.9	
slump at 2h (cm)	8	
$\gamma_{conditioned\ soil}$ at 2h (kg/L)	1.72	
I_{sc} at 2h (kPa)	5.9	
t_0: water leakage if a pressure is applied. The material is pasty and sticky. t_{2h}: stiff slump. Fluid leakage.		

Soil A	**-**	**Picture**
TEST	**8**	
slump at 3h (cm)	8	
$\gamma_{conditioned\ soil}$ at 3h (kg/L)	1.74	
I_{sc} at 3h (kPa)	6.1	
t_{3h}: stiff slump.		

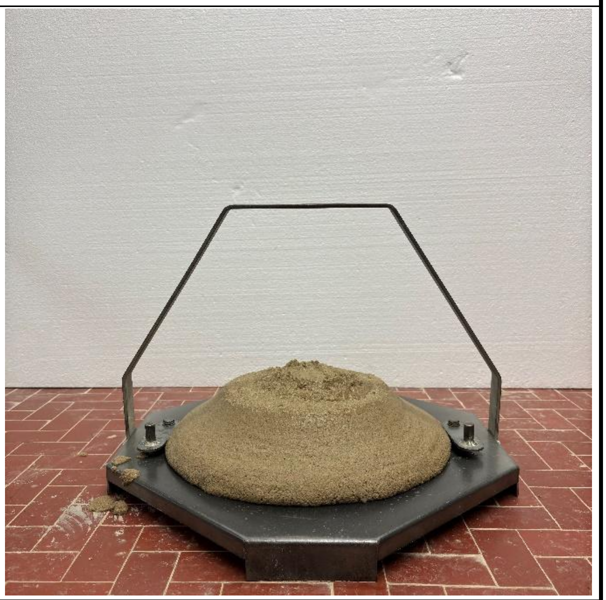
Soil A	**-**	**Picture**
TEST	**9**	
foaming agent C (%)	2.0	
FER (-)	14	
FIR (%)	60+40	
TR (L/m^3)	1.43	
$w_{natural}$ (%)	10.7	
w_{add} (%)	0.0	
w_{tot} (%)	10.7	
γ_{soil} (kg/L)	1.57	
SIR (%)	23	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	1.50	
slump at t_0 (cm)	24	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.15	
I_{sc} at t_0 (kPa)	0.9	
slump at 1h (cm)	/	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	21	
I_{sc} at 1h (kPa)	/	
t_0: some water and fluid leakage. The material is fluid, pasty and sticky. t_{1h}: some water and fluid leakage. The material is fluid.		

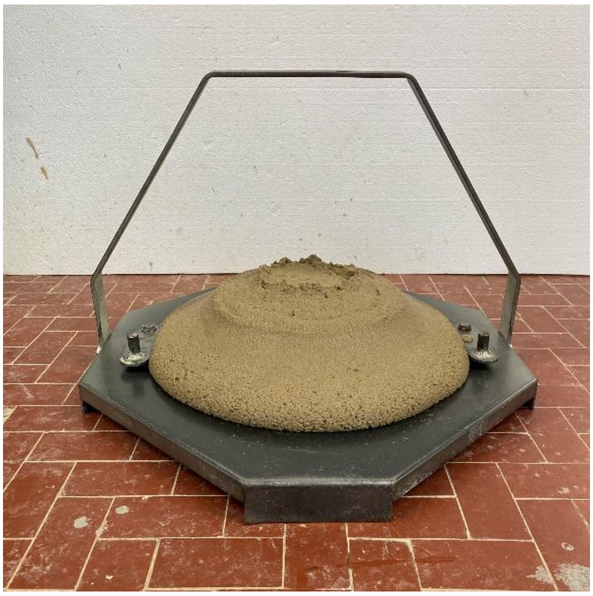
Soil A	**-**	**Picture**
TEST	**9**	
slump at 2h (cm)	22	
$\gamma_{\text{conditioned soil}}$ at 2h (kg/L)	1.48	
I_{sc} at 2h (kPa)	2.1	
slump at 3h (cm)	23	
$\gamma_{\text{conditioned soil}}$ at 3h (kg/L)	1.52	
I_{sc} at 3h (kPa)	1.6	
t_{2h}: water leakage. t_{3h}: foam bubbles are still observable.		

Soil A	**-**	**Picture**
TEST	**10**	
foaming agent C (%)	2.0	
FER (-)	14	
FIR (%)	40+20	
TR (L/m^3)	0.86	
$w_{natural}$ (%)	10.7	
w_{add} (%)	0.0	
w_{tot} (%)	10.7	
γ_{soil} (kg/L)	1.57	
SIR (%)	23	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	1.50	
slump at t_0 (cm)	23	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.37	
I_{sc} at t_0 (kPa)	1.2	
slump at 1h (cm)	1.46	
$\gamma_{conditioned\ soil}$ at 1h (kg/L)	23	
I_{sc} at 1h (kPa)	1.6	

t_0: the material is homogenous.
Note: 2.68 g of pure polymer was added to the slurry during the preparation of the mix.
t_{1h}: no fluid leakage. The material is homogenous and pasty.

Soil A	-	Picture
TEST	10	
slump at 2h (cm)	24	
$\gamma_{conditioned\ soil}$ at 2h (kg/L)	1.53	
I_{sc} at 2h (kPa)	1.4	
slump at 3h (cm)	24	
$\gamma_{conditioned\ soil}$ at 3h (kg/L)	1.55	
I_{sc} at 3h (kPa)	1.7	
t_{2h}: no fluid leakage. The material is homogenous and pasty. t_{3h}: no fluid leakage. The material is homogenous and pasty.		

Soil A	-	Picture
TEST	**11**	
foaming agent C (%)	2.0	
FER (-)	14	
FIR (%)	30+10	
TR (L/m^3)	0.57	
$w_{natural}$ (%)	10.7	
w_{add} (%)	3.3	
w_{tot} (%)	14.0	
γ_{soil} (kg/L)	1.57	
SIR (%)	23	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	1.50	
slump at t_0 (cm)	19	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.54	
I_{sc} at t_0 (kPa)	2.4	
slump at 2h (cm)	20	
$\gamma_{conditioned\ soil}$ at 2h (kg/L)	1.61	
I_{sc} at 2h (kPa)	2.9	
t_0: the material is homogenous and pasty. t_{2h}: the material is homogenous and pasty.		

Soil A	-	Picture
TEST	**11**	
slump at 3h (cm)	21	
$\gamma_{conditioned\ soil}$ at 3h (kg/L)	1.62	
I_{sc} at 3h (kPa)	3.1	
slump at 6h (cm)	22	
$\gamma_{conditioned\ soil}$ at 6h (kg/L)	1.67	
I_{sc} at 6h (kPa)	3.1	
t_{3h}: the material is homogenous and pasty. t_{6h}: the material is homogenous and pasty.		

Soil A	-	Picture
TEST	**11**	
slump at 24h (cm)	17	
$\gamma_{conditioned\ soil}$ at 24h (kg/L)	1.79	
I_{sc} at 24h (kPa)	5.7	
t_{24h}: the material is homogenous, pasty and stiff.		

Soil A	-	Picture
TEST	**12**	
foaming agent C (%)	2.0	
FER (-)	14	
FIR (%)	40+10	
TR (L/m^3)	0.71	
$w_{natural}$ (%)	10.7	
w_{add} (%)	3.3	
w_{tot} (%)	14.0	
γ_{soil} (kg/L)	1.57	
SIR (%)	23	
γ_{slurry} (kg/L)	1.05	
polymer	WATER ABSORBING POLYMER	
polymer dose (L/m^3 of slurry)	1.50	
slump at t_0 (cm)	22	
$\gamma_{conditioned\ soil}$ at t_0 (kg/L)	1.45	
I_{sc} at t_0 (kPa)	1.6	

<table>
<tr><td>slump at 2h (cm)</td><td>23</td><td rowspan="3"></td></tr>
<tr><td>$\gamma_{conditioned\ soil}$ at 2h (kg/L)</td><td>1.57</td></tr>
<tr><td>I_{sc} at 2h (kPa)</td><td>2.1</td></tr>
<tr><td colspan="3">t_0: the material is homogenous and pasty.
t_{2h}: the material is homogenous and pasty.</td></tr>
</table>

Soil A	-	Picture
TEST	12	
slump at 3h (cm)	23	
$\gamma_{conditioned\ soil}$ at 3h (kg/L)	1.59	
I_{sc} at 3h (kPa)	5.2	
slump at 6h (cm)	24	
$\gamma_{conditioned\ soil}$ at 6h (kg/L)	1.67	
I_{sc} at 6h (kPa)	1.7	
t_{3h}: the material is homogenous and pasty. t_{6h}: the material is homogenous and pasty.		

Soil A	**-**	**Picture**
TEST	**12**	
slump at 24h (cm)	22	
$\gamma_{conditioned\ soil}$ at 24h (kg/L)	1.74	
I_{sc} at 24h (kPa)	2.9	
t_{24h}: the material is homogenous.		

3.2.2.1 Summary of slump test

In table 2, it is illustrated an overview of the slump test results.

ID	soil	$w_{natural}$ (%)	w_{add} (%)	w_{tot} (%)	c (%)	FER (-)	FIR (%)	TR (L/m³)	SIR (%)	polymer (L/m³ slurry)	slump t_0 (cm)
1	A	8.0	0.0	8.0	2.0	15	32+24	0.75	32	-	24
2	A	8.0	0.0	8.0	2.0	15	40	0.53	32	-	23
3	A	8.0	0.0	8.0	2.0	15	24	0.32	32	-	19
4	C	10.7	0.0	10.7	2.0	15	25	0.33	32	-	22
5	A	8.0	0.0	8.0	2.0	15	24	0.32	32	0.71	13
6	C	10.7	0.0	10.7	2.0	15	25	0.33	32	0.71	18
7	C	10.7	0.0	10.7	2.0	15	25	0.33	32	0.71	22
8	C	10.7	0.0	10.7	2.0	14	30	0.43	23	0.71	9
9	C	10.7	0.0	10.7	2.0	14	60+40	1.43	23	1.50	24
10	C	10.7	0.0	10.7	2.0	14	40+20	0.86	23	1.50	23
11	C	10.7	3.3	14.0	2.0	14	30+10	0.57	23	1.50	19
12	C	10.7	3.3	14.0	2.0	14	40+10	0.71	23	1.50	22

Table 2_Overview of the performed slump campaign. In light green the best conditioned IDs according to the authors.

3.2.1 Results on slump tests, bulk density tests and modified vane test after the screw conveyor extraction test

A soil sample extracted using the screw conveyor testing apparatus was initially characterized by measuring its bulk density, slump, and initial shear consistency (Isc). To simulate the effects of moderate temperature and time on the rheological behavior of the conditioned material, the sample was subsequently placed in an oven at 45 °C for 24 hours. After the drying period, the same parameters were re-evaluated to detect any variations in flowability and consistency.

To further assess the long-term performance of the conditioned soil, the sample was returned to the extraction tank and sealed for an additional 24 hours under controlled conditions. This step was intended to simulate enclosed underground conditions and to evaluate the stability and homogeneity of the material over time.

The extraction test was carried out to evaluate the mechanical response of the soil under applied loading and its behavior over time. The figures below provide information about both the internal pressure measured at different points in the sample and the corresponding displacement of the system.

In Figure 25, pressure measurements from four different cells along the screw conveyor Figure 19 are shown during the test. The pressure at all cells starts near zero and rises sharply once the screw conveyor is filled. Among the sensors, Pressure Cell 1 records the highest pressure, reaching approximately 60 kPa. Then, Cells 4 and 2 show similar pressure, and Cell 3 shows the lowest pressure. This gradient of pressures is kept constant for all the duration of the teste, suggesting that the system reaches a steady state under constant load. Toward the end of the graph, a gradual decline in pressure occurs, which reflects the relative reduction in loading plate advancement compared to the extraction rate from the tank (Figure 26). During the whole test, the pressure gradient on the four cells clearly show that the conditioned material is suitable for the extraction while gradually reducing the pressure along the screw conveyor.

Figure 27 presents the results of the same test performed on the same material, extracted and then put again inside the tank and let there for 24 hours to evaluate the stability of the conditioned soil in time. Again, the pressures rise quickly and reach similar peak values as the test shown in Figure 25 and the displacement increases steadily from about 150 mm to around 400 mm, indicating continuous movement and extraction of the system.

However, in this phase, the pressure curves show more complexity than the ones of the previous test.

Some cells show a periodic fluctuation that is a sign of a less smooth pressure transfer and damping, that resents also of the revolutions of the screw itself. This behaviour is due to the stiffening of the material. Anyway, the graph shows a suitable behaviour indicating that the soil kept good properties and is still effectively conditioned. Between 910 s and 960 s there is a sudden drop in pressure for all the cells. This behaviour may be due to the formation of a temporary sinkhole in the tank with consequent emptying of the screw conveyor.

After few seconds the material, under the pressure of the hydraulic system, started to flow again in the screw conveyor, leading to an increase of the pressures in all the cells. These fluctuations suggest that the soil is undergoing a change in behaviour that, in a TBM should be reduced by progressively injecting fresh foam and slurry at different stages during the 24 hours of stop that has been simulated with the test.

The results of the screw conveyor extraction test conducted after 24 hours are shown in Figures 26 and 27 and summarized in Table 6.

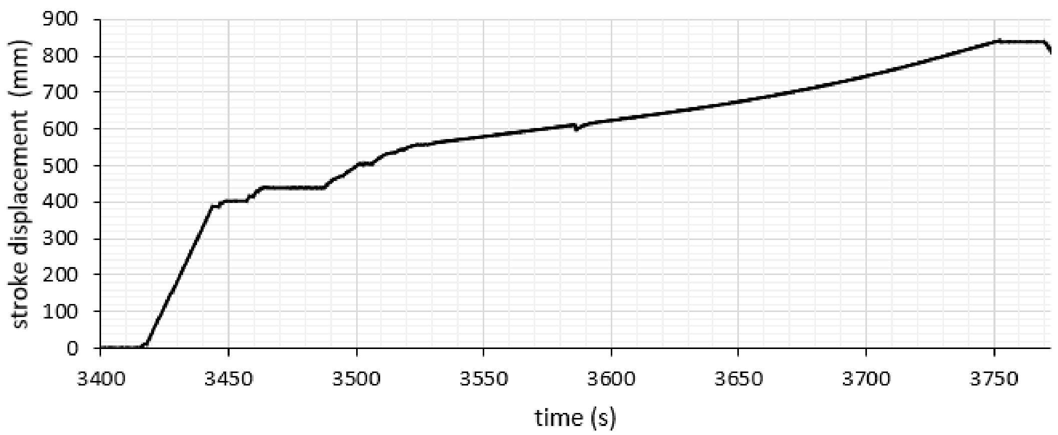


figure24_Stroke displacement for extraction test at t0

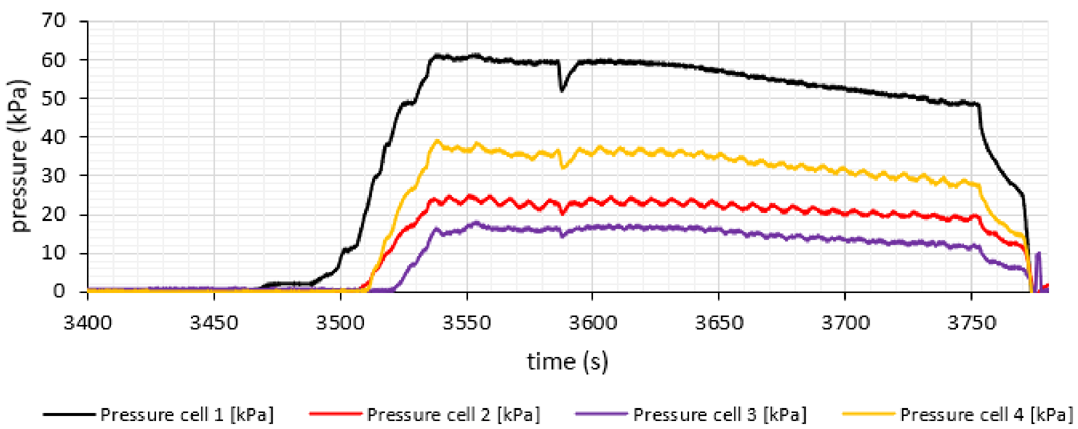


figure 25_ cell pressure for extraction test at t_0.

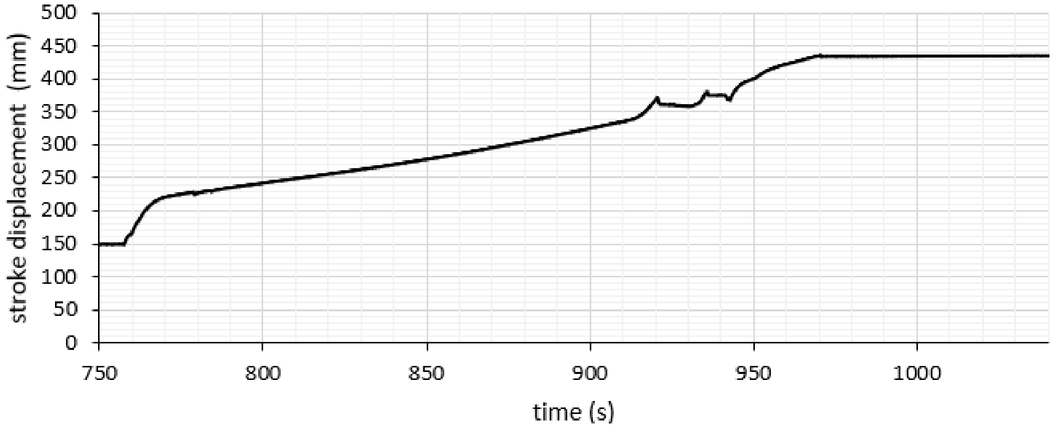


figure 26_ stroke displacement for extraction test at t = 24 h

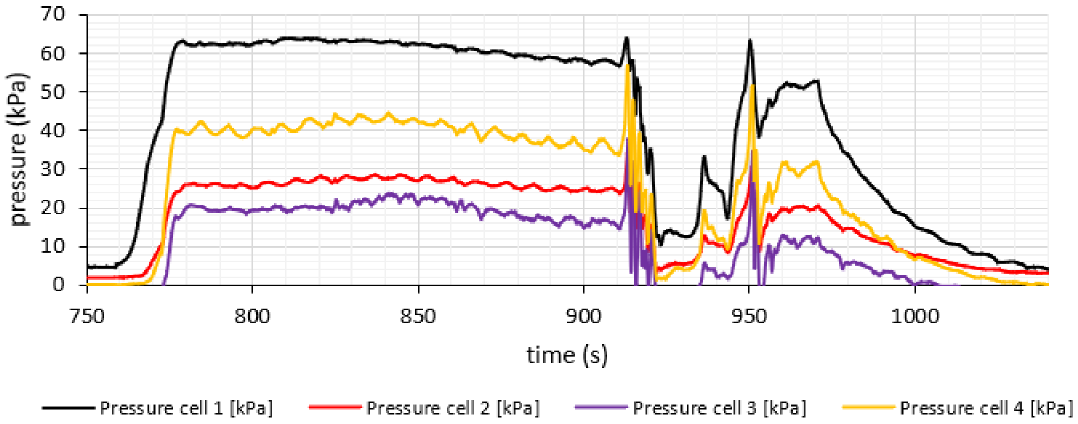


figure27_Cells pressure for extraction test at t = 24 h.

In the following tables are given the result of slump tests conducted on material extracted in the screw conveyor extraction test. Each sample of material was also subjected to modified vane test and bulk density test.

In table 3 and table 5 are given the test result of extracted materials with the extraction test performed at time zero (t_0) while in table 4 and table 6 are given the test results of the extracted material with the extraction test performed after 24 hours.

Table 3_ The Extracted Test Result At t0.

Soil A	**-**	**Picture**
ID	**1**	
$\gamma_{\text{conditioned soil}}$(kg/L)	1.53	
slump (cm)	24	
I_{sc} (kPa)	3.5	
ID	**2**	
$\gamma_{\text{conditioned soil}}$ (kg/L)	1.59	
slump (cm)	23	
I_{sc} (kPa)	4.2	

Soil A	-	Picture
ID	**3**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.47	
slump (cm)	23	
I_{sc} (kPa)	4.3	
ID	**4**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.48	
slump (cm)	24	
I_{sc} (kPa)	4.3	
ID	**5**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.45	
slump (cm)	24	
I_{sc} (kPa)	4.2	

Soil A	**-**	**Picture**
ID	**6**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.42	
slump (cm)	25	
I_{sc} (kPa)	3.8	

ID	**7**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.46	
slump (cm)	25	
I_{sc} (kPa)	4.3	
ID	**8**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.50	
slump (cm)	25	
I_{sc} (kPa)	3.5	

ID (in oven for 24 h at 45 °C)	**9**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.72	
slump (cm)	22	
I_{sc} (kPa)	4.2	

Table 4_ The Test Result of Extracted Test After 24 Hours

Soil A	**-**	**Picture**
ID	**1**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.80	
slump (cm)	22	
I_{sc} (kPa)	4.9	
ID	**2**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.80	
slump (cm)	21	
I_{sc} (kPa)	4.5	

Soil A	-	Picture
ID	**3**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.83	
slump (cm)	23	
I_{sc} (kPa)	3.5	
ID	**4**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.83	
slump (cm)	24	
I_{sc} (kPa)	3.6	
ID	**5**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.84	
slump (cm)	24	
I_{sc} (kPa)	3.5	

Soil A	**-**	**Picture**
ID	**6**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.86	
slump (cm)	24	
I_{sc} (kPa)	3.1	

ID	**7**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.81	
slump (cm)	20	
I_{sc} (kPa)	4.2	
ID	**8**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.82	
slump (cm)	22	
I_{sc} (kPa)	4.3	

Soil A	-	Picture
ID	**9**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.81	
slump (cm)	20	
I_{sc} (kPa)	4.2	

ID	**10**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.81	
slump (cm)	19	
I_{sc} (kPa)	5.2	
ID	**11**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.82	
slump (cm)	9	
I_{sc} (kPa)	7.5	

Soil A	-	Picture
ID	**12**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.79	
slump (cm)	20	
I_{sc} (kPa)	4.5	

ID	**13**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.82	
slump (cm)	20	
I_{sc} (kPa)	4.9	
ID	**14**	
$\gamma_{conditioned\ soil}$ (kg/L)	1.87	
slump (cm)	25	
I_{sc} (kPa)	3.1	

In table 7 and 8 the overview of the extracted test results on the soil A is presented.

Table 5_ overview of extraction test Results at t0

ID	Density (kg/L)	I_{sc} (kPa)	Slump (cm)	Note
1	1.53	3.5	24	
2	1.59	4.2	23	
3	1.47	4.3	23	
4	1.48	4.3	24	
5	1.45	4.2	24	
6	1.42	3.8	25	
7	1.46	4.3	25	
8	1.50	3.5	25	
9	1.72	4.2	22	in oven for 24 h at 45 °C

Table 6_ overview of extraction test result after 24 hours

ID	Density (kg/L)	I_{sc} (kPa)	Slump (cm)	Note
1	1.80	4.9	22	
2	1.80	4.5	21	
3	1.83	3.5	23	
4	1.83	3.6	24	
5	1.84	3.5	24	extracted with no pressure
6	1.86	3.1	24	extracted with no pressure
7	1.81	4.2	20	from tank bottom
8	1.82	4.3	22	from tank bottom
9	1.81	4.2	20	from tank bottom
10	1.81	5.2	19	from tank bottom
11	1.82	7.5	9	from tank bottom
12	1.79	4.5	20	from tank bottom
13	1.82	4.9	20	from tank bottom
14	1.87	3.1	25	from screw conveyor

4 Discussion

The experimental results from the mini flow, standard slump, and screw conveyor extraction tests collectively provide valuable insights into the effectiveness of soil conditioning strategies for EPB-TBM tunneling in cohesionless soils.

4.1 Mini-Slump Test Insights

The mini-slump tests served as an initial, small-scale screening to assess the soil's response to foam and water conditioning. The results indicated distinct behavioral patterns between various foam injection ratios (FIR), foam expansion ratios (FER), and slurry injection ratios (SIR). the results highlighted that:

- Low FIR and FER values (e.g., FIR 32% and FER 10) resulted in inadequate flow and poor slump spread, indicating that the material was under-conditioned and exhibited excessive stiffness;
- High FIR values (e.g., 65–80%) produced more workable and flowable material, but often led to foam leakage and instability when some pressure was applied, suggesting an upper limit beyond which conditioning becomes counterproductive;
- The order of foam and slurry addition impacted soil homogeneity and foam absorption. Tests with foam added before slurry generally yielded better homogeneity and improved slump consistency.

These outcomes demonstrated that mini flow testing is a cost-effective and rapid method to screen the effects of various conditioning regimes before scaling up.

4.2 Standard Slump Test Observations

The standard slump test provided a more accurate estimation of workability. The test results correlated well with the optimal ranges observed in EPB practice, where acceptable slump values fell within 12–20 cm, denoting a plastic and pulpy consistency required for EPB operation.

- Over-conditioned samples exhibited excessive fluidity and slump beyond 20 cm, posing risks of loss of confinement and uncontrolled flow through the screw conveyor;
- Under-conditioned samples, on the other hand, had low slump values (<12 cm), suggesting inadequate flowability and potential for clogging or increased torque requirements during extraction.

The addition of water-absorbing polymers in some tests improved the material's viscosity while preserving a cohesive structure, leading to suitable slump results without excessive fluid loss during compaction.

4.3 Screw Conveyor Extraction Test Results

The screw conveyor test, simulating in-situ pressurized extraction, validated whether the laboratory-optimized conditioning parameters translated into effective flow under pressure.

- Materials conditioned with FER values of 16 and FIR of 30%, C: 2%, w_{tot}: 12%. The foam was produced using a commercial foaming agent. particularly those including water-absorbing polymers, showed stable pressure transmission, moderate torque requirements, and smooth discharge;

The screw conveyor test outcomes confirmed that optimal conditioning is not only a matter of fluidity but also of maintaining rheological properties under pressure. This reinforced the role of balanced conditioning agents and appropriate application sequence to simulate EPB excavation conditions accurately.

4.4 Evaluation of Stability of Conditioned Soil for EPB Application

Throughout the several tests being performed via the experimental campaign several trials have demonstrated consistent and stable performance by showing successful soil conditioning. The most compelling results were taken from soil A for which test 1 which shown optimal mechanical and rheological behaviour. The additional confirmation of these results was obtained by test 7 whereby adding water-absorbing polymer led to the enhancement of the result. This could be observed as well in screw conveyor extraction test, performed with the conditioning parameters of test 7, where the conditioned soil maintained its flowability and rheological properties under the simulated pressurized condition in the lab.

Test 1 (soil A): optimal conditioning performance

Test 1 resulted highly satisfactory outcome across all analysed parameters to certify its effectiveness for the application of the EPB tunneling. By using a foaming agent concentration of 2%, with a FER of 15 two-step FIR of 32% followed by 24%, and SIR of 32% the soil was conditioned. As the result the slump test showed good consistency by an initial slump value of 24 cm which stayed unchanged after one hour, showing the strong time dependant stability. The density of conditioned soil raised slightly from 1.43 kg/L to 1.48 kg/L however the shear strength I_{sc} has increased from 0.7 KPa to 0.9 Kpa, demonstrating stability of the material's behaviour.

No leakage of foam or fluid were detected, and the soil has shown a uniform, pasty texture to confirm that the soil is sufficient to sustain the face pressure, minimizing wear, and ensuring smooth transport via the screw conveyor in EPB.

Test 7 (Soil A + Polymer): Reinforced Stability with Polymer Addition

In test 7, the use of water-absorbing polymer ($0.71\ L/m^3$) was presented for further improvement in the behaviour of the soil. The slump was constant at 22 cm at both t_0 and t_{1h}, density has slightly increased from 1.69 to 1.71 Kg/L, and I_{sc} has increased from 1.7 to 2.1 KPa. There is no sign of leakage of water or foam; in addition, the good cohesion, plasticity, and stable pasty behaviour in soil could be observed.

Addition of polymer enhanced the rheological property of the soil. The material resisted against drainage and bubble collapse, extending the effective conditioning window, that is crucial for large-scale excavation.

Screw Conveyor Extraction Test Results: Post-Conditioning Stability

The stability of the conditioned soil was assessed also by testing the material under pressurised condition with the screw conveyor extraction test. The following key results emphasise the behavior of the soil after being exposed to 1 bar of pressure replicating the environment inside an EPB machine.

Test ID 1 (Post-Extraction):

- Slump: 22 cm
- Density: 1.80 kg/L
- Shear Strength (Isc): 4.9 kPa
- Material Behavior: Maintained a uniform, flowable consistency under pressure

Test ID 4 (Post-Extraction):

- *Slump: 24 cm*
- *Density: 1.83 kg/L*
- *Shear Strength (Isc): 3.6 kPa*
- *Observation: No phase separation; the material remained cohesive and suitable for mechanical extraction and transport*

These results confirm that the soil held its conditioned properties even under pressurized conditions, demonstrating good resistance to structural breakdown. The recorded slump values, slightly above the standard target range (12–20 cm), still reflect favorable workability and adequate face support capacity, reinforcing the effectiveness of the selected conditioning parameters.

Considering the results obtained from all the tests the optimal soil conditioning parameters can be summarized as follows:

Parameter	**Optimal Range**	**Stability Tests results**
Slump	12–20 cm	22–24 cm
Density	1.4–1.8 kg/L	1.43–1.83 kg/L
I_{sc} (Shear Strength)	0.7–5.0 kPa	0.7–4.9 kPa
FIR (Foam Injection Ratio)	25%–65%	32% + 24% (best)
FER (Foam Expansion Ratio)	10–15	15
SIR (Slurry Injection)	~32%	Constant across tests
Polymer Use	Optional but effective	Test 7 (0.71 L/m^3)

5 Conclusions

This thesis investigated the conditioning of cohesionless soils for use in Earth Pressure Balance (EPB) shield tunneling, with a focus on identifying optimal formulations of foam, bentonite slurry, and polymers to enhance soil behavior during excavation. Through a comprehensive laboratory testing campaign involving mini-slump tests, bulk density assessments, modified vane tests, and screw conveyor extraction simulations, it was possible to evaluate the mechanical and rheological performance of conditioned soils under controlled conditions.

The study successfully demonstrated that a balanced combination of foam and water, supplemented in some cases with bentonite slurry or long-chain polymers, can transform cohesionless sandy soils into a homogeneous, flowable, and plastic material suitable for EPB operations. Among the tested materials, the mixture of soils A and B (referred to as Soil C) exhibited the most favorable behavior in terms of slump, density, and Isc values, making it highly compatible with EPB requirements. The use of polymers was especially effective in stabilizing foam bubbles and maintaining consistency over time, particularly in soils with higher moisture content.

A key contribution of this research lies in the simulation of real EPB excavation conditions using a custom-built screw conveyor extraction apparatus. This device allowed for a realistic evaluation of the soil's flow behavior and mechanical response under pressurized conditions. Results confirmed that proper soil conditioning ensures consistent and controlled extraction while maintaining face stability and reducing mechanical wear.

The research also emphasized the importance of time in foam-based conditioning. Time-dependent degradation of foam leads to changes in soil consistency, such as reduced plasticity and increased stiffness. These findings suggest that soil conditioning must be carefully managed in both timing and formulation to ensure continuous and effective tunneling performance.

Despite its valuable insights, the study is limited by its laboratory scale, which may not fully replicate in-situ TBM conditions. The research was also confined to cohesionless sands, and further investigations are required to extend the conclusions to cohesive or mixed soils. Moreover, while the environmental impact of conditioning agents was considered, a full environmental risk assessment was beyond the scope of this work.

Future research should focus on scaling up testing procedures, incorporating cohesive soil types, and validating laboratory results with field data. Additionally, the development of environmentally sustainable and biodegradable conditioning agents is a promising area for further exploration. Real-time monitoring of soil conditioning parameters during EPB tunneling could also enhance process control and efficiency.

In summary, this work contributes to the ongoing optimization of EPB tunneling technology by offering a practical and experimentally grounded framework for evaluating and improving soil conditioning in cohesionless environments.

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