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RESEARCH PAPER

The Significance of Bentonite in Achieving Optimal Conditioning Design for EPB tunneling through rock mass Under Groundwater

Yavar Firouzei [1], Jafar Hassanpour [1,*], Daniele Peila [2], Sadegh Tarigh Azali [3], Jamal Rostami [4]

[1] School of Geology, College of Science, University of Tehran, Tehran, Iran
[2] DIATI, Politecnico di Torino, Turin, Italy
[3] RahsazTarh Consulting Engineers, Tehran, Iran
[4] Colorado School of Mines, Golden, Colorado, United States of America

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Abstract
Earth pressure balancing (EPB) technology was initially developed for mechanized tunneling in soft soils rich in fines. Recently, it has been successfully applied in coarse-grained soils and even rock formations, reducing the need for slurry shield machines and overcoming challenges related to hydraulic transportation and separation plants. EPB tunnel boring machine (TBM) performance depends significantly on proper conditioning of the excavated material, whether soil or rock, by adding appropriate additives to achieve the desired properties. However, varying geological conditions and excavated material characteristics present challenges, necessitating different conditioning strategies. This paper explores the role of bentonite in transforming excavated rock material into a suitable support medium, particularly in groundwater environments. The study employs slump tests and pressurized permeability cell tests (PPCT) to assess bentonite's effectiveness in improving the workability and permeability of conditioned mixtures. Results from 400 slump tests reveal that bentonite can convert loose, cohesionless material into a uniform plastic paste. However, accurately adding dry bentonite in a lab setting is challenging and nearly impossible during actual excavation. Conditioning with bentonite in pre-made suspension form mitigates issues related to powder handling, although the conditioned material still exhibits a relatively high unit weight. In 22 PPCT trials, bentonite-conditioned mixtures showed strong resistance to water pressure up to 5 bar. Notably, the mix becomes impermeable before fully transforming into a plastic paste. A statistical analysis of slump values led to the development of an empirical model demonstrating bentonite's performance in conditioning excavated rock material.

Keywords: Conditioning, Bentonite, Slump Test, Pressurized Permeability Cell Test, Unit Weight, Empirical Model.

Introduction

Decades since its inception in mid-1970’s, the utilization and adoption of Earth Pressure Balance (EPB) machines has steadily increased, serving as an effective solution for the challenging conditions encountered in soft ground tunneling (Clough & Schmidt, 1981). EPB tunnel boring machines (TBMs) are currently the top choice for mechanized tunneling in soft ground, making them one of the most commonly used TBM types globally (Borio et al., 2008; Forsat et al., 2022; Herrenknecht et al., 2011; Hussaine & Mu, 2022; Li et al., 2022; Peila et al., 2008, 2009; Sun & Zhao, 2022; Vinai et al., 2008; Wan et al., 2021). EPB technology's advantages have led to its use in different grounds, such as coarse grain soils, mixed grounds,

* Corresponding author e-mail: Hassanpour@ut.ac.ir

soft and weathered rock masses, and even excavation through the full face of hard rock. However, effective utilization of EPB machines in coarse grain soils and rock conditions requires modifications in the technical aspects and more importantly, a deeper understanding of the conditioning process. (Budach & Thewes, 2015; Merritt et al., 2021; Shin et al., 2021; Sun & Zhao, 2022; Wan et al., 2021; Wang et al., 2022; Xu et al., 2020).

Despite the overall effectiveness of conventional TBMs in tunnel construction in hard rock, there are conditions that can disrupt or completely stop their operation. These conditions include severe groundwater inrush, leakage of toxic and explosive gases, and the need to ensure face stability in fault zones or unstable ground (Bayati & Hamidi, 2017; Gong et al., 2016; Jiang et al., 2021; Ma et al., 2015; Marinos et al., 2019; Tang et al., 2021; Tóth et al., 2013).Conventional techniques like forepoling, pre-injection, dewatering, and freezing to address these challenges are time-consuming, expensive, and can have environmental repercussions (Afshani & Akagi, 2015; Barton & Quadros, 2019; Font-Capó et al., 2011; Juneja et al., 2010; Marwan et al., 2016; Powers et al., 2007; Tunçdemir et al., 2012). In contrast, equipping hard rock TBMs with EPB technology is a cost-effective and dependable alternative. These machines can switch to closed mode in adverse conditions and seamlessly transition back to open mode when conditions improve. (Babendererde et al., 2017b; Chao et al., 2015; Copur et al., 2012; Martinelli et al., 2015; Zhao et al., 2019).

The fundamental principle of EPB technology relies on pressure transmitting from machine's bulkhead to the tunnel face using the excavated material to ensure stability throughout the excavation process and mitigate the risk of potential ground settlement (Anagnostou & Kovári, 1996; Herrenknecht, 1994). However, it is essential to note that the excavated material, which is supposed to act as a support medium, rarely forms a plastic paste in natural conditions. Moreover, efficient excavation depends on modifying the properties of the excavated material, such as shear strength, stickiness, and permeability are essential to helps minimize machine torques, prevent clogging risks, and avoid the formation of seepage forces in the ground. To improve the properties of the excavated material, conditioning is implemented by adding chemicals such as foam and polymers to the excavated material. (Babendererde, 1998; Langmaack, 2000; Langmaack & Lee, 2016; Mooney et al., 2017; Thewes & Budach, 2010).

Despite extensive research in the past few decades that has provided detailed insights into various aspects of soil conditioning, the understanding of the conditioning process in rock remains limited. Published studies in this area are primarily focused on specific case histories that highlight successful implementation of the method to overcome challenging conditions (Babendererde et al., 2017a; Firouzei et al., 2019; González et al., 2015a, b; Shirlaw, 2016; Tóth et al., 2013), or laboratory evaluations aiming to determine the optimal conditioning design for assessing the feasibility of tunnel construction using EPB hard rock TBMs (Firouzei et al., 2023; Martinelli et al., 2015; Peila et al., 2013; Zhao et al., 2019). However, there is still a need for further investigation and understanding of rock conditioning techniques to enhance knowledge and expand the application of EPB technology in rock formations.

The conditioning process during mechanized tunneling in rock masses using EPB machines significantly differs from that employed in fine-grained soils and clays, due to variations in geological conditions and the characteristics of the excavated material. Unlike conditioning in soft ground excavation, where the primary intention is to improve the workability of the excavated material, conditioning in rock mass aims to control groundwater by decreasing the permeability and ensure face stabilization during excavation through fault zones, transitional zones, and other unstable conditions, especially when the overburden is low. Additionally, it is important to reduce the internal friction of the excavated material to minimize torque on the cutter head and screw conveyor. This reduction in friction helps decrease the specific energy required for excavation, while also minimizing tool consumption and wear of metallic parts.

Previous research on the conditioning design required for EPB machines in rock tunneling has highlighted the challenges of achieving proper conditioning using conventional foam and polymer additives, due to the presence of groundwater (Firouzei et al., 2023). Accordingly, this study examines the application of bentonite as a conditioning additive capable of overcoming groundwater in the rock mass. While bentonite is commonly used in slurry machines, where it serves as the primary component of the slurry its application as a conditioning additive in rock excavation is a novel concept.

To investigate the application of bentonite in creating a favorable conditioned mix under real rock excavation conditions, a campaign of slump tests was conducted on specimens consisting of excavated materials in a saturated state. These specimens were conditioned using bentonite in dry powder form and suspension in water with various concentrations. Subsequently, the most suitable conditioning designs derived from the slump tests were evaluated through pressurized permeability cell tests. Additionally, the unit weight of the conditioned mix was recorded for each trial as a negative aspect.

Finally, the practical insights gained from experience with the application of bentonite during mechanized tunneling in rock masses with groundwater, along with workability and permeability evaluations from tests, are utilized to develop an empirical model for future use.

Material and method

In this research, actual TBM muck obtained from the excavation of the Tehran Metro Line 6 southern expansion sector project was utilized as the test specimen. The project involved excavating approximately 1.8 kilometers of tunnel through a dense and massive limestone rock mass using a Herrenknecht soft ground EPB machine (S-523), which had previously been employed in the construction of Tehran metro line 3 (Firouzei et al., 2019).

The collected excavated material for the laboratory tests was obtained from a relatively uniform face with no visible joints or cracks. The material was extracted while the machine was operating in the open mode without any conditioning. This approach ensured that the test specimens were not influenced by conditioning additives or the presence of fine fillers derived from weathered joints and cracks. The exclusion of these factors was crucial as they could significantly alter the behavior of the excavated material, particularly due to the presence of clay minerals.

In preparation for testing, the collected samples underwent a series of laboratory procedures to ensure precise control over the grain size distribution and to exclude the presence of clay in the test specimens. The collected excavated material from the job site was subjected to a thorough process, including washing, drying, and sieving to separate different grain sizes. Subsequently, the material was remixed in accurate proportions to achieve a controlled test specimen with a specified particle size distribution (PSD) in line with the grain size distribution curves established in previous related research on Hard rock TBMs (Firouzei et al., 2023; Peila et al., 2013) (Figure 1).

Through these preparation steps, the obtained test specimens were completely under control, which leads to consistency and reliability of the results. Moreover, the results could be compared to the findings of other studies in this field. The test specimen consisted of 80% Medium to Fine Gravel, 18% sand, and less than 2% coarse silt, as indicated in Figure 2. The material's gradation characteristics, represented by D_{60}=8.5, D_{10}=0.75, D_{30}=3.5, C_u=11.33, and C_c=1.92, classified it as GP (Poorly graded or clean gravel) according to the unified soil classification system (USCS).

In addition to the lithology and physical characteristics of the excavated material, the performance of an EPB machine is significantly influenced by the geological conditions along the tunnel route, particularly the groundwater conditions.

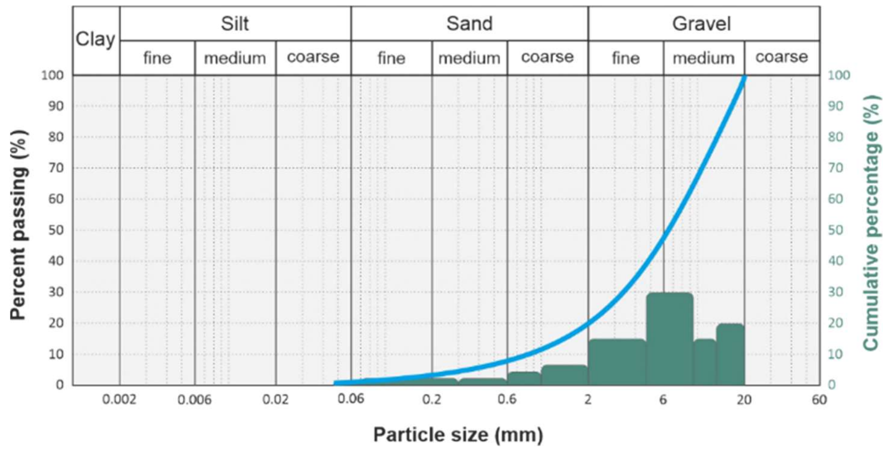

Figure 1. Granulometry curve of the test specimen

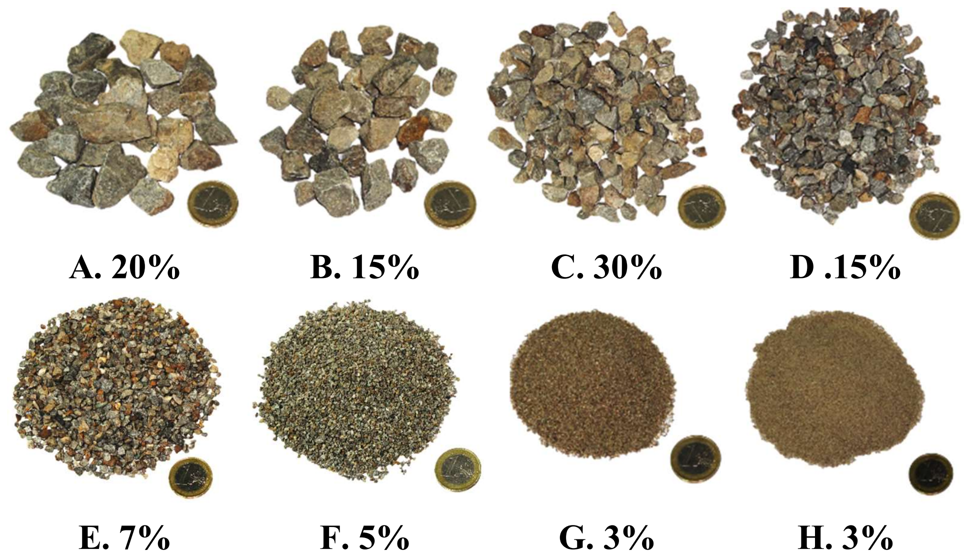

Figure 2. Dominant grain sizes in the test specimen. A: Medium Gravel (19 - 12.5 mm), B: Medium Gravel (12.5 - 9.5 mm), C: Medium-Fine Gravel (9.5 - 4.75 mm), D: Fine Gravel (4.75 - 2.00 mm), E: Coarse Sand (2.00 - 1.18 mm), F Coarse Sand (1.18 - 0.59 mm), G: Medium Sand (0.59 - 0.29 mm), H: Medium-Fine Sand (0.29 - 0.074 mm)

Unlike the relatively consistent water content found in soil, the presence of groundwater in a rock mass can appear as sudden inrushes with relatively high pressure, especially when the tunnel alignment intersects open joints, cracks, or fractured zones that serve as pathways for groundwater flow.

For the laboratory tests in this study, the specimens were prepared to simulate the saturated state of the excavated material, which requires a water content of approximately 33%. This moisture level ensures that the material is in its fully saturated condition.

Bentonite, known for its exceptional water absorption properties, was selected as the conditioning additive to counteract the adverse effects of groundwater. In this study, pure Bentonite with a relatively high liquid limit (400) was chosen to maximize its water absorption capacity while it is used in the form of dry powder.

The mixing procedure, an important aspect of the conditioning process that has received limited attention in researches, was conducted using a laboratory concrete mixer with a bowl capacity of 140 liters. However, due to the limitations of the mixer, the maximum amount of material loaded into it was approximately 30 kilograms. The mixing process lasted until the additive was thoroughly blended with the soil, which typically took no more than 1 minute. In fact, in most cases, the specimen and additive were fully mixed within less than 30 seconds.

Although it is important to assess the properties of conditioned mixes in the laboratory, there is still a lack of an approved standard test method specifically designed for this purpose. Currently, the available testing procedures consist of index tests originally designed for other applications, as well as innovative techniques that are limited to specific research centers worldwide, resulting in restricted accessibility to such testing devices.

The slump test was chosen to evaluate the workability of the materials due to its status as the most widely used testing method. It offers several advantages, such as a simple and cost-effective apparatus, a straightforward and easy-to-perform procedure, and applicability both in the laboratory and on-site. Furthermore, the data obtained from the slump test does not require complex analysis, as empirical models and established interpretations have been available for decades. Although the test specimens may contain coarse grains that approach the limits of the slump test, considering the aforementioned factors, the slump test was the most appropriate choice for this research. Apart from the slump value, shape and quality unite weight of the material was also measured after each trial. This is because, unlike foam, bentonite significantly increases the unit weight of the conditioned mix.

In situations where the presence of groundwater is predicted, it is essential to establish a suitable support medium to prevent water from entering the chamber or at least form an impervious plug inside the screw conveyor to prevent water from entering the shield area. Although some innovative methods have been proposed in previous studies to measure the permeability of conditioned soil, these methods are effective for soil conditioning but are not applicable to conditioned rock fragments. This is because the impermeability of rock conditioned material should be evaluated while considering the relatively high-water pressure in the rock mass.

In this research, the impermeability of the conditioned rock fragments was evaluated using the PPCT method, which is specifically designed to simulate high-water pressures in the rock mass. By subjecting the specimens to different water pressures, the ability of the conditioned material to act as an impervious plug was evaluated.

Test results

Slump test results

The initial set of tests were conducted on saturated material conditioned with dry bentonite. Bentonite powder was gradually added to the mixer containing rock fragments and water, and the changes in slump value and consistency were recorded after each addition. Five sets of tests were performed using 15 kg, 17.2 kg, 20 kg, 25 kg, and 30 kg of material that were prepared with water contents of 32.7%, 33.1%, 33%, 33.4%, and 33.8%, respectively.

The results of the slump test campaigns are presented in Figure 3, where the amount of bentonite in the conditioned mix for each test is indicated using the C_{sucp} (%) parameter which is calculated using Equation 1.

$$C_{susp} = \frac{M_{fine,susp}}{M_{susp}} * 100\ (\%) \qquad \text{(Equation 1)}$$

In this equation, C_{sucp} (%) represents the bentonite suspension concentration, $M_{fine,susp}$ denotes the amount of fine material in suspension, and M_{susp} represents the total amount of suspension (Budach & Thewes, 2015).

According to the observations the conditioned material exhibits five states of behaviors in terms of uniformity and plasticity. Initially, the mix consists of two distinct phases of liquid and solid.

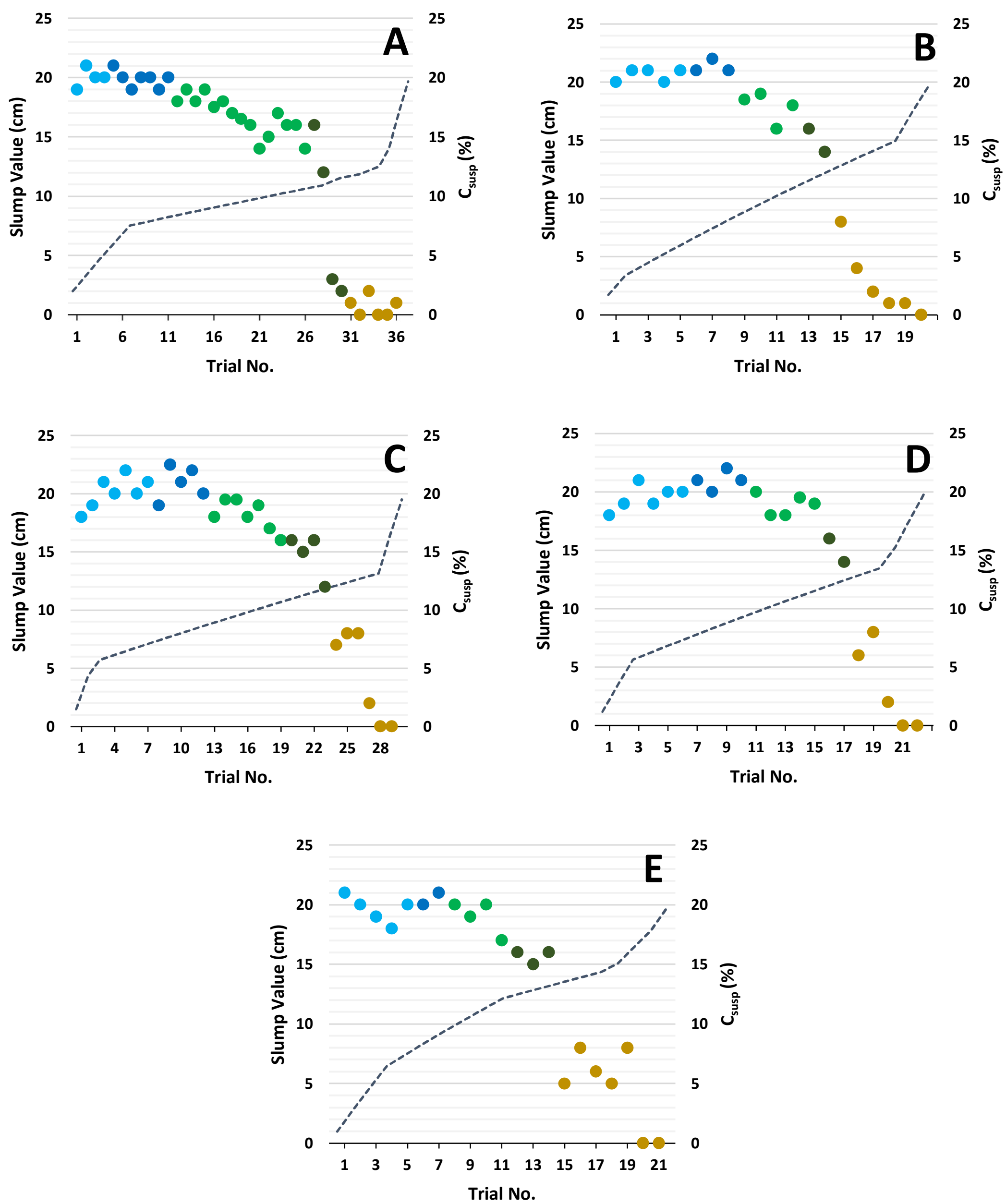

Figure 3. Slump values of test specimens after the addition of dry bentonite and trend of changes in the created suspension concentration (C_{susp}) in the mix. A: 15Kg Specimen, B: 17.2Kg Specimen, C: 20Kg Specimen, D: 25Kg Specimen, E: 30Kg Specimen

● Two distinct phases, ● Semi uniform non plastic, ● Well-conditioned, ● Cohesive, ● Adhesive

As bentonite is increased, the mix becomes more uniform as the liquid phase transforms into a bentonite suspension capable of carrying solid particles. By further increase in the amount of bentonite in the mix, material exhibits plasticity while maintaining uniformity, which is considered as the favorable conditions. Cohesiveness and eventually adhesion are observed with further addition of bentonite powder to the well-conditioned mix.

When the concentration of bentonite suspension is less than 7.5%, the excavated material behaves as two distinct phases of solid particles and liquid. The liquid phase freely flows through the porous medium between the coarse particles, aiding in the separation of fine and coarse grains within the mix. This behavior is not observed when the initial water content is less than 7.5%, as the water exists as surface moisture on the grains rather than as a separate phase. In this state, the slump test result would be a wet pile of loose material with a separated phase of watery bentonite suspension, having slump values between 18 and 23. (Figure 4).

Upon reaching a bentonite concentration of approximately 7.5%, the suspension undergoes a transition from a diluted fluid to a relatively thick mixture capable of suspending silt and fine sand particles. This transition is evident as the height of the material pile decreases after the slump test to a range of 19 to 23, indicating a reduction in internal friction as the particles are covered by the suspension. Although the conditioned mix is more uniform in this state, since the suspension at this concentration still can't carry coarse sand and gravel particles, it is not capable of inducing substantial changes in the overall rheology and plasticity of the conditioned mix (Figure 5).

Favorable conditioning is achieved when the liquid phase is transformed into a suspension with a concentration of at least 8.5% bentonite, achieved at an injection rate of around 35%. At this stage, the suspension exhibits sufficient strength to lift and suspend all particles, exerting dominant control over the overall behavior of the mixture. Slump values between 14 and 20 were observed at this state (Figure 6).

As the suspension concentration increases in a well-conditioned mix, the cohesion of the material becomes more pronounced, resulting in a tendency to stick together. This behavior is characterized by a decrease in the material's flow behavior within the mixer cup during the mixing process, as well as an increase in the slump cone height to 2 to 16 as well as changes in the form from cone to cylindrical form (Figure 7).

Figure 4. Two distinct phases of diluted liquid and solid grains in the conditioned mix

Figure 5. Semi uniform non plastic state of the conditioned mix

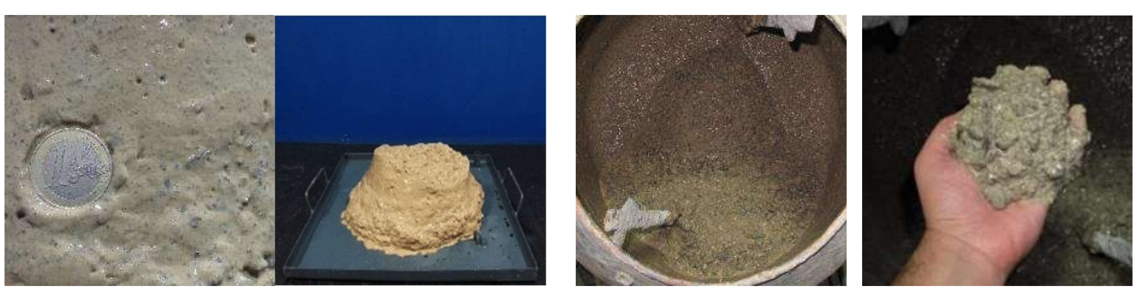

Figure 6. Well-conditioned state

As the amount of dry bentonite powder increases further, the mixture transitions into the adhesive state, which is characterized by strong adhesion to metallic surfaces. In this state, the material no longer flows during the mixing process and instead forms a uniform layer at the bottom of the mixer cup. Conducting slump tests becomes difficult in this state due to the high stickiness of the material, resulting in the tendency to stick to the slump cone. In any case, slump values ranging from 0 to 8 are observed, and the resulting cone retains almost the same shape as the slump cone (Figure 8).

The behavior of the material is illustrated in the graph showing the relationship between suspension concentration (C_{susp}) and suspension injection rate (SIR) (Equation 2). These two parameters encompass all the variables that influence the mix's behavior.

$$\mathrm{SIR} = \frac{M_{susp}}{M_s} * 100\ (\%) \qquad \text{(Equation 2)}$$

SIR is calculated as the ratio of suspension mass (M_{susp}) to excavated soil mass (M_s), expressed as a percentage (Budach and Thewes, 2015).

The graph visually depicts the trend of SIR and C_{susp}, providing insights into the changes in the mix's behavior (Figure 9).

It should be noted that achieving a homogeneous mix by adding dry bentonite powder to the mixer is not easy. The powder tends to form clumps that do not easily mix with the rest of the material. These clumps consist of a wet outer layer and a dry inner core, creating uneven distribution within the mix. Additionally, bentonite may adhere to the corners of the mixer, maintaining its dry powder form on the inside and wet layers on the outside. These challenges persist even with increased mixing (Figure 10).

To overcome the challenges associated with using dry bentonite and to achieve a more practical approach in harnessing its potential effectiveness, bentonite suspension was employed as the conditioning additive in the second set of tests. The bentonite suspension was prepared using a high-turbulence mixer at various concentrations ranging from 2.5% to 20%. It is important to note that for high-concentration suspensions (15% and above), the mixture needed to rest for 24 hours prior to the test to ensure the formation of a uniform suspension.

During each trial of this phase, a total of 17.2 kg of dry material (equivalent to 10 liters) was placed in the mixer. The dry material was then incrementally treated with increasing amounts of a specified suspension concentrations.

Figure 7. Conditioned mix in the cohesive state

Figure 8. Conditioned mix in the adhesive state

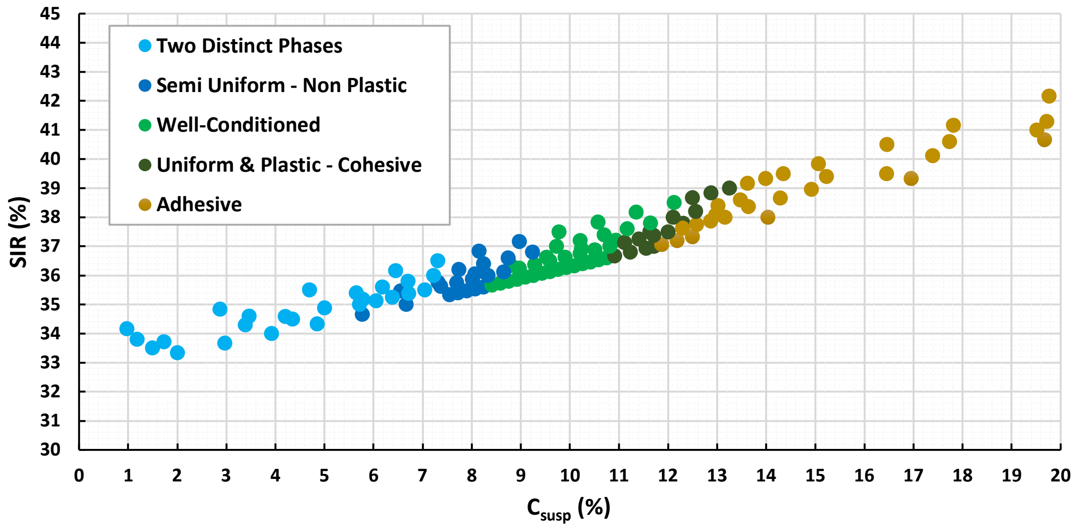

Figure 9. The effect of increasing suspension concentration on the behavior of the conditioned mix

Figure 10. Formation of dry bentonite clumps during the mixing process

At each step, the resulting mix was evaluated based on the slump value, shape, and quality as well as observation of the conditioned material inside the mixer cup. In this phase, in addition to the five previously mentioned states of behavior, three additional states of behavior were observed.

Regardless of the concentration, addition of the bentonite suspension first result in the formation of a damp pile of loose material, characterized by a slump value between 16 to 20 (Figure 11).

The dampen loose state was mainly observed after the addition of water or thin suspensions with a bentonite concentration of 2.5% and 5%, up to injection rates of 7.6%, 9.3%, and 15.7%, respectively. In this state Increasing the amount of these suspensions will result in the transformation of the conditioned mixture into the two distinct phases of solid and water that was previously explained. (Figure 12). For higher concentrations of more than 12.5% this behavior was only observed in very low injection rates of less than 5%.

While using suspensions with a bentonite concentration of more than 5.5%, increasing the SIR causes the solid particles in the mix to adhere to each other, transforming the conditioned mix into a state where the slump cone shows low values; However, it would collapse a few seconds after the cone is pulled up or lightly tapping the slump plate with the tapping rod (Figure 13). It is important to note that the slump values obtained in this state were not valid and should not be relied upon for evaluating the results. Further increase of suspension injection in the mix will result in the formation of two distinct phases of solid and suspension for C_{susp} up to 7.5% and semi-uniform, non-plastic state for C_{susp} between 7.5% to 9%. Adhesive state is faced for thicker concentrations of more than 9%. (Figure 15, A).

The final state observed in this set of tests is the over-conditioned state, where an excessive amount of suspension is present in the mix. In this state, although the conditioned mix is plastic and the separated liquid phase is not observed, a separated suspension phase is present. This indicates that the excessive amount of additive is not effectively contributing and is being wasted Slump values of more than 20 were observed in this state (Figure 14).

Figure 11. Test specimen in the dampen loose state

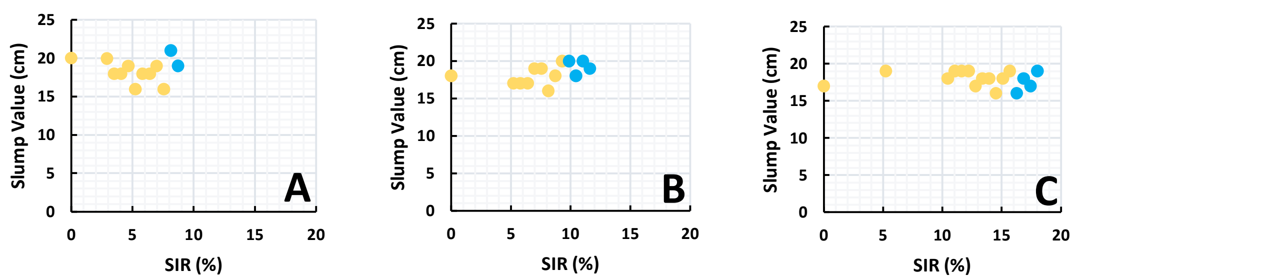

Figure 12. Changes in the slump value after the addition of A: Water, B: Suspension 2.5%, and C: Suspension 5%. ● Dampen loose state, ● Semi uniform non plastic

Figure 13. Test specimen exhibiting unstable low slump behavior

Figure 14. Conditioned material in the over conditioned state

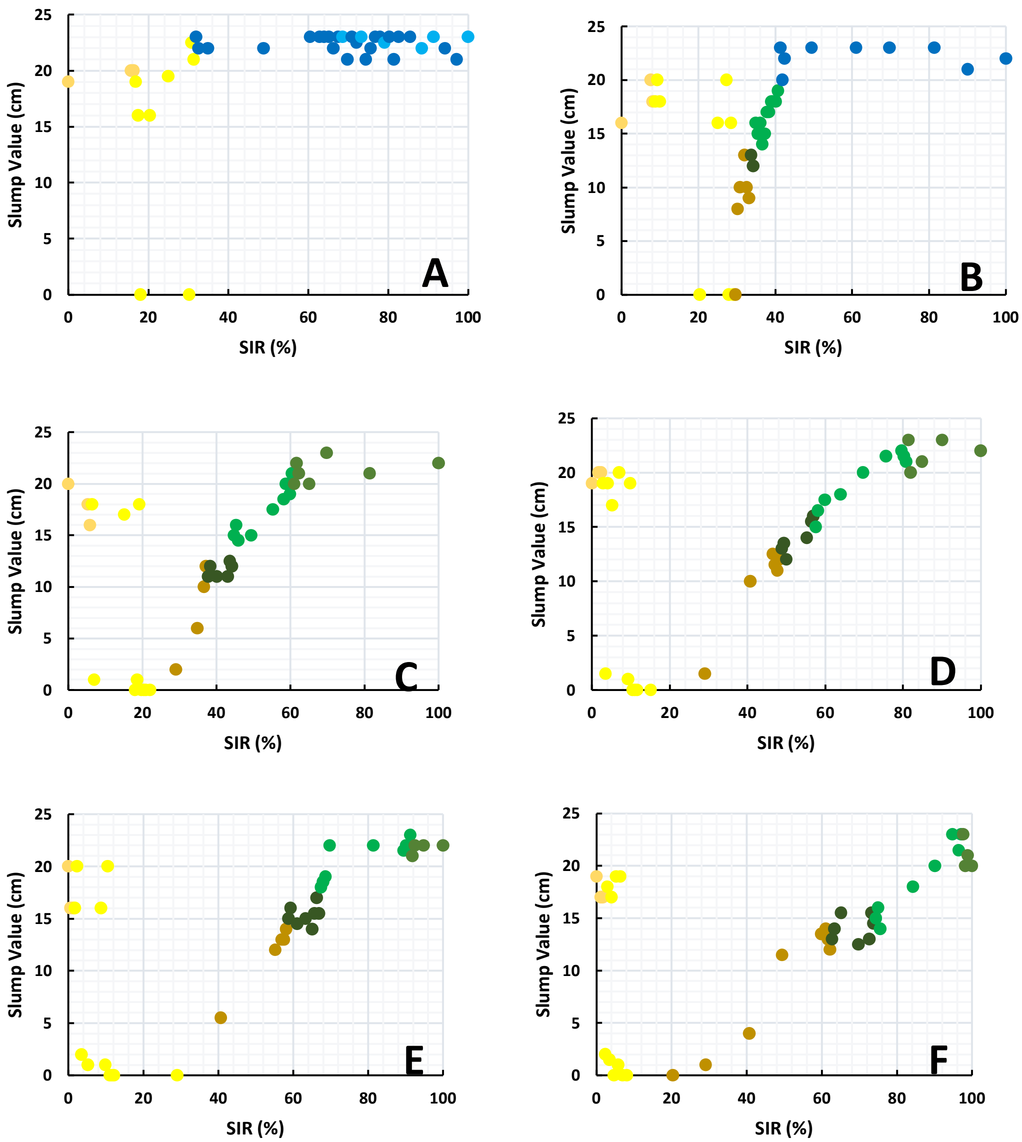

Figure 15. Trend of changes in slump value of the conditioned mix with increasing the injection rate for various suspensions. A: 7.5%, B: 10%, C: 12.5%, D: 15%, E: 17.5%, F: 20%
● Dampen loose state, ● Unstable low slump, ● Adhesive, ● Cohesive, ● Well-conditioned, ● Over conditioned

While using bentonite suspension as the conditioning additive, favorable conditions were achieved when the concentration of bentonite was at least 10% with an injection rate between 35 to 40%. Above this injection rate, the material will exhibit a semi-uniform, non-plastic behavior (Figure 15 B).

The application of thicker suspensions (12.5%, 15%, 17.5%, and 20%) results in similar behavior. In all cases, the conditioned mix exhibits the loose state, unstable slump, adhesive, cohesive, well-Conditioned, and over conditioned states of behavior by increasing the injection rate of the suspension. Details of the behavior by increasing the suspension injection rate are displayed in Figure 15.

Results of PPCT

PPCT was employed to evaluate the impermeability of the conditioned mix under high pressure conditions of the groundwater in the rock mass. Considering the typical water pressure in the rock mass and the duration of time that the conditioned material normally remains inside the chamber, the test specimen was subjected to a water pressure that gradually increased by one bar after a 20-minute interval between each step. The test continued until the water pressure reached 5 bars, at which point the test did not proceed further due to safety purposes.

Results from 22 trials revealed that the conditioned mixture achieved impermeability when the concentration of bentonite in the suspension reached approximately 8%, accompanied by an injection rate exceeding 30%. Higher suspension concentrations led to impermeability at lower proportions; however, even with dense suspensions (around 15% bentonite), a minimum 10% suspension was still necessary for achieving impermeability.

Once the conditioned mix became impermeable, it forms an impervious plug capable of withstanding even the highest applied water pressures. Under high pressures, water caused movement within the cell and potential apparatus damage, but no water leakage occurred from the conditioned material. The trend of changes in the permeability of the conditioned mix is displayed in the Figure 16.

Actual performance of bentonite

One of the main challenges in using bentonite powder as the conditioning additive for EPB TBMs is the absence of a dedicated pumping and injection system for dry powder on tunnel boring machines. Designing and installing such pumps can be time-consuming and costly. Additionally, it is difficult to achieve and maintain the optimum conditions as pumping large quantities of dry bentonite into the excavation chamber can result in the formation of bentonite clumps, leading to inadequate mixing with the excavated material (Figure 17).

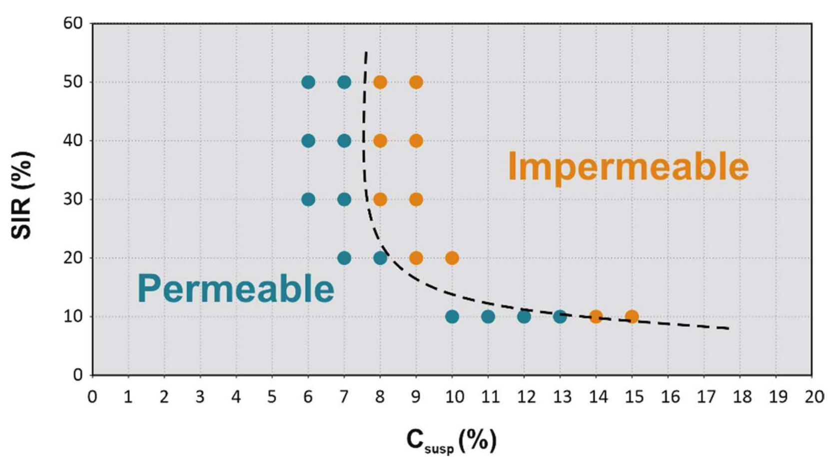

Figure 16. Trend of changes in the state of permeability of the bentonite conditioned material with varying concentrations and injection rates of bentonite suspensions

Furthermore, variations in the groundwater flow rate into the excavation chamber can cause a mismatch between the bentonite injection rate and the water content. Insufficient addition of bentonite leads to the formation of two distinct phases of liquid and solid, which can be addressed by increasing the bentonite dosage. Conversely, excessive addition of bentonite, even in small amounts, can cause clogging of the cutter head, resulting in increased torque. In severe cases, the disc cutters may become jammed, requiring time-consuming measures to remove the clogging or replace the discs (Figure 18).

Additionally, bentonite conditioned material has a higher unit weight compared to the excavated material. To be more precise, bentonite conditioned material in the well-conditioned state has a unit weight of around 2.06, which is 14.5% higher than the unconditioned wet material with a unit weight of 1.8. This will result in a heavier full chamber, leading to higher cutter head torque and thrust force, and consequently, higher specific energy for excavation.

Discussion

According to the findings of this study, bentonite is capable of resolving the problem of groundwater in EPB tunneling in rock. Its high liquid limit allows for significant water absorption and the creation of consistency in loose material. This results in the conversion of excavated material into a uniform and plastic paste, which cannot be achieved with conventional additives such as foam.

Changes in the behavior of the excavated material are classified into eight different categories based on the slump value and observations. The first category observed in 49 cases is the dampen loose state, in which the bentonite is not strong enough or insufficient to alter the behavior of the material. This state of behavior is characterized by a slump value ranging from 16 to 20, with a mean value of 18.18 and a standard deviation of 1.36 (Figure 19, A).

Figure 17. Images depicting well-conditioned material (left), Distinct phases of thin suspension and solid (middle), and formation of bentonite clumps (right)

Figure 18. Clogging of disc window due to the injection of bentonite powder (left), Cleaned up disc window (right)

The second category is known for unstable slump cones that collapse within a few seconds after the test, either by pulling the cone up or by slightly tapping it on the slump plate using the Slump rod. Slump values in this state appear in two different ranges: near 0 when the cone hasn't collapsed and 20 when it has collapsed. This behavior, observed 45 times in the tests, is described by mean and median values of 11.71 and 16, respectively. However, these values can be misleading without considering the highest standard deviation of 8.74, which is the highest among all the different categories. (Figure 19, B).

Utilizing a watery suspension will lead to the formation of two distinct phases: liquid and solids, which is classified as the third category. Among all the tests, 44 trials resulted in this state, where slump values ranged between 18 to 23. The mean and median values were 20.12 and 20, respectively, with a standard deviation of 1.67 (Figure 19, C).

When the suspension starts gaining the ability to float particles of silt and fine sand, the resulting mix appears in the semi-uniform state, but it is still not plastic. This condition was observed 52 times in the tests, with slump values ranging between 19 to 23. The median, mean, and standard deviation of this condition were 21.61, 22, and 1.25, respectively (Figure 19, D).

In these tests, well-conditioned material that was both uniform and plastic was observed with slump values ranging from 14 to 23. Analysis of 82 cases where this behavior was identified shows that the mean and median values are 18.18 and 18, respectively, and the standard deviation is 2.35 (Figure 19, E).

When the amount of suspension is increased in a well-conditioned mix, the over-conditioned state appears, which is identified by the presence of a separated heavy suspension phase in the mix. This state was encountered 20 times in the tests. The range of slump in this state is between 20 to 23, with a mean and median of 21.24 and 21.5, respectively. It has the lowest standard deviation in the tests, which is 1.09 (Figure 19, F).

By increasing the concentration of suspension in a well-conditioned mix, the material starts to exhibit cohesion, which is identified by a decrease in the flowability of the mix, lower slump values, and a change in the slump shape. This state of behavior, encountered 44 times, shows slump values ranging from 2 to 17, with a mean and median of 13.59 and 14, respectively, and a relatively high standard deviation of 2.96 (Figure 19, F).

The final state of behavior is encountered when the concentration of bentonite in a cohesive mix increases or when the amount of thick suspension is insufficient to form a well-conditioned mix. This behavior was observed 73 times. In this state, the slump ranges from 0 to 14, with a mean and median of 4.9 and 2, respectively, and a standard deviation of 5.05 (Figure 19, F).

To evaluate the overall performance of the conditioned mix, it is crucial to consider the permeability of the conditioned mix in addition to other evaluations. One notable finding from the pressurized permeability test is that bentonite-conditioned material becomes impermeable even before reaching the desired state of workability. This means that the bentonite-conditioned mixes exhibit impermeability, even when they are not yet plastic or fully uniform. Table 1 provides a comprehensive assessment of the quality of conditioning in each of the observed states of behavior, considering plasticity, uniformity, and permeability.

The results of the laboratory experiments and the observed behavior of the conditioned material on the job site are summarized in the empirical model shown in Figure 20. According to this model, achieving the optimum conditions using dry bentonite is only possible if the excavated material contains at least 30% water. Conditioning lower water contents with dry bentonite will lead to clogging. Conversely, adding bentonite suspensions at low injection rates will also result in clogging, which cannot be resolved by further injection of the suspension. Therefore, the best approach would be to inject thick suspensions into the chamber with approximately 30% water.

Table 1. Overall test results and observed behavior of bentonite conditioned muck

The State of the mix	Slump Range	Most frequent Slump value	Plasticity	Uniformity	Permeability	Overall Conditioning
Dampened Loose	16-20	18 & 19	Not plastic	Not uniform	Permeable	Unfavorable
Unstable Low slump	Collapse	0&20	Not plastic	Semi Uniform	Both	Unfavorable
Distinct Phases	18-23	20	Not plastic	Not uniform	Permeable	Unfavorable
Semi Uniform non-Plastic	19-23	23	Not plastic	Semi Uniform	Impermeable	Unfavorable
Well-Conditioned	14-23	18	Plastic	Uniform	Impermeable	Favorable
Over Conditioned	20-23	22	Plastic	Semi Uniform	Impermeable	Acceptable
Cohesive	2-17	11 & 16	Plastic	Uniform	Impermeable	Acceptable
Adhesive	0-14	0	Plastic	Uniform	Impermeable	Unfavorable

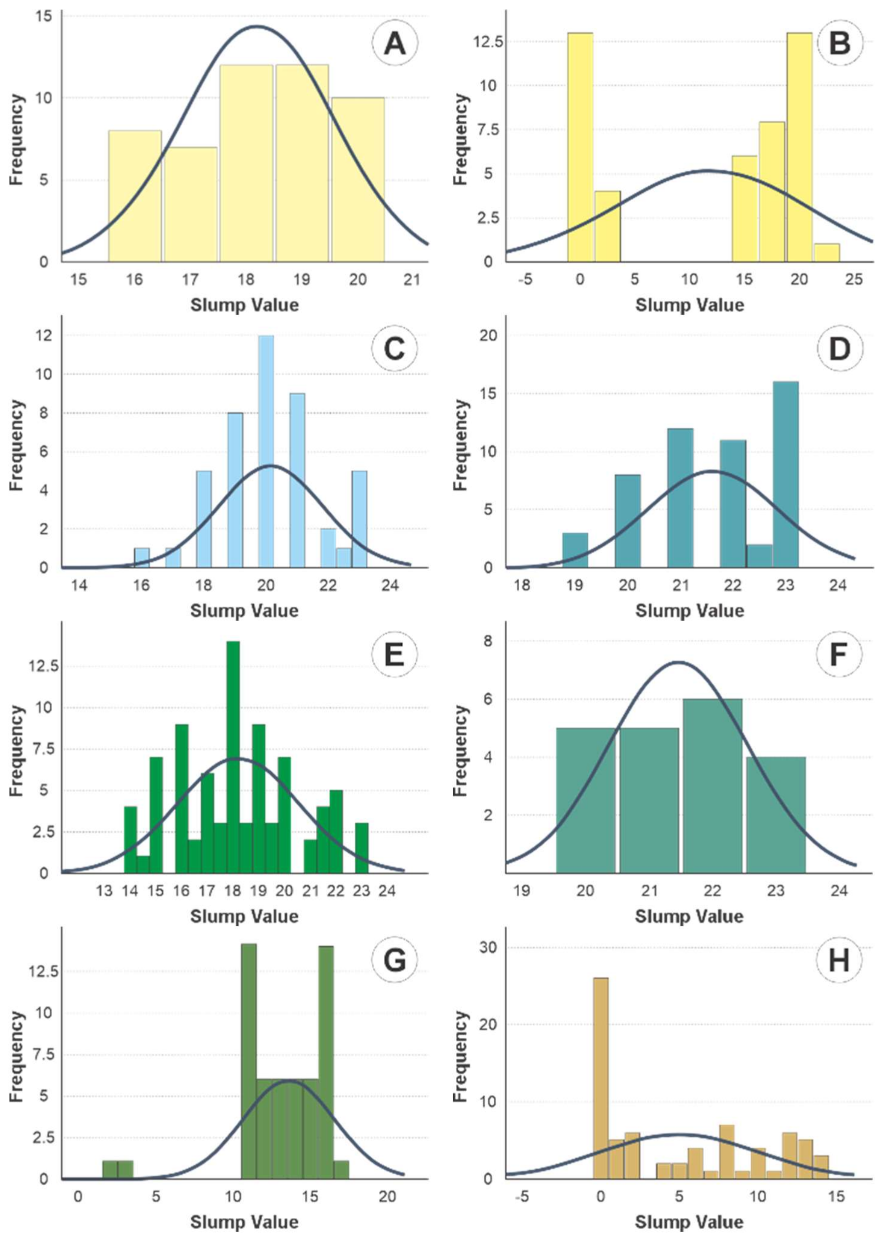

Figure 19. Frequency of the slump values for all different states of conditioned material's behavior. A: Dampened Loose, B: Unstable Low slump, C: Distinct Phases, D: Semi Uniform non-Plastic, E: Well-Conditioned, F: Over Conditioned, G: Cohesive, H: Adhesive

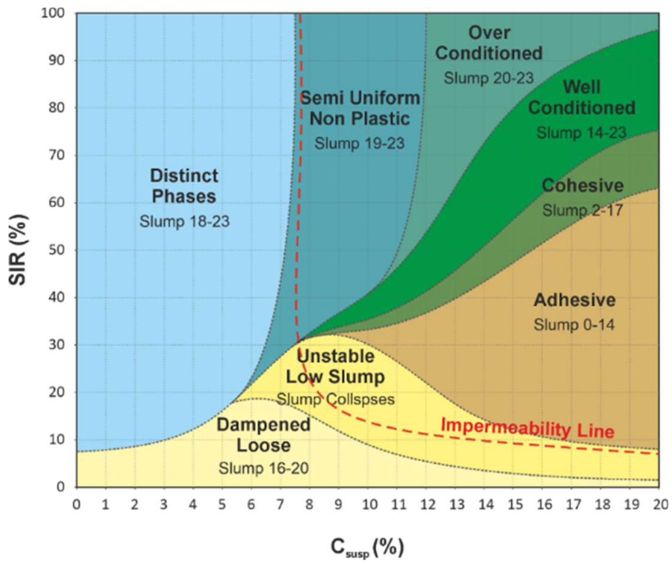

Figure 20. Empirical model illustrating the different states of behavior exhibited by Bentonite conditioned excavated material

Conclusion

The conditioning requirements for mechanized tunneling in rock and coarse-grained soils using EPB machines are significantly different from conditioning in soft grounds containing fines and clay minerals. These differences stem from variations in excavated material characteristics and geological conditions, leads to distinct challenges and concerns in the conditioning process.
In EPB tunneling through rock masses, the main goal of conditioning is to convert the excavated material into an impermeable and plastic paste. However, Conventional additives such as foam and polymer are not effective in achieving the desired workability or permeability because of the considerable difference in grain size distribution between the excavated material in rock and the suitable range for foam application. Moreover, the presence of groundwater degrades foam bubbles and makes them impractical for use.

Bentonite, known for its water-absorbing properties, emerges as a promising additive for modifying the grain size distribution and achieving desired soil conditioning. Its ability to absorb water and form a gel-like substance proves beneficial in altering the mixture's rheology and imparting impermeability.

The results of the slump tests on bentonite-conditioned material demonstrate its effectiveness in modifying excavated rock to achieve acceptable behavior. However, achieving optimum conditions using dry bentonite alone is challenging, if not impossible, as even slight additions of bentonite can lead to dramatic changes in behavior. On the other hand, the use of bentonite suspension at an appropriate density can effectively condition the coarse-grained muck, providing the desired permeability and workability.

Once the excavated material is conditioned with bentonite, further modification can be achieved by the addition of foam. This addition serves to reduce the relatively high unit weight and cohesion of the mix as well as decreasing the wear and the risk of clogging to facilitate a more efficient excavation.

Despite the promising results achieved in practice, further laboratory research is needed for the utilization of the combination of foam and bentonite in conditioning the excavated rock.

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