

REDUCTION OF ENVIRONMENTAL IMPACT OF A TBM PROJECT USING INNOVATIVE SOLUTIONS FOR SOIL CONDITIONING AND BACKFILLING GROUT

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ABSTRACT: As all the most relevant industries in the economic world, construction is moving towards the research and development of innovative technologies and materials to improve the environmental sustainability of both existing and new infrastructures. This trend inevitably involves the tunnelling sector, one of the most dynamic within the industry. Mechanized tunnelling is already considered among the least environmentally impacting methods in terms of carbon footprint; however, significant improvements can still be achieved by acting on specific processes and materials. For example, cement-based backfilling grout accounts for a significant portion of the CO₂ eq. emissions in shielded TBM tunnelling. The development of cement-free two-component grout represents an innovation that allows TBM tunnelling to take a further step toward sustainability, enabling CO₂ eq. emission reductions of up to 70% without altering existing batching or application equipment. This solution has been successfully tested and applied in major projects such as the Oslo clean water tunnel, where a synergic collaboration between contractor and supplier allowed to fine-tune the system on site and meet performance requirements while reducing the project's environmental footprint.

At the same time, tunnel excavation with TBM involves another relevant environmental aspect: water consumption. Large volumes are required for several applications, especially when EPB machines are used, where soil conditioning is a major contributor to water demand, particularly in cohesive ground formations. Traditional conditioning processes typically result in Water Injection Ratios (WIR) of 10–30%, but recent studies carried out at the “Politecnico di Torino” demonstrated that newly developed conditioning agents can reduce water usage by 20–25%. Such a reduction translates into thousands of tons of water saved, along with additional benefits: lower muck volume, reduced truck transport, and consequently fewer CO₂ emissions. These advantages gain particular importance in contexts where water is increasingly scarce, and sustainability is a priority.

The paper therefore presents two innovative directions for more sustainable tunnelling: the development and application of cement-free backfilling grout and the adoption of new soil conditioning agents. Both approaches demonstrate how targeted technological advances can reduce environmental impact while ensuring, or even improving, technical performance in the construction of major underground infrastructures.

1. INTRODUCTION

The construction industry is increasingly focused on sustainability across the entire project lifecycle, from planning and design to construction and operation, with the aim of minimizing the environmental footprint of new infrastructure. Tunnelling, despite being one of the most resource- and energy-intensive construction activities, follows the same trend, as many tunnelling projects ultimately contribute to environmental improvements through more efficient transport and infrastructure systems. When applicable, mechanized tunnelling using Tunnel Boring Machines (TBMs) offers advantages over conventional methods due to higher process electrification, reduced material handling, and lower overall project impacts.

Water consumption represents a critical sustainability challenge in TBM tunnelling, especially when EPB machines are used for the tunnel construction. While part of the water used on mechanized jobsites is continuously recycled, a significant share is lost into the muck, particularly during soil conditioning. In Earth Pressure Balance (EPB) tunnelling, cohesive and highly sticky soils often require high Water Injection Ratios (WIR) or extensive foam usage. As soil conditioning constitutes the main source of water demand in TBM operations, reducing its environmental impact is essential for lowering overall water consumption and improving the sustainability performance of mechanized tunnelling projects.

Out of TBM tunnelling, two-component backfill grout cement based is recognized to contribute about 10% of the total CO₂ eq. emission in a hard rock shielded TBM tunnel (Baucal et al. – 2025). To address this contribution, a cement-free two-component backfilling grout has been developed to significantly reduce CO₂-equivalent emissions while maintaining equivalent performance and full compatibility with existing mixing, transport, and injection systems.

Mapei S.p.A., is at the forefront of innovation in sustainable TBM operations by developing new products capable of reducing the environmental impact of mechanized tunnelling. This has resulted in a wide range of products dedicated to reducing the amount of CO₂, emissions and the overall environmental impact of a TBM project.

2. FOAM AND POLYMER FOR THE WATER SAVING PROGRAM

2.1 INNOVATIVE SOIL CONDITIONING PRODUCTS

Within the framework of Mapei's Water Saving Program (WSP), a new range of soil conditioning products has been developed with the specific objective of reducing the Water Injection Ratio (WIR). Within this paper the experimental investigation carried out to develop the innovative soil conditioning products Polyfoamer ECO WSP and Mapedisp ECO WSP is presented together with their comparison with a reference soil conditioning product. The study focuses on laboratory testing procedures aimed at the characterization of a clayey soil sampled from a quarry located near Reggio Emilia, carried out in accordance with the technical partnership between the Department of Environment, Land and Infrastructure Engineering (DIATI) of Politecnico di Torino and Mapei S.p.A.

The newly developed products are designed and manufactured to ensure effective conditioning of cohesive soils while minimizing the amount of water required during the conditioning process. The experimental program included: mini flow tests, mini slump and flow table tests, standard slump tests, and dynamic adhesion tests.

2.2 MATERIALS USED

The purpose of the research was to carry out soil conditioning test on "Reggio" clay (a very plastic clay collected by a quarry in the central part of Italy) using specific conditioning agents for clays. Three different soil conditioning agents supplied by Mapei S.p.A. have been tested, defined as follows:

- reference conditioning agent - "REF";
- innovative anti-clay foam - "Polyfoamer ECO WSP";
- innovative anti-clay polymer - "Mapedisp ECO WSP".

The clay soil used for the experiments was supplied to the Tunnels & Underground Space Research Center of the Turin Polytechnic University directly by Mapei S.p.A. From this sample, two different types of clays were produced:

- dry crushed clay ($w_n = 0\%$), hereinafter referred to by the acronym "DCC"
- chip clay ($w_n = 12.6\%$), hereinafter referred to by the acronym "NCC".



Figure 1: Clay samples used in the laboratory for the test campaign. DCC (left) e NCC (right). The difference in color is due to the different water content in the samples.

The conditioning agents for clays used in the study were the below ones:

- a) "REF" (reference) conditioning agent. "Traditional" foaming agent, formulated with anionic surfactants of the SLES (Sodium-Lauryl -Ether-Sulphate)
- b) "Polyfoamer ECO WSP" innovative anti-clay foam, formulated with the aim of reducing the amount of water required in comparison to a 'traditional' foaming agents;
- c) "Mapedisp ECO WSP" innovative anti-clay polymer, formulated with the aim to help foams on reducing the amount of water required

2.3 MINI FLOW TESTS

Mini flow tests, recently introduced for the characterization of conditioned clays, employ a scaled-down cone (44 mm base diameter, 66 mm height) derived from standard slump tests (CEN 2009).



Figure 2: Mini flow cone front and from-above views.

Tests were performed on "Reggio" clay using a fixed dosage of 0.5 g conditioning agent (0.5% w/w). Results show that the new generation products significantly improve workability: flow values increased up to 8-fold and slump values more than 3-fold compared to the reference product. Specifically, Polyfoamer ECO WSP (ID 10) achieved flow and slump values approximately 4 and 3 times higher than the reference (ID 6), despite a 17% reduction in added water, while Mapedisp ECO WSP (ID 9) exhibited 3- and 2-fold increases with a 22% water reduction.

Table 1: Mini flow tests results for "Reggio" clay.

ID	Conditioning agent	w _{add} (%)	flow (%)	slump (%)	w _{saved} (%)
6	REF	90	16	24	/
7	Mapedisp ECO WSP	90	126	84	0
8	Polyfoamer ECO WSP	90	126	83	0
9	Mapedisp ECO WSP	70	43	56	22
10	Polyfoamer ECO WSP	75	61	69	17



Figure 3: Mini Flow tests for "Reggio" clay. IDs are labeled

2.4 SLUMP TESTS

Mini-slump tests were conducted on NCC “Reggio” clay using a standardized cone (100 mm diameter, 150 mm height). Soil, water, and foam were mixed to achieve homogeneity before testing. Initial and post-jolting (15 jolts at 25 mm) slump dimensions were measured. A constant clay density of 1.786 kg/L and fixed conditioning parameters were used for all tests. The soil conditioning parameters have been kept constant for all the tests ($C_f=2\%$, $FER=8$, $FIR=60\%$).

Flow and slump results were evaluated relative to the initial mini-slump geometry after jolting. The addition of Polyfoamer ECO WSP or Mappedisp ECO WSP significantly increased flow (approximately $1.5\times$) under constant water content. Similar flow improvements could alternatively be achieved by reducing water content by 17–22%. Slump values remained largely unaffected by conditioning, ranging between 30% and 36%.






NCC “Reggio” clay has been used also for the slump tests which have been conducted at different time frames. The results are summarized in Table 2. Test ID5 was performed using Mappedisp ECO WSP at a fixed dosage of 2.02 g per 12,000 g of clay, corresponding to 0.3 kg of polymer per 1 m^3 of in situ soil. Given the low additive dosage (on the order of grams), its contribution was considered negligible in the calculation of water content. For the evaluation of the water-saving parameter (w_{saved}), tests ID2–ID3 were referenced to ID1, while ID5 was referenced to ID4.

Table 2: Slump tests results.

Test ID	Conditioning agent	w_{add} (%)	w_{tot} (%)	Slump A (cm)	φ_A (cm)	Slump B (cm)	φ_B (cm)	Slump C (cm)	φ_C (cm)	w_{saved} (%)
1	REF	32	45	19	28	11	25	25	49	/
2	Polyfoamer ECO WSP	22	34	13	27	0	20	17	34	33
3	Polyfoamer ECO WSP	26	38	17	34	5	22	22	41	20
4	REF	26	38	12	23	1	20	18	38	/
5	REF + Mappedisp ECO WSP	26	38	16	30	7	21	24	46	20

The interpretation of slump test results was not limited to the numerical slump value at the cone. Especially for clayey materials, additional qualitative parameters such as sample homogeneity, pulpy consistency, and stickiness were considered essential for a reliable assessment. To support interpretation, a qualitative scale was introduced for pulpy consistency (1 = low, 5 = high) and stickiness (1 = low, 5 = high). These qualitative evaluations were carried out after the execution of slump B and C.

Table 3: Slump tests pictures

ID 1 – Slump A	ID 2 – Slump A	ID 3 – Slump A	ID 4 – Slump A	ID 5 – Slump A
				
<p>Pulpy consistency: 4 Stickiness: 2 Additional comments: pulpy soil, presence of chips in the pulp.</p>	<p>Pulpy consistency: 3-3.5 Stickiness: 2 Additional comments: pulpy soil, presence of chips in the pulp.</p>	<p>Pulpy consistency: 3 Stickiness: 1.5 Additional comments: homogeneous material, slightly less homogeneous than slump A of test ID 2.</p>	<p>Pulpy consistency: 2 Stickiness: 3.5 Additional comments: less homogeneous material, the creamy outside hides the chips, which are still hard to the touch.</p>	<p>Slump A Pulpy consistency: 4 Stickiness: 2 Additional comments: homogeneous material, creamy paste.</p>

A comparison between ID1 and ID2 showed similar pulpy consistency and stickiness for slumps A and B, despite ID2 exhibiting a w_{saved} of 33%. However, ID1–slump C was deemed unacceptable due to excessive fluidity and material leakage from the plate, whereas ID2–slump C remained within acceptable limits without leakage.

Tests ID1 and ID3 exhibited comparable behavior in slumps A and B, with ID3 achieving similar performance despite a *w*_{saved} of 20%. ID3–slump C remained within the acceptable range without material loss.

For tests conducted at equal water content (ID4 vs. ID5), ID5 showed improved pulpy consistency in slump A. Slump B in ID5 was less stiff and less sticky than in ID4, with cone slump values of 7 cm and 1 cm, respectively. In slump C, ID5 showed limited spreading beyond the plate, with fewer fragments and a more cohesive paste compared to ID4. Comparing ID3 and ID4 (equal water content), ID4–slump A exhibited slightly higher stickiness, whereas ID3–slump C was significantly more pulpy. Conversely, ID4–slump C showed pronounced stickiness during cone lifting, which was not observed in ID3.

2.5 DYNAMIC ADHESION TEST

A dynamic adhesion test campaign was conducted following the procedures proposed by Todaro et al. (2022) and Carigi et al. (2023) to evaluate adhesion and clogging behavior of clay soils. The test consists of rotating a 120 mm diameter aluminium disc in contact with clay material at a constant speed of 90 rpm under a controlled normal pressure of 1 bar. The pressure is applied through a hydraulically actuated plate to ensure consistent contact between the disc and the conditioned clay. Adhesion effects are quantified by continuously measuring the torque required to maintain constant rotational speed.

Tests were performed on NCC “Reggio” clay at its natural water content. Average torque values were calculated over a 300 s testing period, excluding an initial pressure stabilization phase of approximately 120 s. Conditioning parameters and results, including average torque and saved water content (*w*_{saved}), were analyzed relative to a reference test. The tests were conducted on: ID 1 = REF, ID2 = Polyfoamer ECO WSP, ID3 = REF + Mapedisp ECO WSP. Results (Figure 4) showed similar torque–time trends across all tests, with torque values consistently below 7 Nm and average values between 3 and 4 Nm. These findings indicate that the adopted conditioning strategies effectively control adhesion and clogging phenomena, even with reduced water content, and yield consistent mechanical behavior in dynamic adhesion testing.

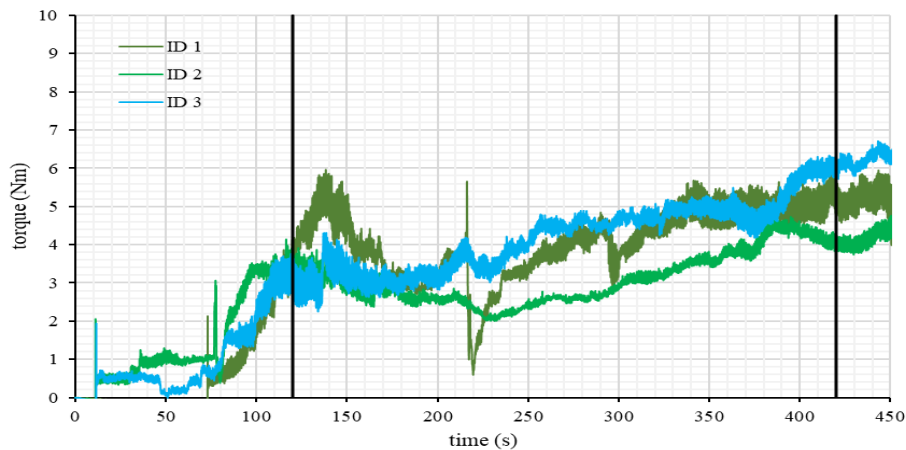


Figure 4: Torque over time graph for dynamic adhesion tests.

3. CEMENT FREE TWO COMPONENT BACKFILL GROUT

3.1 A NEW SOLUTION FOR BACKFILLING GROUT

Based on the typical requirements for two-component backfilling grouts (Table 4), the R&D laboratory of Mapei’s Underground Technology Team developed a dedicated binder obtained from a blend of geopolymers, pozzolanic materials, and specific additives.

This binder, named Mapequick CBS ACTIVE CF, is designed to undergo a binding reaction when combined with a specific activator. The main challenge in formulating a two-component backfilling grout lies in achieving a controlled gel reaction with reaction times and strength development comparable to

conventional systems, despite operating at a typically high water-to-binder ratio (around 2.5) and in the absence of cement.

Table 4. Typical backfill grout parameters and related acceptance range.

Parameter	Test	Reference Value	Unit
Viscosity	Marsh Funnel – EN445	30 - 50	“
Gel Time	Cup Test	5 - 15	“
Bleeding	EN445	2	% @3 hrs
Bleeding	EN445	8	% @24 hrs
Compressive strength	EN445	1.5 - 3	MPa at 28 days

These requirements were successfully met through the development of a dedicated powder activator, Mapequick CBS ACTIVE ACF, capable of triggering the gel reaction and ensuring sufficient strength development to allow application in TBM tunnelling, with performance comparable to traditional cement-based technologies.

The changes in mix design composition are shown in Figure 5. A performance comparison with a standard cement-based two-component backfilling grout is reported in Table 5. The mix designs considered contain similar amounts of powder components and were specifically engineered to exhibit comparable fresh-state properties and gel reaction behavior.

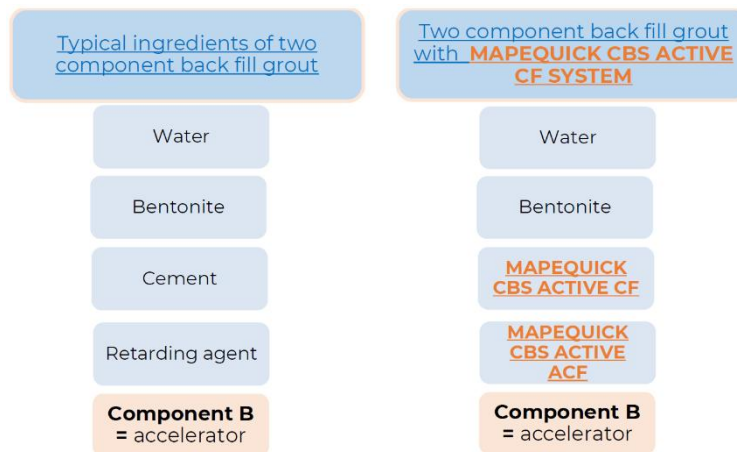


Figure 5. Comparison of the mix design between cement based grout (left) and cement free system (right)

The cement-free two-component backfilling grout achieves compressive strengths greater than 5 MPa without requiring a significant increase in ingredient dosages. In contrast, conventional cement-based two-component backfilling grouts typically reach compressive strengths of approximately 1.5–2.5 MPa at 28 days. Although higher strengths can be obtained with certain types of cement by substantially increasing cement and accelerator dosages, this approach often leads to drawbacks such as excessive viscosity, overly rapid reactions with the accelerator, and related handling issues.

Table 5. Typical backfill grout parameters and related acceptance range.

Parameter	Cement based mix		Cement free mix
	Results	Results	Results
Viscosity	39”	41”	41”
Gel Time	8”	9.5”	9.5”
Bleeding @ 3h	0.8%	0.5%	0.5%
Bleeding @ 24h	5.5%	6%	6%
UCS @ 1 day	1.5 MPa	1.2 MPa	1.2 MPa
UCS @ 28 days	2.2 MPa	7.3 MPa	7.3 MPa

3.2 APPLICATIVE ASPECTS OF THE CEMENT-FREE SOLUTION

Based on the analysis of the test results and the mix design characteristics, the cement-free solution is considered suitable for use with the plant and equipment commonly used on TBM jobsites. The presence of three powder-based materials requires the availability of at least three silos for raw material storage.

It should be noted that most batching plants currently installed on TBM projects with tunnel boring machines exceeding 6 m in diameter are typically equipped with two cement silos and one bentonite silo. Due to the reduced binder demand compared to a conventional cement-based formulation, the cement-free binder can be stored in a single silo while still ensuring adequate storage capacity.

As the formulation is aggregate-free and characterized by a specific water-to-powder ratio, the use of a high-shear colloidal mixer is appropriate for the production of Component A.

Additional advantages associated with the low powder content, high fluidity, and absence of aggregates include the ability to pump the grout through standard Victaulic-coupled pipelines with the nominal diameters commonly used for cement-based grouts.

For the same reasons, TBM installations are not adversely affected by the adoption of the alternative system. The fine particle size of the powders allows the use of progressive cavity pumps for grout dosing and pumping operations. Furthermore, the high-water content ensures the correct operation of standard flowmeters, while the very fluid consistency enables accurate pressure transmission to pressure sensors, comparable to that observed with traditional cement-based grouts.

As evidence of the excellent fresh-state performance of Cement-Free Component A, it is worth noting that the material is successfully pumped over long distances, approximately 15 km, from the batching plant to the storage tanks installed on a TBM project in Norway.

3.3 ENVIRONMENTAL IMPLICATION THROUGH LIFE CYCLE ASSESSMENT

The main advantage of the cement-free two-component grout formulated with the MAPEQUICK CBS ACTIVE CF SYSTEM lies in the significant reduction of CO₂ emissions, achieved through the replacement of cement with alternative constituents characterized by a lower environmental impact.

The Life Cycle Assessment (LCA) methodology, in accordance with ISO 14040:2006 and ISO 14044:2018 (see <https://ec.europa.eu/environment/ipp/lca.htm>), is applied to evaluate the environmental impact of chemical products throughout their entire life cycle, from raw material extraction to end-of-life disposal. The Global Warming Potential over 100 years (GWP100) indicator can be calculated for all components of the two-component backfill grout, both in cement-free and conventional cement-based formulations. On the basis of the GWP100 values, a comparison between the CO₂ emissions associated with one cubic meter of cement-free grout and one cubic meter of cement-based grout can be performed (Table 6).

Table 6. Global warming potential GWP comparison between Cement base and Cement Free mix-designs

<i>Global warming potential GWP</i>	<i>Cement base for 10 MPa</i>	<i>Cement free mix for 10 MPa</i>
<i>GWP emitted for m³ grout mix (kg CO₂ eq)</i>	488	102
<i>GWP emitted for the whole tunnel (ton CO₂ eq)</i>	21,500	4,500

The resulting difference depends on several factors, including the type of cement adopted, the dosage of each individual component (which in turn depends on the technical requirements of each TBM project), and therefore must be assessed on a case-by-case basis. In order to provide a tangible quantification of the environmental impact saving due to the use of a Cement Free solution some data comparisons are reported in the Table 7.

Table 7. Quantification and comparison among different CO₂ sources.

Activity / Item	Typical Emissions	Equivalent to 17,000 t CO₂e	Main Source
Gasoline car	~120 g CO ₂ /km	~141,600,000 km (≈ 142 million cars driving 1 km)	EEA, ICCT
Passenger flight Rome-Milan	~120 kg CO ₂ e per passenger	~141,700 passenger trips	ICAO Carbon Emissions Calculator
Household electricity consumption (Italy)	~0.23 kg CO ₂ e/kWh	~73.9 million kWh ≈ annual consumption of ~28,300 households	Terna, ISPRA 2022
Beef production	~60 kg CO ₂ e per kg of beef	~283,300 kg (≈ 283 metric tons) of beef	FAO, Poore & Nemecek (Science, 2018)

4. CONCLUSION

The conditioning of clay soils represents a complex process that cannot be adequately assessed through a single laboratory test. In this study, the conditioning performance of *Reggio* clay was evaluated using both homogenized clay samples (DCC) and clay chips (NCC), treated with conditioning agents specifically developed for cohesive soils. The test results demonstrated that Polyfoamer ECO WSP and Mapedisp ECO WSP (the latter used as an additive in combination with a reference conditioner) provide effective conditioning performance comparable to the reference product, while requiring significantly lower water addition. Mini-flow and mini-slump tests indicated potential water savings in the range of 17–22% when Polyfoamer ECO WSP was used instead of the reference conditioner. Comparable reductions were observed when Mapedisp ECO WSP was added to the reference conditioner. Slump test results further highlighted water savings of up to 33% when Polyfoamer ECO WSP was adopted. Dynamic adhesion tests confirmed a consistent water saving of approximately 17% for samples treated with next-generation conditioning products. Overall, a minimum water reduction of 17% was consistently achieved across all evaluated performance parameters, indicating a strong potential for reducing water demand at TBM job sites, with associated environmental and economic benefits.

In parallel, the study confirms the feasibility of a cement-free two-component backfilling grout. The development of this technology results from the integration of expertise in chemistry, tunnelling engineering, and materials engineering, supported by both contractor-level material departments and site application experience. The cement-free system fully meets the technical requirements and application limits of conventional cement-based grouts, without performance compromises. The backfilling process remains unchanged, except for the handling of three powder components during material loading. In addition to technical compliance, the cement-free technology achieves a substantial reduction in GWP100, based on an A1–A3 Life Cycle Assessment, representing a further step toward more sustainable tunnelling. Its successful validation demonstrates that on-site implementation is feasible, provided that all stakeholders support the adoption of innovative and environmentally responsible technologies.

5. REFERENCES

- L. Baucal–Poyac, L. D’aloia Schwartzentruber, G. Lechantre, E. Humbert, M. Rocca, M. Giacoia & A. Feraille (2025). Life Cycle Assessment of mechanized tunnelling – TELT case study. Tunnelling into a sustainable future-Methods and Technologies; Proceedings of the ITA-AITES World Tunnel Con-gress 2025 (WTC 2025), Stockholm, May 9 – 15 2024. CRC Press/Balkema, pp. 2571-2578.
- S. Liepins, C. Budach, & D. Handke (2025). Grouting the annular gap: CO2 reduction potential for dif-ferent materials. Proceedings of the ITA-AITES World Tunnel Congress 2025 (WTC 2025), Stock-holm, May 9 – 15 2024. CRC Press/Balkema, pp. 2916-2923.
- Todaro, C.; Martinelli, D.; Boscaro, A.; Carigi, A.; Saltarin, S.; Peila, D. (2022). Characteristics and testing of two-component grout in tunnelling applications. *Geomechanics and Tunnelling* 15, No. 1, pp. 121–131. <https://doi.org/10.1002/geot.202100019>
- Borio L., Peila D. (2011), Laboratory test for EPB tunnelling assessment: results of test campaign on two different granular soils. *Gospodarka Surowcami Mineralnymi*, 27(1), 85-100.
- Carigi, A., Di Giovanni, A., Saltarin, S., Peila, D., Todaro, C. 2023. “Influence of chip-size on development of adhesion for conditioned clayey soils” Proceedings of the ITA-AITES World Tunnel Congress 2023 (WTC 2023), 12-18 May 2023, Athens, Greece
- Peila D., Oggeri C., Borio L. (2009), Using the slump test to assess the behavior of conditioned soil for EPB tunneling, *Environmental & Engineering Geoscience*, XV (3), 167-174.
- Peila D., Picchio A., Chierigato A. (2013) Earth pressure balance tunnelling in rock masses: Laboratory feasibility study of the conditioning process. *Tunnelling and Underground Space Tech.*, 35, 55-66.
- Peila D., Picchio A., Martinelli D., Dal Negro E. (2016) Laboratory tests on soil conditioning of clayey soil. *Acta Geotechnica*. DOI: 10.1007/s11440-015-0406-8.
- Todaro C., Carigi A., Peila L., Martinelli D., Peila D. (2022) Soil conditioning tests of clay for EPB tunnelling, *Underground Space*, Volume 7, Issue 4, 2022, Pages 483-497, <https://doi.org/10.1016/j.undsp.2021.11.002>
- Dal Negro E., Boscaro A. and Plescia, E. (2014). Two-component backfill grout system in TBM: The experience of the tunnel “Sparvo” in Italy, Proceedings of TAC Congress 2014: “Tunnelling in a Resource Driven World”, Vancouver ,26-28 October 2014.

Dal Negro E., Schulkins R., Boscaro A., Pediconi, P. (2014). Two-component backfill grout system in double shield hard rock TBM. The “Legacy Way” tunnel in Brisbane, Australia, Proceedings of ITA-AITES World Tunnel Congress 2014: “Tunnels for a better life”, Foz do Iguacu, Brazil , May 2014.

Dal Negro E., Boscaro A., Barbero E., (2023) Mechanized tunnelling: improving the environmental impact of chemical products without impacting technical performance, Proceedings of the ITA-AITES World Tunnel Congress 2023 (WTC 2023), 12-18 May 2023, Athens, Greece.

Thewes M., and Budach C. (2009). Grouting of the annular gap in shield tunnelling – An important factor for minimization of settlements and production performance, Proceedings of the ITA-AITES World Tunnel Congress 2009 “Safe Tunnelling for the City and Environment”, Budapest, 23-28 May 2009.

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