POLITECNICO DI TORINO
Repository ISTITUZIONALE

Bentonite slurry for TBM application, the laboratory tests for rheological properties

Original
Bentonite slurry for TBM application, the laboratory tests for rheological properties / Di Giovanni, A., Carigi, A., Saltarin, S., Berariu, R.M.B., Todaro, C., Peila, D.. - In: GEAM. GEOINGEGNERIA AMBIENTALE E MINERARIA. - ISSN 1121-9041. - 172-173(2024), pp. 37-43. [10.19199/2024.172-173.1121-9041.037]

Availability:
This version is available at: 11583/3016356 since: 2026-10-06T10:06:03Z

Publisher:
Geoingegneria Ambientale e Mineraria

Published
DOI:10.19199/2024.172-173.1121-9041.037

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

16 November 2026

DX.DOI.ORG//10.19199/2024.172-173.1121-9041.037

Bentonite slurry for TBM application, the laboratory tests for rheological properties and soil interaction

Alfio Di Giovanni*
Andrea Carigi*
Simone Saltarin*
Raluca Maria Bogdana Berariu*
Carmine Todaro*
Daniele Peila*

* DIATI, Politecnico di Torino

Corresponding author:
carmine.todaro@polito.it

Bentonite slurries are essential for the operation of Slurry Tunnel Boring Machines (TBMs), helping to stabilize the excavation face, prevent soil collapse, and control groundwater inflow. This study examines the performance of a sodium-activated bentonite slurry used in tunnelling, focusing on its physical-chemical properties, rheological behavior, and interaction with soil. Tests were conducted to measure parameters such as unit weight, flowability, bleeding, fluid loss, filter cake quality, and pH. Rheological properties like apparent viscosity, plastic viscosity, yield point, and gel strength were also evaluated. Additionally, the interaction between the slurry and soil was analyzed to study the filter cake formation.

The results showed that slurry with 5% bentonite performs well for TBM applications, offering strong stability, effective fluid loss control, and good rheological properties. This highlights the importance of optimizing bentonite slurries, future research could explore the potential of using additives to enhance performance to ensure safe and efficient tunnelling, especially in challenging ground conditions.

Keywords*: bentonite, bentonite slurry, TBM, tunnelling, rheology, Slurry Shield TBM.*

1. Introduction

Bentonite is essential in Slurry Tunnel Boring Machine (TBM) operations because of its properties that help to keep tunnels stable during the excavation. In Slurry TBMs, a mix of bentonite and water, called slurry, is used to support the excavation face, prevent soil from collapsing, and manage groundwater (Anagnostou and Kovári, 1994; Bezuijen *et al.*, 2006; Bezuijen *et al.*, 2016; Thewes *et al.*, 2016). Bentonite provides the necessary viscosity and thixotropic behavior to the slurry, making it possible to perform both the mucking phase and keeping the tunnel face steady.

Understanding how slurry interacts with soil is fundamental for tunnelling projects because it affects the efficiency, safety, and costs of the work. The behavior of slurry in different soil conditions affects factors such as soil displacement, clogging, and filter cake formation. Studies by Fritz (2007), Zizka and Thewes (2016), and Zizka *et al.* (2019) identify two different mechanisms for transferring pressure to the soil. The first involves the formation of an impermeable filter cake directly at the interface between the slurry and the soil. The second mechanism occurs when the slurry penetrates the soil skeleton. Xu and Bezuijen (2019a, 2019b) and Kube *et al.* (2023) investigated how bentonite slurry interacts with different types of soil, focusing on the process of filter cake formation and its implications for pressure transfer efficiency. This work is intended to overcome the scientific gap pertaining to a defined protocol that allows the selection of a slurry for a suitable application with the slurry machines, especially important for improving TBM performance and sustainability in challenging ground conditions.

2. Materials and methods

2.1. Materials

Bentonites are a group of natural clays that are widely used in various industries, including tunnelling. They are mainly composed of montmorillonite, a type of mineral that gives bentonite its ability to absorb water and swell (Mesboua *et al.* 2018). There are three main types of bentonites: sodium, calcium, and sodium activated. Sodium bentonite has a high swelling ability, high liquid limit, and low filter loss. Calcium bentonite has calcium ions as the predominant exchangeable cation. It has a lower swelling ability and liquid limit, and a higher fluid loss compared to sodium bentonite. Sodium-activated bentonite is made by adding sodium carbonate to calcium bentonite, replacing the calcium ions with sodium ions. This process enhances the characteristics of bentonite, making it similar to natural sodium bentonite but at a lower cost. In tunnelling, sodium-activated bentonites are commonly used to create support fluids for Slurry TBMs. Sodium-activated bentonite

If there are references to colour figures in the text, the articles are available in open-access mode on the site www.geam-journal.org



Fig. 1 – Bentonite used.

has better rheological properties than natural sodium bentonite. It typically has a higher viscosity, which is crucial for stabilizing the slurry in TBM operations. It also has superior fluid loss control and better thixotropic properties, which means it can return to a gel-like state after being disturbed, making it ideal for tunneling applications. The bentonite used in this study (Fig. 1) is a high-performance sodium-activated bentonite specifically designed for use in TBMs.

As concerning the water, it came from the local supply network in Turin.

Pertaining to the soil used in this research, it is sand that comes from an area near Turin, and it is characterized by particle sizes ranging between 0.25 and 0.50 mm. The grain size distribution and a picture of the soil are reported in Figure 2. The bulk density of the saturated sand is 1780 kg/m^3. The soil used for the test has been artificially realized by appropriately combining the grain classes.

2.2. Testing procedure

The testing protocol conducted at Politecnico di Torino is structured into four phases. The first one is related to the characterization of the bentonite, with a similar procedure commonly used also for the two-component grout backfilling assessment (Todaro *et al.*, 2022). The second and the third ones are related to the characterization of the slurry (intended as a suspension of swelled bentonite and water) while the last phase is focused on the mutual interaction between the slurry and the specific soil intended to be tested. In the following, the 4 phases are reported with the relative specific tests:

1. Physical-Chemical properties of the bentonite: characterizing particle size, swell index, liquid limit, water content and wet residue at 63 μm;
2. Physical-Chemical properties of the slurry: assessing unit weight, flowability, bleeding, fluid loss, filter cake quality, and pH;
3. Rheological properties of the slurry: measuring parameters such as apparent viscosity (AV), plastic viscosity (PV), yield point (YP), and gel strength (10 seconds and 10 minutes). These properties indicate the slurry's stability, ability to suspend particles, and fluid flow control;
4. Interacion of the slurry with soil: investigating filter cake formation and how the slurry interacts with soil.

As already mentioned, in the performed study the water is collected from the aqueduct of Turin. It is important to highlight that the aptitude of the bentonite to swell, as well as the stability of the slurry and its rheological properties are strictly water dependent. It is well known, indeed, that potential salts dissolved in water can get worse the final quality of the slurry (Qin *et al.* 2023).

2.2.1. Slurry preparation

In this work, a slurry mixtures was prepared with bentonite concentrations of 5% by weight. The slurries were made by adding the respective amount of bentonite to water and mixing with an ARGO LAB AM20-D mixer at 2000 rpm for 15 minutes with the impeller shown in Figure 3.

In Table 1 the procedure is summarized.

2.2.2. Unity weight

The unit weight of the slurry was measured using a mud balance,

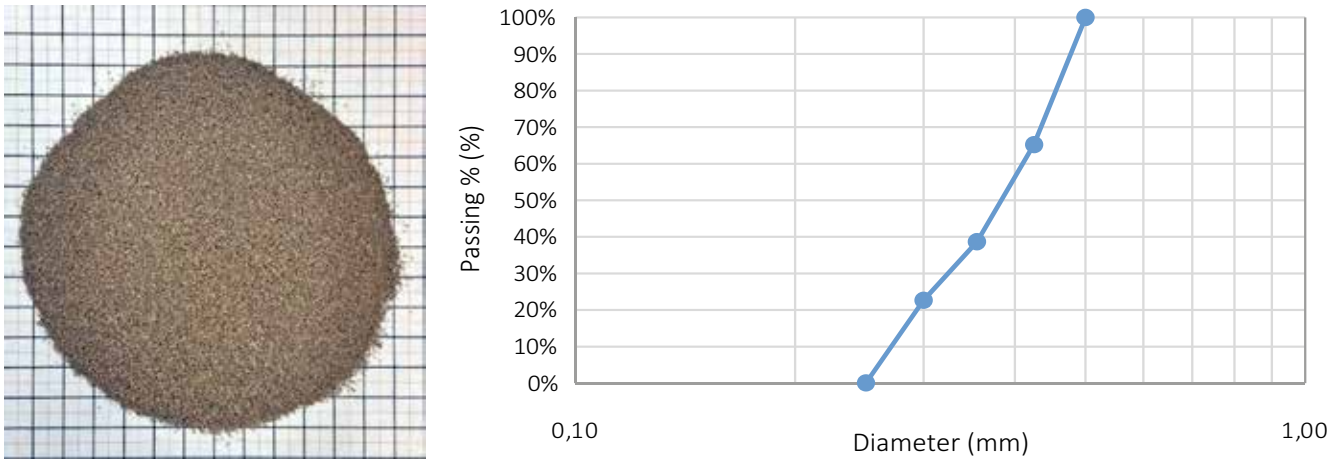


Fig. 2 – Soil sample (left) and its grain size distribution (right).

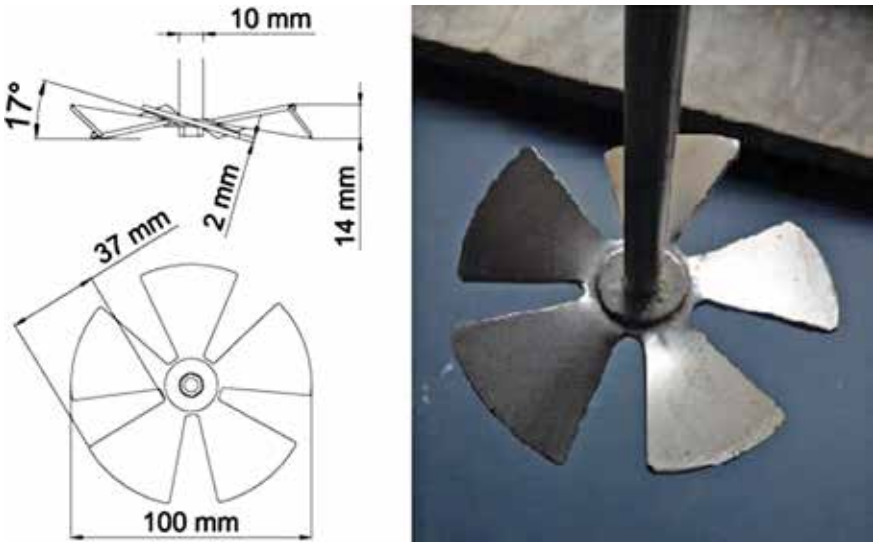


Fig. 3 – Scheme and photo of the used impeller (Todaro *et al.*, 2019).

Tab. 1 – Slurry mixing procedure.

Phases	Impeller rotation speed (rpm)	Duration (min)
Start – only water	800	–
Adding of the bentonite	800	Within the first minute
Bentonite mixing phase – end	2000	15

according to ASTM D4380 (2020). This test is simple and can be performed both in the laboratory and on construction sites. It provides a quick and efficient way to check the slurry's properties.

2.2.3. Flowability

The flowability of the slurry was evaluated according to the UNI 11152 standard by using the Marsh funnel. This test determines whether the slurry can be pumped through the system. The results depend on the slurry's yield point, plastic viscosity, thixotropy, and density.

2.2.4. Bleeding

The bleeding test evaluates slurry physical stability over time. The test has been carried out according to UNI 11152. The bleeding is expressed as a percentage, calculated by dividing the volume of separated water V_w by the initial slurry volume (1*L*).

$$\text{bleeding}(\%) = \frac{V_w\,(L)}{1(L)} \cdot 100$$

As the curing time increases, the bleeding typically becomes more pronounced. This test is essential for assessing the stability of the slurry when no mixing occurs and it is commonly performed after 1, 3 and 24 hours. For a fixed testing time and a fixed type of water, increasing bentonite concentration typically led to a bleeding reduction, indicating an improved stability.

2.2.5. Fluid loss and quality of cake

The fluid loss and quality of the filter cake were evaluated by applying a pressure of 7 bar for 30 minutes to the slurry in a filter press, following API Specification 13B-1. These tests assess the slurry's ability to waterproof the ground interface by forming a filter cake. The quality and quantity of bentonite in the slurry directly affect the results. The filter cake is then evaluated based on its thickness and its homogeneity.

2.2.6. pH

The pH value measures the acidity or alkalinity of an aqueous solution and is evaluated using a pH meter. It is an important parameter for quickly detecting potential contamination by acidic components (such as organic matter) or basic components (such as cement), which could negatively affect the slurry's performance.

2.2.7. Apparent Viscosity (AV), Plastic Viscosity (PV), Yield Point (YP), 10-s gel strength, 10-min gel strength

Due to the nature of the bentonite slurry the Herschel-Bulkley model is the more appropriate for accurately representing the rheological behavior of the slurries, particularly at low shear rates. The constitutive equation of the Herschel-Bulkley model is:

$$t = t_0 + k \cdot \dot{\gamma}^n$$

Where t is the shear stress, t_0 is the yield stress, k is the consistency index, $\dot{\gamma}$ is the shear rate; n is the flow index. In the Herschel-Bulkley model, the fluid's behavior depends on the flow index n. When $n = 1$, the fluid behaves like a Bingham plastic, meaning it exhibits a linear relationship between shear stress and shear rate. If $n < 1$, the fluid displays shear-thinning, or pseudoplastic, behavior, becoming easier to deform as the shear rate increases. Conversely, when $n > 1$, the fluid shows shear-thickening behavior, making it more resistant to flow as the shear rate increases. In Figure 4, the consistency chart of Newtonian and Bingham fluid models is presented.

The AV, PV, YP, 10-s gel strength and 10-min gel strength were

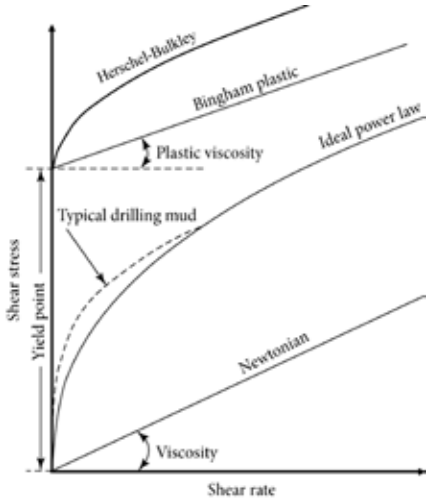


Fig. 4 – Consistency chart for Newtonian and Bingham fluids (modified from Caenn *et al.* 2011).

estimated, according to API Specification 13B-1, with a Fann rheometer. This standardized device applies shear stress to a fluid with a rotating immersed cylinder and measures the fluid's response by tracking the stress applied to a free-turning concentric cylinder. Apparent Viscosity is evaluated as the ratio of shear stress to the shear rate. It is high at low velocities, such as during filtration into the soil, and low at high velocities, like during the mucking phase. Plastic Viscosity is important for calculation of pressure losses in the slurry pipes. Yield Point is a key rheological parameter that indicates the minimum stress needed to start slurry flow i.e. it measures the slurry's initial resistance to deformation. Lastly, 10-s gel strength and 10-min gel strength are the two parameters used to assess thixotropy, which refers to the slurry's ability to quickly reform a cake behind the cutting tools.

2.2.8. Slurry-Soil interaction test

The laboratory setup includes a compressed air system and specimen holding cells. The compressed air system provides a controlled and consistent pressure source, ensuring precise and stable testing conditions. The specimen holding cells are designed to securely contain both the soil and the slurry during testing, allowing accurate measurement of the slurry's interaction with the soil under different conditions of pressure.

The compressed air system is made up of galvanized steel pipes and fittings with a nominal diameter of 1/2", to which vertical branches are connected, allowing the attachment of the specimen holding cells. The system includes a pressure regulator with a manometer, a ball valve, a vent valve, and a pressure gauge to monitor the applied pressure, as shows Figure 5.

The cells, which hold the soil samples during the test, are made of Plexiglass tubes with an inner diameter of 50 mm, a thickness of 5 mm, and a length of 380 mm. The lower end has a sealed Plexiglass disc with the same diameter as the tube. A threaded hole in the center of the disc holds a valve at the bottom. Millimeter strips are placed on the outer cylindrical surface of the cell to allow the measurement of the sample height. At the base of the cell, a porous stone (Fig. 6) and a filter cloth are placed to blocking the sand grains while letting the water to flow. The filter cloth was added to prevent clogging of the porous stone.



Fig. 5 – Slurry-Soil interaction Laboratory setup.

The specimen cells are filled by inserting the loose, pre-saturated sand in different steps. Each 5 cm layer of sand is compacted by dropping a weight of 2 kg from a height of 5 cm from the free surface of the soil, 5 times per layer. This process is repeated until the soil specimen thickness ranges from 15 to 17 cm. The soil compaction is carried out increase the material density with respect to the bulk density, at which is easy the formation of prefe-

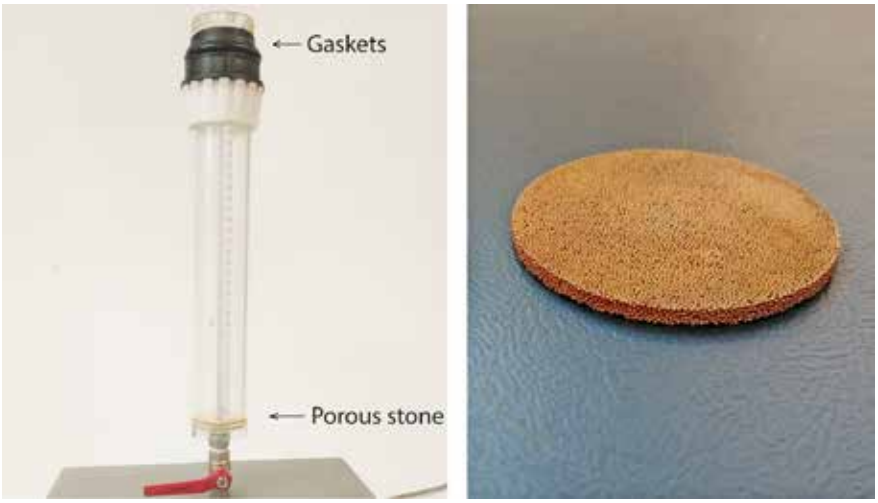


Fig. 6 – Specimen holding cell (left) and detail of the porous stone (right).

rential channels and is not representative of the in situ conditions. After that the remaining part of the specimen cells are filled with the bentonite slurry. A pressure of 2 bar is applied at the top, and after 60 minutes, the valve at the bottom is closed, and the air pressure at the top is released. After the discharging of the exceed slurry, the bentonite cake is then subjected to a pressure of 2 bar, measuring the cake's pressure holding capacity over time. After 20 minutes the cake characteristics are evaluated.

3. Results

The outcomes are presented in the following. Firstly, the results about the chemical and physical properties of the bentonite are presented. Then a focus on the rheological properties of the slurry and at least the results about the slurry – soil interaction.

In Table 2 are presented the chemical and physical properties of the bentonite used in this study.

The results related to the chemical-physical characteristics of this bentonite slurry are reported in Table 3.

In Figure 7 and Figure 8, the outputs of the test are shown. Figure 7 illustrates the bentonite cake, while Figure 8 displays the pressure-holding capacity of the cake over time. The formation of the bentonite cake was observed with an average thickness of about 2.8-3.0 mm at the edges of the specimens and 2.3-2.5 mm at the center of the specimens.

4. Comments on the results

The analysis of the chemical-physical properties of bentonite slurry and the results of the permeation test can reveal important correlations between the slurry's characteristics and the behavior of the bentonite cake formed during its interaction with the soil. The results highlight the high-quality properties of the bentonite used in this study. The low wet residue indicates good fineness, essential for uniform slurry preparation. The high swell index and liquid limit demonstrate very good water absorption and swelling capacity. Regarding the chemical and physical characteristics of the slurry it is possible to see that the pH value of the slurry is within the range of 7-10 (Longchamp *et al.* 2005), so it means that the clay particles are well-dispersed, which enhances the slurry's rheological properties. The Apparent Viscosity and the Plastic Viscosity results show rheology suitable for controlling filtration and guarantee good cake formation. The range 3.6-7-5 Pa for the YP reflects the slurry's ability to resist flow under low stresses, which is essential for maintaining

Tab. 2 – Bentonite chemical-physical characteristics.

Wet residue 63 µm (%)	3.1
Swell Index (mL/g)	20.4
Liquid Limit (%)	602
Water content (%)	13.5

Tab. 3 – Rheological characteristics of slurry.

Parameter	**Slurry 5% of bentonite**
Unit weight (kg/L)	1.03-1.05
Marsh Cone (s)	38-51
$Bleeding_{24h}$ (%)	0.0
pH (-)	9.6-9.9
AV	9.8-15.8
PV (mPa*s)	6.0-8.0
YP (Pa)	7.5-15.5
Gel strength 10" ($lb/100ft^2$)	3.6-7.5
Gel strength 10' ($lb/100ft^2$)	10-20
Fluid loss (ml)	14-17
Cake Thickness (mm)	2.0



Fig. 7 – Filter cake after filtration test (left), focus on the cake (right).

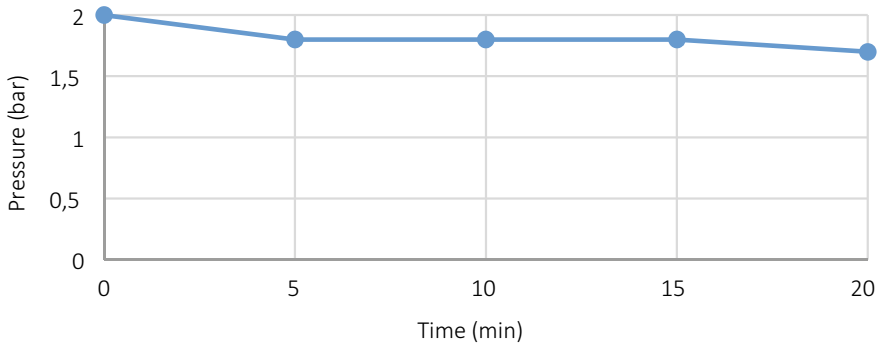


Fig. 8 – Pressure holding capacity of the cake over time.

stability in static conditions. The increasing values between the Gel strength 10" and Gel strength 10' reflect a good gel structure, representing the ability of the slurry to reform a cake behind the cutting tools rapidly. The results obtained fall within the range of values associated with Soil Type 2, as reported in Longchamp *et al.* (2005). This alignment provides strong evidence of the accuracy and reliability of the findings, and it also shows that the results are consistent with well-established technical references.

Regarding the slurry soil interaction, the average filter cake thickness, ranging from 2.8-3.0 mm at the edges and 2.3-2.5 mm at the center, exceeds the 2.0 mm observed in the filter press tests (API 13B-1). This increase can be attributed to the interaction between the soil particles and the slurry, which enhances the formation of a homogeneous filter cake, improving the pressure holding capacity. This is supported by the pressure diagram over time (Fig. 6), which shows optimal performance of the bentonite cake: after 20 minutes, the pressure drop is only 0.3 bar compared to the initial pressure of 2 bar.

5. Conclusion

This study highlights the critical role of bentonite slurries in tunnelling operations, particularly in Slurry TBMs, where their properties play a significant role in excavation performance and stability. The research focused on analyzing the chemical-physical characteristics, rheological behavior, and the interaction between bentonite slurries and soil.

The slurry with 5% bentonite exhibited good physical-chemical properties, including negligible bleeding, controlled fluid loss, and suitable pH values. These properties ensure the slurry's stability and effectiveness during TBM operations. The slurry also demonstrated appropriate rheological properties for tunneling applications. The apparent and plastic viscosity values supported efficient pumping and flow control, while the yield point and gel strength values indicated strong suspension capabilities and rapid cake formation. These characteristics are essential for stabilizing the excavation face and ensuring smooth operations under varying excavation conditions.

Considering the slurry-soil interaction, the filtration tests shown the formation of a homogeneous and compact filter cake, with thicknesses surpassing those seen under standard conditions. This enhanced cake formation is likely due to the interaction with soil particles, which improve the slurry's pressure holding capacity and reduce permeability.

These results confirm the suitability of bentonite slurries for tunnelling applications, emphasizing their ability to stabilize the excavation face and efficiently control filtration. The findings also highlight the importance of optimizing bentonite dosage and slurry preparation methods to meet specific project requirements.

Future research could explore the long-term performance of bentonite slurries in varying soil conditions and the impact of environmental factors on their behavior. Additionally, investigating additives, i.e. polymers, to increase the rheological properties could further improve the efficiency and sustainability of Slurry TBMs in more permeable and difficult soils.

References

Anagnostou, G., Kovári, K. (1994). The face stability of slurry-shield-driven tunnels. Tunn. Undergr. Space Technol. 9 (2), 165-174

API (American Petroleum Institute) (2003). Recommended practice standard procedure for field testing water-based drilling fluids, 13B-1, 3rd edn. Washington, DC, USA: American Petroleum Institute

ASTM D4380 (2020). Standard Test Method for Determining Density of Construction Slurries. American Society for Testing and Material International.

Bezuijen, A., Pruiksma, J.P., van Meerten, H.H. (2006). Pore pressures in front of tunnel, measurements, calculations and consequences for stability of tunnel face. In: Bezuijen, A., van Lottum, H. (Eds.), Tunnelling. A Decade of Progress. GeoDelft 1995-2005. CRC Press, pp. 35-41.

Bezuijen, A., Steeneken, S.P., Ruigrok, J.A.T. (2016). Monitoring and analysing pressures around a TBM. Proceeding of the 13th International Conference Underground Construction, Prague.

Caenn, R., Darley, H.C., Gray, G.R. (2011). *Composition and Properties of Drilling and Completion Fluids*, 2011, Gulf Professional Publishing.

Fritz, P. 2007. Additives for slurry shields in highly permeable ground. *Rock Mech. Rock Eng.* 40 (1): 81-95.

Kube, S.; Schoesser, B.; Thewes, M. (2023). Penetration behaviour of slurry in saturated soil – analysis of particle deposition on the basis electrical resistance. In *Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – WTC 2023. DOI: 10.1201/9781003348030-155*

Longchamp, P. *et al.* (2005). AFTES recommendations concerning slurry for use in slurryshield TBM Tunnels et Ouvrages Souterrains – Hors-Serie N.1, 164-183.

Mesboua, N., Benyounes, K., Benmounah, A. (2018). Study of the impact of bentonite on the physico-mechanical and flow properties of cement grout, Cogent Eng. 5 (1) (2018), 1446252, https://doi.org/10.1080/23311916.2018.1446252.

Qin, S., Zhou, W., Xu, T. (2023). Effects of seawater on the infiltration behavior of bentonite slurry into sand, Con-

struction and Building Materials, Volume 371. doi.org/10.1016/j.conbuildmat.2023.130759.

Thewes, M., Schoesser, B., Zizka, Z., (2016). Transient face support in slurry shield tunneling due to different time scales for excavation sequence of cutting tools and penetration time of support fluid. ITA-AITES World Tunnelling Congress 2016, San Francisco.

Todaro, C., Peila, L., Luciani, A., Carigi, A., Martinelli, D., Boscaro, A. (2019). Two component backfilling in shield tunneling: laboratory procedure and results of a test campaign. In: Proceedings of the ITA WTC World Tunnel Congress 2019, Naples (IT), May 3-9. 10.1201/9780429424441-340.

Todaro, C., Saltarin, S., Cardu, M. (2022). Bentonite in two-component grout applications, Case Studies in Construction Materials, 16, e00901, https://doi.org/10.1016/j.cscm.2022.e00901.

UNI 11152 (2005). Sospensioni acquose per iniezioni a base di leganti idraulici – caratteristiche e metodi di prova, Ente Naz. Ital. di Unifi.

Xu, T. & Bezuijen, A. (2019a). Bentonite slurry infiltration into sand: filter cake formation under various conditions. Géotechnique 69, No. 12, 1095-1106 doi.org/10.1680/jgeot.18.P.094

Xu, T.; Bezuijen, A. (2019b). Experimental study on the mechanisms of bentonite slurry penetration in front of a slurry TBM. In: *Tunnelling and Underground Space Technology* 93: 103052.

Zizka, Z. & Thewes, M. (2016). Recommendations for face support pressure calculations for shield tunnelling in soft ground. Cologne, Germany: Deutscher Ausschuss fuer unterirdisches Bauene. V. German Tunnelling Committee (ITA-AITES).

Zizka, Z., Schoesser, B., Thewes, M., Schanz, T. (2019). Slurry Shield Tunneling: New Methodology for Simplified Prediction of Increased Pore Pressures Resulting from Slurry Infiltration at the Tunnel Face Under Cyclic Excavation Processes. Int J Civ Eng 17, 113-130 (2019). https://doi.org/10.1007/s40999-018-0303-2

Acknowledgments

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