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Laboratory investigation of the performance of two-component grout behind the segment in sandy soils below the water table level

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Abstract
The increasing use of TBMs in urban areas has heightened the significance of grouting behind tunnel segments. A key aspect of mechanized tunnelling is the application of grout for injection behind the tunnel segments (support system) to prevent ground settlement. This study aims to investigate the extent of two-component grout washout behind the segments and also simulates the presence of water flow in laboratory tests, which distinguishes it from other studies. Issues such as groundwater seepage and grout washout behind the segments—particularly when there are failures in the brush (caused by factors like reduced tail thickness from friction with the segment ring, misalignment in the shield from improper assembly, or damage to articulation jacks)—can lead to incomplete filling of the space and cause surface settlements. As a result, selecting an appropriate grout mixing design under these conditions is critical. A study was conducted to assess the injection of two-component grout with varying amounts of bentonite and sodium silicate. Different injection pressures and water conditions were simulated to evaluate grout penetration in coarse-grained soils. The grout injection tests at pressures of 1 and 2 bars showed that increasing the bentonite and sodium silicate in the grout mix not only reduces penetration into the soil but also helps prevent washout due to water flow. It is important to note that sodium silicate has a greater effect on this process than bentonite.

Keywords:
mechanized excavation, washout, brush, two-component grout, injection pressure

1. Introduction

Throughout their lives, humans are always seeking to make tasks easier and to solve problems and difficulties. One of these challenges that people face is transportation, which becomes increasingly important with the growing population. In this regard, rock mechanics, with its expertise in tunnelling and underground spaces for various applications, comes to the rescue. The tunnel support system in soft soils is comprised of segments. The void spaces in the segments may lead to ground settlement or groundwater infiltration into the tunnel. These voids are filled with grout.

The grout is injected into the space behind the segment under controlled pressure. This fills the void space behind the segment. It also fills the natural cavities in the ground, such as pores and fissures. Over time, it gradually hardens, reducing the permeability of the ground and increasing its resistance. The main objectives of grout injection include preventing ground settlement, preventing water flow and its movement, increasing the final resistance of the ground, especially in non-cohesive soils below the water table level, and ultimately enhancing operational safety. Nowadays, filling the void space behind the segment uses various natural and chemical fillers, one of which is two-component grout.

A two-component grout is made up of two separate elements that are pumped through different pipes and combined at the injection point. The first element is a cement-based mortar that maintains its chemical and physical stability. This portion of the grout contains cement, water, bentonite, and various additives. The second component is an accelerator blend, which is introduced to the first component just a few centimeters before the grout nozzle. Sodium silicate is commonly used as the primary ingredient in this accelerator mixture. In different excavation conditions, the compositions of the grout and the amounts of materials may also change. For this reason, examining the mechanical properties of the grout and the impact of each component on its performance and characteristics can be very important and practical (**Andre et al. 2022**).

Due to its short setting time and high resistance, two-component grout is widely used where drilling is carried out below the water table level. However, in case of brush failures (see **Figure 1**) at the end of the shield, this type of grout can be washed out with the regular mix-

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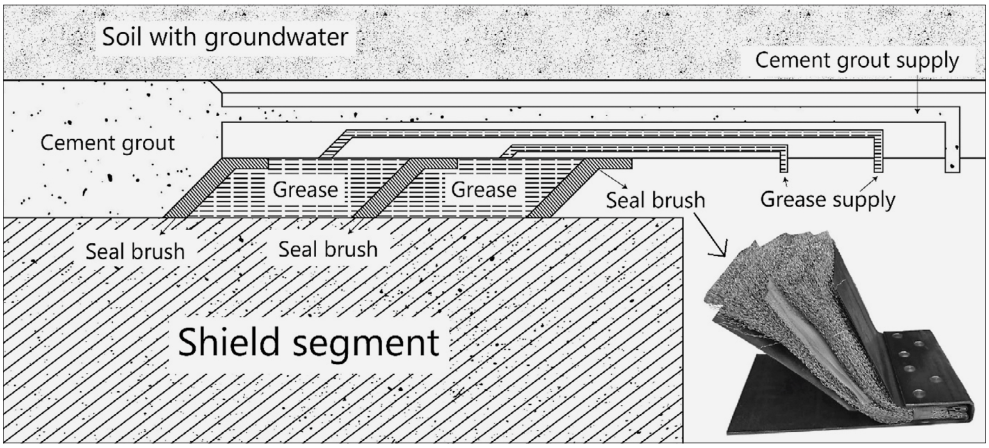

Figure 1. Injecting grout into the void space behind the segment and the position of the brush (**Yu et al. 2020**)

ture. Without a doubt, the washing out of the grout and the failure to fill the void space behind the segment can pose significant risks regarding ground settlement, segment instability, and water ingress into the tunnel (**Song et al. 2022; Yu et al. 2020; Liu et al. 2018; Zheng et al. 2017; Wang et al. 2023; Soga et al. 2017**).

Numerous researchers have explored the key factors influencing the physical and mechanical characteristics of two-component grout, its role in ground settlement, and the causes of brush failures. **Jorne & Henriques (2016)** investigated grout injectability and resistance to grout flow. Their study utilized 11 different small-scale porous cylinder media to assess grout injection efficiency by measuring velocity and injected mass. The experiments revealed that fine particles in the grout mixture promote water absorption, increasing viscosity.

Sharghi et al. (2017, 2018) examined how various constituent materials of two-component grout influence its properties and established optimal compressive strength ranges for grout behind segments. Their parameters included bleeding, fluidity, Marsh funnel results, setting and gelling times, and compressive strength. Findings indicated that exceeding a specific grout strength threshold adds cost without significantly affecting settlement. Furthermore, a lower water-to-cement ratio and higher bentonite or cement content increased viscosity (per Marsh funnel tests), reduced pumpability, and decreased bleeding. Greater cement and sodium silicate content enhanced short- and long-term compressive strength.

Yang et al. (2019) investigated the effect of bentonite on the pore structure and permeability of cement-based mortar. Bentonite, used as a swelling clay, was added at concentrations of 0%, 4%, and 8% of the cement weight. The results showed that adding 8% bentonite led to increases in compressive strength, flexural strength, and permeability by 61.48%, 42.09%, and 76.47%, respectively, compared to the control mortar.

Cui et al. (2020) evaluated the washout resistance of cement-based grouts considering time-dependent viscosity using computational fluid dynamics (CFD). Experiments with KC-1 and KC-2 grouts assessed their resistance to high-speed water flow. While both grouts performed well at velocities below 1 m/s, KC-1 exhibited better washout resistance at higher velocities but had reduced injectability due to higher viscosity. **Rahmati et al. (2022)** analyzed the uniaxial and triaxial compressive strength of various grout mixtures. Their results highlighted that increasing bentonite or cement content raised viscosity, reduced bleeding, and enhanced compressive strength. Sodium silicate addition shortened gelation time and further increased strength. Conversely, a higher water-to-cement ratio decreased the modulus of elasticity, while more cement improved cohesion and reduced internal friction angle.

Gomez et al. (2023) comprehensively studied the properties of cement-based grout, typically consisting of cement, water, and sand, with additives to optimize performance. They noted that fluidity and cohesion are crucial, as excessive water increases porosity and reduces strength. While silica enhances fluidity, strength, and reduces viscosity, bleeding, and porosity, excessive amounts impair flowability and efficiency. **Xue et al. (2023)** investigated ground behaviour after grout injection near tunnel boring machine (TBM) excavation sites, utilizing a three-dimensional model to simulate changes. **Khoshzaher et al. (2024)** examined sodium silicate and bentonite effects on grout used behind lining segments in mechanized tunnelling, conducting extensive laboratory tests to evaluate strength and stability. Their results indicated that these additives significantly improve grout performance for tunnelling applications.

Zhu et al. (2023) investigated the mechanics of cement-based grout penetration and filtration in porous media using coupled CFD–DEM simulations. Their study provided new insight into the interaction between grout flow and granular particles, highlighting the effects of particle size distribution and permeability on grout infiltration. The results demonstrated that fine particles in the porous media significantly influence the grout's filtration behaviour, leading to variations in permeability and flow resistance. They observed that grout penetration is largely dependent on injection pressure and rheological properties, which directly affect the formation of filtration cakes. The study also emphasized the role of particle clogging and network formation in limiting grout propagation, which has important implications for underground construction and tunnelling projects. Overall, their findings contribute to improving grouting techniques by optimizing material properties and injection parameters for better performance in geotechnical applications.

In their study, **Khoshzaher et al. (2024)** analyzed injection parameters such as water-to-cement ratio, injection pressure, and grout hole spacing. Findings showed that water-to-cement ratio had the greatest influence on grout quality, while increasing pressure from 2 MPa to 4 MPa raised the injected grout volume.

In the Tabriz Metro's Line 2 project, excavation is ongoing with two TBM-EPB machines (9.49 m diameter). The tunnel support system includes 35 cm thick segments, with the 15 cm gap behind them filled with two-component grout. Notably, deformation of the western TBM shield led to brush failures, water entry, and grout washing out. In some areas, grout washing created voids, increased settlement, and water ingress through segment gaskets. Secondary grouting was conducted to address these issues, increasing project costs. Factors such as shield pre-assembly issues, sudden directional changes, articulation jack failures, uneven injection pressures, and improper segment installation likely contributed to shield deformation and grout loss.

The innovation of this research lies in its novel approach to simulating water flow during grout injection, providing a more realistic testing environment for tunnelling applications. It investigates the combined effects of sodium silicate and bentonite in two-component grout to assess their influence on grout penetration and washout resistance under water-bearing conditions. The study also explores the impact of varying injection pressures (1 bar and 2 bars) on grout performance, which helps optimize injection practices. A custom-designed laboratory system was developed to replicate the grout injection process, ensuring controlled testing under realistic conditions. The research uses actual soil from the Tabriz Metro Line 2 project, enhancing the real-world relevance of the findings. This comprehensive approach provides new insight into grout performance, specifically for mechanized tunnelling below the water table.

2. Materials and methods

One of the essential parameters in grout injection behind the segments in coarse-grained soils below the water table level is filling the existing void space and preventing the washing out of grout along with increased grout penetration into the surrounding soil. In such soils, water is essential to the effectiveness of two-component grout, as it significantly influences its performance. Therefore, laboratory studies and device construction to investigate the performance of two-component grout in environments with water table flow and determine the penetration rate and the filling process of this space in the presence of water will be of great importance. The most significant problem observed in mechanized excavation regarding inadequate injection of grout behind the segments in various projects (including the project under investigation) is water flow, and consequently, the washing out of grout behind the segments. The brush is installed (see **Figure 1**) in the space between the shield and the segments, and it is filled with grease. This prevents water from entering the tunnel and disrupting the grout injection process. When the brush breaks, water enters the tunnel, and the injected grout enters the space behind the segments. As a result, the grout injection process is compromised, and essentially no injection takes place.

To investigate the performance of grout under such conditions, an injection simulation system (see **Figure 2**) has been designed and constructed in the laboratory. In this section, an overview and description of this system are provided. The injection system used for the permeability test consists of a water chamber, grout chamber, a soil chamber, and a compressor for generating injection pressure. The grout chamber is a cylindrical container made of Plexiglass, with a height of 40 centimeters and a diameter of 12.2 centimeters, serving as the grout reservoir. The connections of this chamber must be robust enough to endure the pressure exerted by the compressor without any disruption, remaining securely in place at its installation location. Each end of the grout chamber is sealed with a polyethylene cover. The upper cover features two openings: one for introducing grout into the chamber and another for applying pressure using a compressor. The applied pressure, before entering the grout chamber, can be observed and adjusted using a visible pressure gauge to precisely achieve the desired injection pressure in the grout chamber. The final cover of the chamber also includes an opening for grout discharge. This opening is connected to the soil chamber using a hose. The grout discharge opening in the final cover consists of a valve, controls the grout flow from the grout chamber into the soil chamber.

The soil chamber (the dimensions and the materials of this chamber are the same as the grout chamber), made of Plexiglass, is cylindrical, and it is covered at both ends by polyethylene covers. The coarse-grained soil used in the experiments was collected from the Tabriz Metro Line 2 project site and is classified as SP (Poorly Graded Sand) based on the Unified Soil Classification System (USCS). The top cover of the soil chamber includes an opening for grout injection, an opening for water injection, and a pressure gauge.

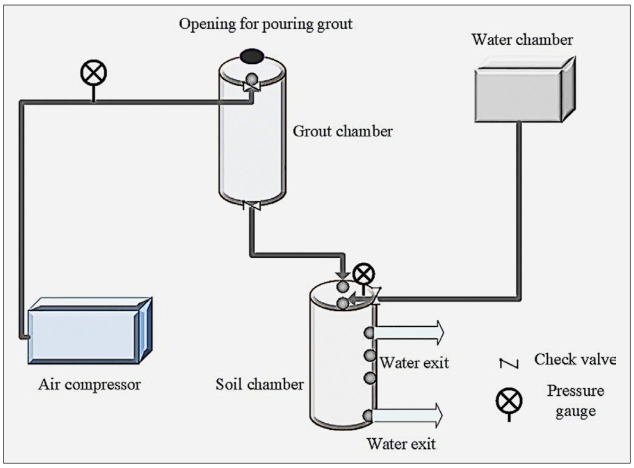

Figure 2. The Schematic Diagram of Laboratory Injection System

Two-component grout comprises distinct elements such as water, cement, bentonite, and sodium silicate, which acts as an accelerator. Water serves as the fundamental ingredient in cement-based grout, and the research utilized potable water free from organic impurities and solid particles. Cement's critical properties include fineness and particle flow, which influence its stability, fluidity, and penetration capacity in joints. This study employed Sofian Type 2 cement with a density of 3050 kg/m³. The bentonite used is an active type sourced from Salafchegan, possessing a specific gravity of 2132 kg/m³. To address challenges in grout application or structural issues, additives are introduced. The selected additive for this study is SA-161, a liquid sodium silicate accelerator with a specific gravity of 1500 kg/m³ in solution.

In this article, the grout injection and permeability experiments were conducted for eight mixing designs introduced in **Table 1**, with an applied injection pressure of 2 bars. Mixing Design 1 was selected as the baseline (control sample) due to its lowest content of sodium silicate (50 kg) and bentonite (40 kg). This control sample allowed us to assess the effects of increasing sodium silicate and bentonite on grout performance, including penetration and washout resistance.

To get data accuracy and obtain reliable results, the experiment was repeated with an injection pressure of 2 bars for mixing designs 1 and 3. Furthermore, to investigate the effect of injection pressure on the permeability, the experiment was performed with an applied injection pressure of 1 bar for mixing designs 1, 3 and 8. Additionally, during these experiments, the influence of water flow on grout washout was examined by injecting water into the chamber. Mixing design number 3 in **Table 1** represents the main mixing design used in the Tabriz Metro Line 2 project.

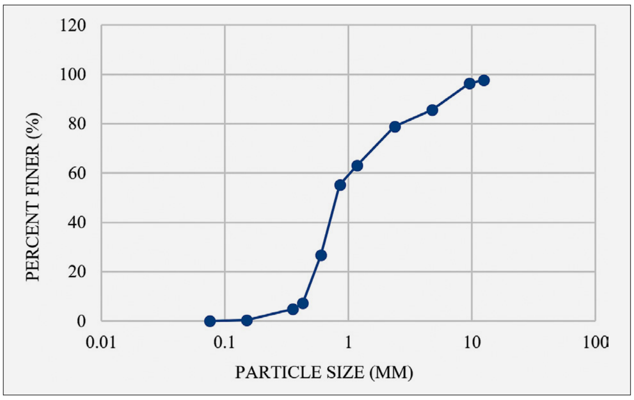

Figure 3. Soil gradation chart used in grout penetration test

3. Results and discussion

This section presents the results of the laboratory experiments performed to evaluate the penetration and washout resistance of two-component grout under different conditions.

The effects of bentonite content, sodium silicate proportion, and injection pressure on grout behaviour are analyzed in detail. Additionally, the influence of water flow on grout washout is discussed, providing a comprehensive understanding of grout performance in mechanized tunnelling applications below the water table level. To do these tests, the first component of the grout, according to the desired mixing design, was prepared.

The second component of the grout, sodium silicate, was prepared in a separate container. The outlet valve of the grout reservoir was closed, and the grout was poured

Table 1. Mixing designs used to make grout

No.	Sodium Silicate		Bentonite		Cement	Water	Density (g/cm³)	W/C
	kg	Percent in Weight	kg	Percent in Weight	kg	kg		
1	50	4	40	3.2	360	799	1.35	2.21
2	75	5.88	40	3.13	360	799	1.32	2.21
3	90	6.98	40	3.1	360	799	1.3	2.21
4	100	7.69	40	3.07	360	799	1.26	2.21
5	125	9.4	40	3.02	360	799	1.2	2.21
6	90	7.03	30	2.34	360	799	1.31	2.21
7	90	6.9	50	3.84	360	799	1.21	2.21
8	90	6.87	60	4.58	360	799	1.1	2.21

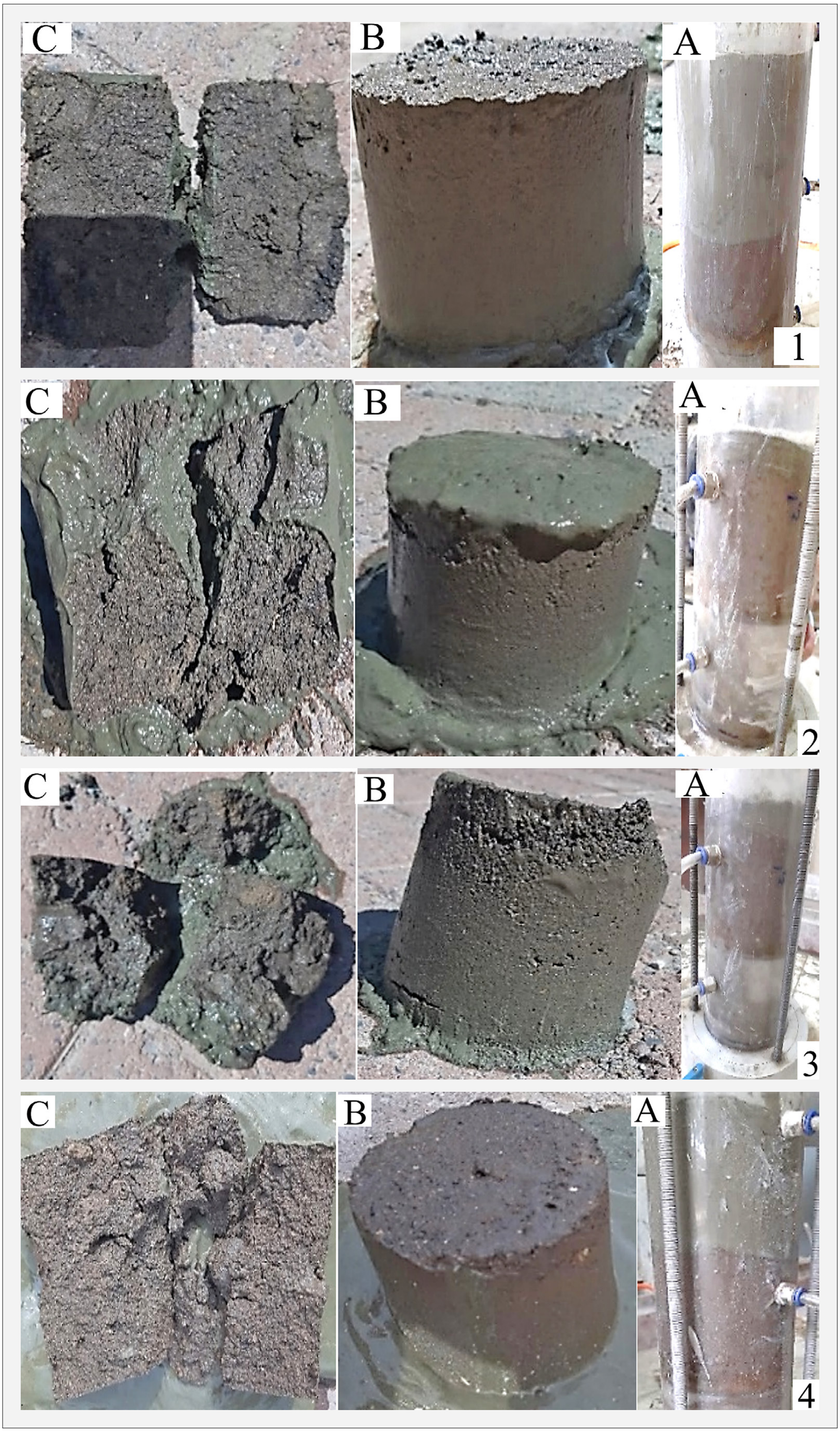

Figure 4. From the right side: A) Soil chamber after injection; B) Soil sample extracted from the soil chamber; C) Broken sample for penetration assessment (2 bars injection pressure).

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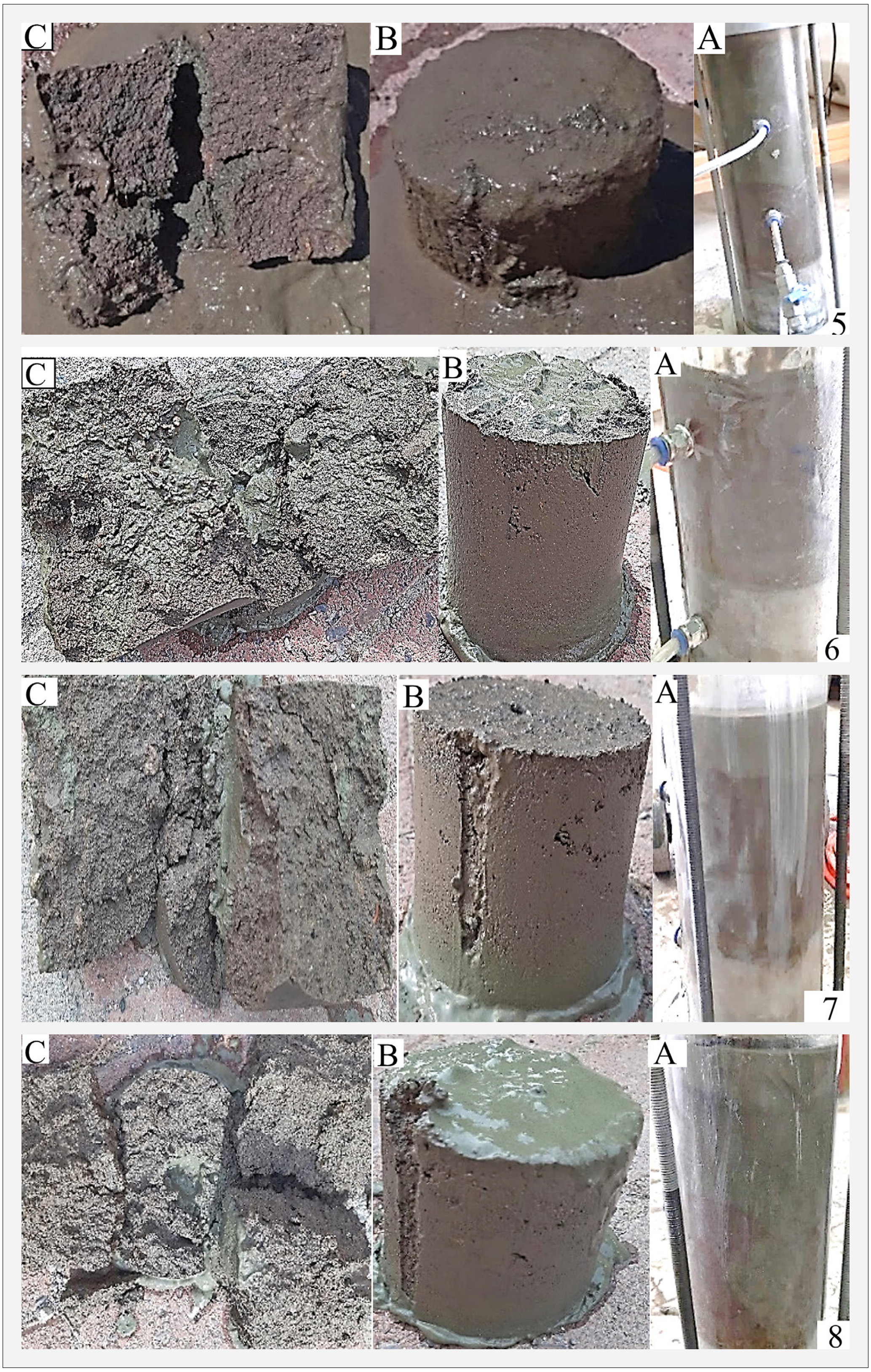

Figure 4. Continued

into the chamber. The pressure valve to the grout chamber was closed, and the desired pressure was applied based on the installed pressure gauge. Inside the soil chamber, soil with a specific particle size distribution (see **Figure 3**) was poured and compacted by impact to a certain height. Soil compaction is performed with the aim of achieving the desired density of the soil. This is done using a special compaction tool called a compac-

Table 2. Recorded data for changes in the height of grout inside the injection chamber and soil sample for 8 Mixing designs (2 bars injection pressure)

Mixing Design No.	Sodium Silicate (kg)	Bentonite (kg)	Height of the grout in the soil chamber after injection (cm)	Height of the soil sample extracted from the soil chamber (cm)	Has there been any penetration in the soil?
1	50	40	2	7	✓
2	75	40	2	7	✓
3	90	40	3.5	8.5	✓
4	100	40	14	7.5	×
5	125	40	20	6	×
6	90	30	3	8	✓
7	90	50	3	9	✓
8	90	60	13	9	×

tion hammer. (In this study, the goal of compaction is to achieve the soil density at the project site).

A hose connected to the water reservoir was attached to the soil chamber to reach a specific water height and maintain it constant (the water height is higher than the soil height inside the soil chamber). After adding sodium silicate to the grout, the pressure valve to the grout chamber was opened, followed by the opening of the outlet valve of the grout reservoir to inject the grout from the grout chamber to the soil chamber under applied pressure from the compressor. Finally, the height of the injected grout inside the soil chamber was measured. Then, the cover of the soil chamber was opened, and after emptying the grout from the chamber, the soil sample inside the chamber was extracted and its height was measured to examine the grout penetration into the soil sample. Lastly, the variations in the height of the injected grout and the soil sample inside the chamber were recorded for all eight mixing designs.

3.1. First Stage (Injection Pressure Equivalent to 2 bars)

As mentioned in the previous section, the grouting experiment with the laboratory injection system was conducted for eight mixing designs in the first stage, with an applied injection pressure equivalent to 2 bars. Additionally, this experiment was repeated for designs 3 and 1 with the same injection pressure, and the results were recorded. **Figure 4** presents the results obtained from the experiment with an injection pressure of 2 bars for the selected eight mixing designs with different bentonite and sodium silicate values.

The results regarding the height of the injected grout and the extracted soil sample for the selected eight mixing designs are presented in **Table 2**. The results of the injection experiment to examine the effect of bentonite and sodium silicate on the height of the injected grout and the extracted soil sample from the injection chamber are shown in **Figures 5** and **6**.

Mixing Design 1 (Control, 50 kg Sodium Silicate, 40 kg Bentonite): the grout penetration was minimal, with only 2 cm of grout injected into the soil, while the extracted soil sample height was 7 cm. This indicates limited grout movement and minimal interaction with the soil. Mixing Design 3 (90 kg Sodium Silicate, 40 kg Bentonite): grout penetration increased to 3.5 cm in the soil chamber, with the extracted soil sample height being 8.5 cm. This represents moderate grout penetration, suggesting that increasing sodium silicate improves grout stability but also reduces penetration due to the increased viscosity. Mixing Design 8 (90 kg Sodium Silicate, 60 kg Bentonite): this design exhibited the highest grout penetration, with 13 cm of grout in the soil chamber and 9 cm of soil sample height. This shows a significant improvement in the grout's ability to resist washout, likely due to the combined effects of sodium silicate and bentonite increasing the grout's viscosity and stability.

Based on the presented results in the graphs and table, increasing bentonite and sodium silicate; permeability is observable. It was observed during these experiments that as the amount of bentonite and sodium silicate in the injected grout composition increases, the height of the grout within the soil chamber after injection also increases, indicating that the grout does not penetrate the soil sample. However, in this regard, the effect of sodium silicate is significantly greater than the effect of bentonite.

The results show that as the amount of bentonite increases, the permeability in the soil decreases, but it does not mean that no injection occurs (except for very high amounts of bentonite where no injection may occur). However, unlike bentonite, with the increase in sodium silicate, no penetration is observed in the soil sample. Instead, the grout remains in a gel-like state on the soil.

As the graph showed in **Figure 5**, increasing bentonite from 50 to 60 kilograms results in a quadruple increase in the height of the grout inside the injection chamber. This indicates the lack of grout penetration into the soil due to the increase in fine particles in the

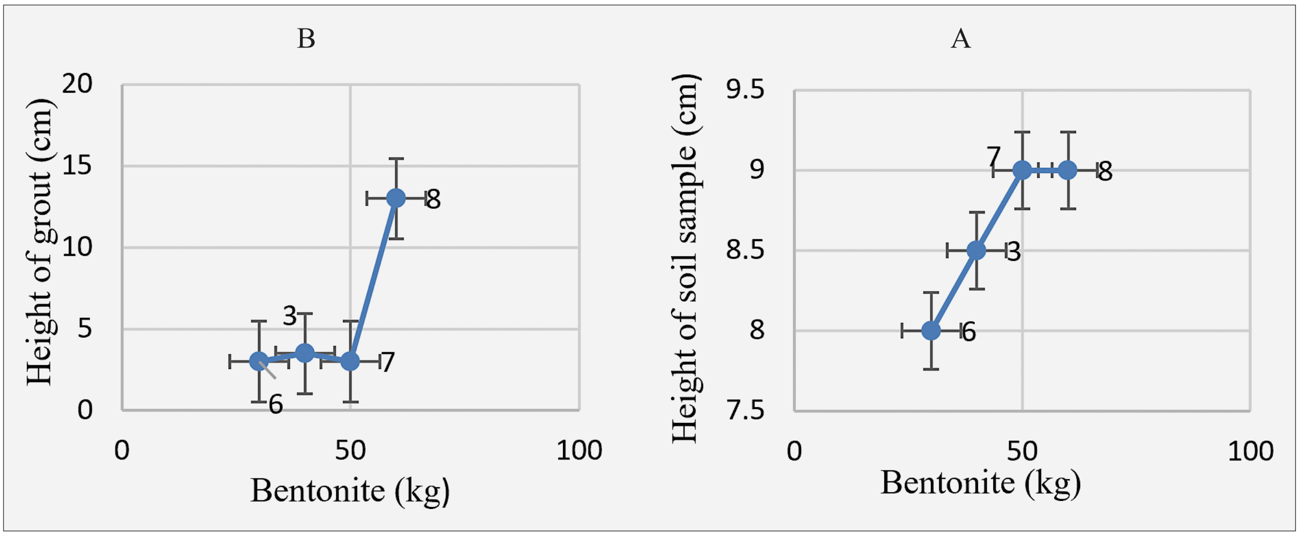

Figure 5. The effect of bentonite on: A) The height of the soil sample extracted from the soil chamber; B) The height of the grout inside the soil sample after injection.

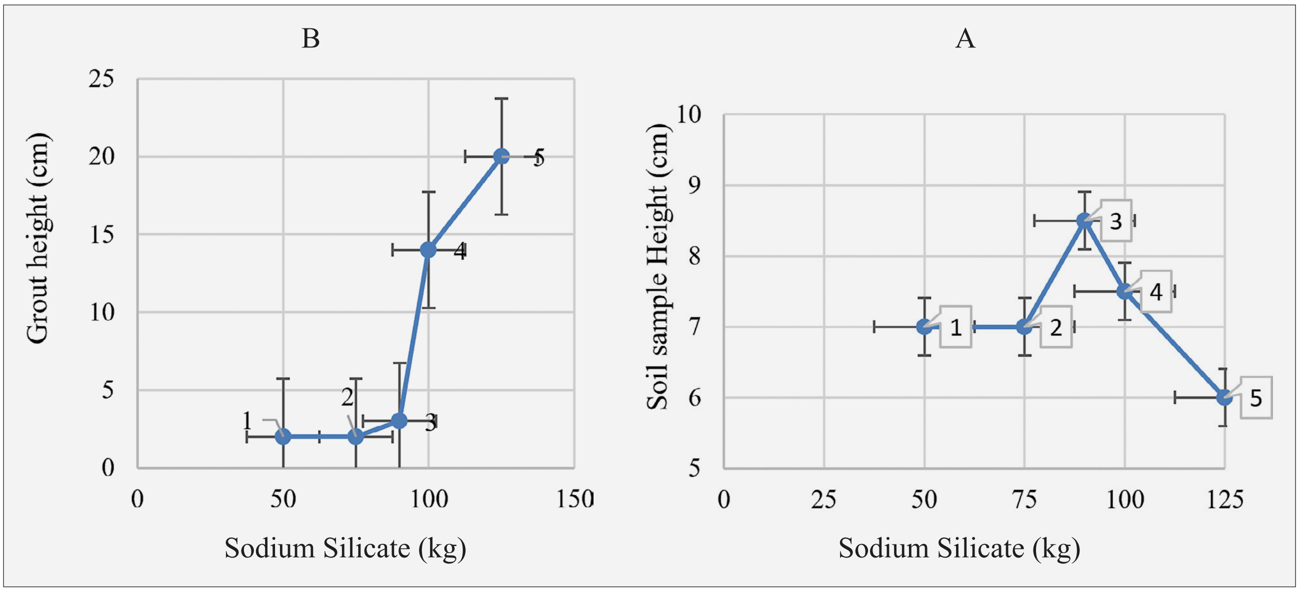

Figure 6. Sodium Silicate effects on: A) The height of the soil sample extracted from the soil chamber; B) The height of the grout inside the soil sample after injection (on each chart, the number of the mixing design is mentioned).

grout and the reduced flushing of the grout with flowing water. Furthermore, with an increase in sodium silicate from 90 to 100 and 125 kilograms, the height of the grout shows a significant six-fold increase. This is also due to the quick-setting property of sodium silicate and the lack of grout flushing with flowing water.

3.2. Second Stage (Injection Pressure Equivalent to 1 bar)

In this stage, the grout penetration experiment using the laboratory injection system was conducted with a modified injection pressure equivalent to 1 bar for mixing designs 3, 1, and 8. The collected data for these three mixing designs were compared with the previous data obtained under a pressure of 2 bars. The results of the experiment with the three mixing designs and the injection pressure equivalent to 1 bar are presented in **Figure 7**.

Mixing Design 1 (Control): no grout penetration was observed; the grout remained on the soil surface or was flushed out due to low pressure. Mixing Design 3 (90 kg Sodium Silicate): similar to the control, no grout penetration occurred. The grout remained stationary on the surface and experienced some flushing due to water flow. Mixing Design 8 (90 kg Sodium Silicate, 60 kg Bentonite): despite the high viscosity of this grout, no significant penetration occurred. The grout was displaced by water flow, confirming the importance of injection pressure for grout mobility.

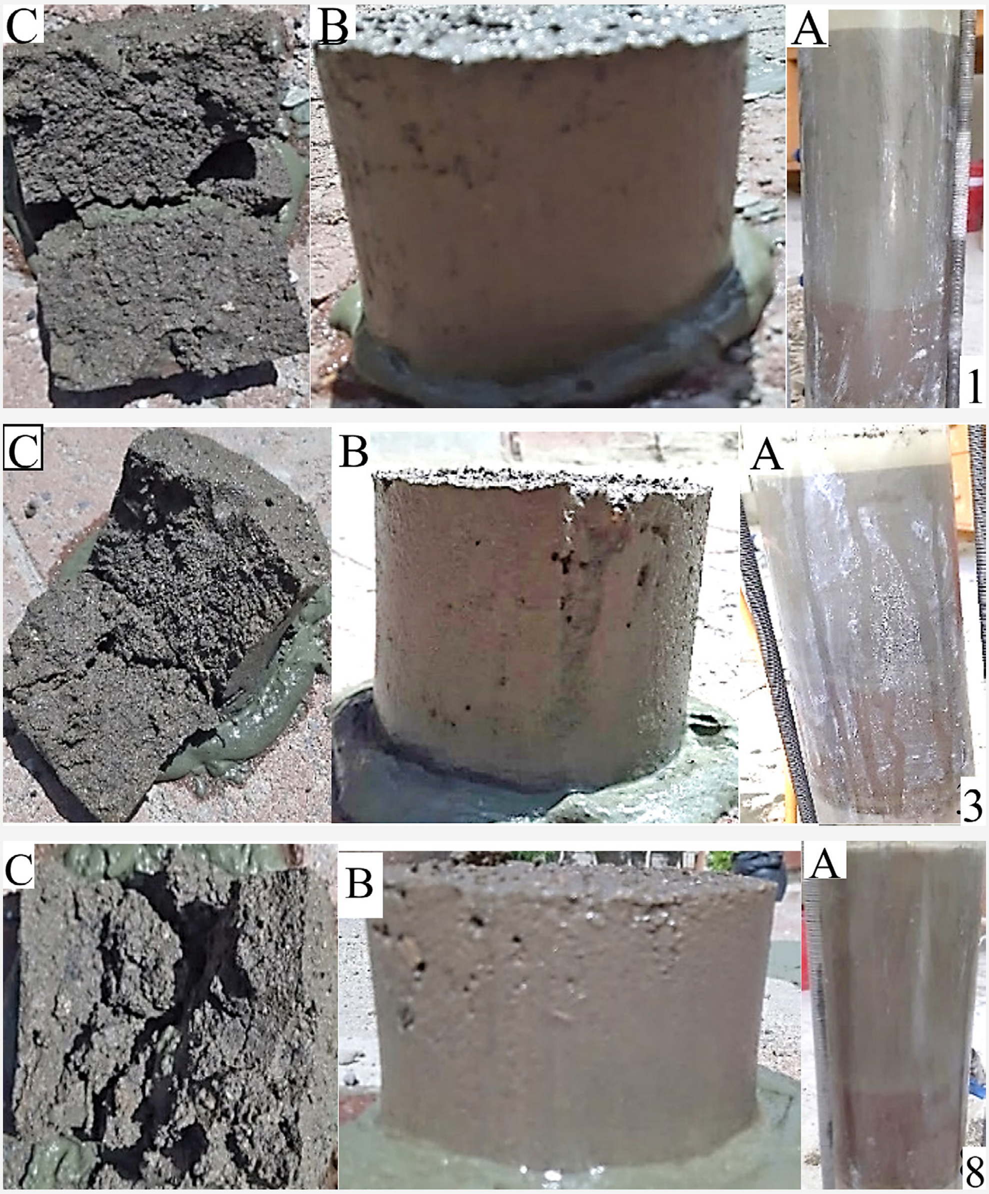

Figure 7. From the right side: A) Soil chamber after injection; B) Soil sample extracted from the soil chamber; C) Broken sample for penetration assessment (1 bar injection pressure).

The tests conducted with the pressure of 1 bar indicate that the injection pressure has an important effect on grout penetration to the soil. Under the injection pressure equivalent to 1 bar, no permeability was observed in any of the three tested mixing designs. Instead, all the injected grout remained on the soil surface or experienced flushing by flowing water.

Increasing the content of sodium silicate and bentonite, the viscosity of the grout increased, leading to rapid gelation and reduced final setting time (increasing the viscosity of the grout leads to a reduction in its dilution with groundwater, resulting in less washing out). As a result, the grout flushing due to flowing water decreased under both injection pressures (equivalent to 1 and 2 bars). Conversely, reducing the content of these two materials resulted in grout dilution and increased flushing due to the influence of flowing water. Sodium silicate's rapid-setting properties reduce grout penetration into the surrounding soil, especially under water flow conditions, thereby minimizing the risk of washout. This makes it particularly valuable in mechanized tunnelling projects below the water table, where washout can compromise structural stability and lead to costly secondary grouting. The obtained results for the selected three mixing designs under different pressures are presented in **Figure 8**.

This study was conducted under the provided conditions and with the introduced materials and tools. In this

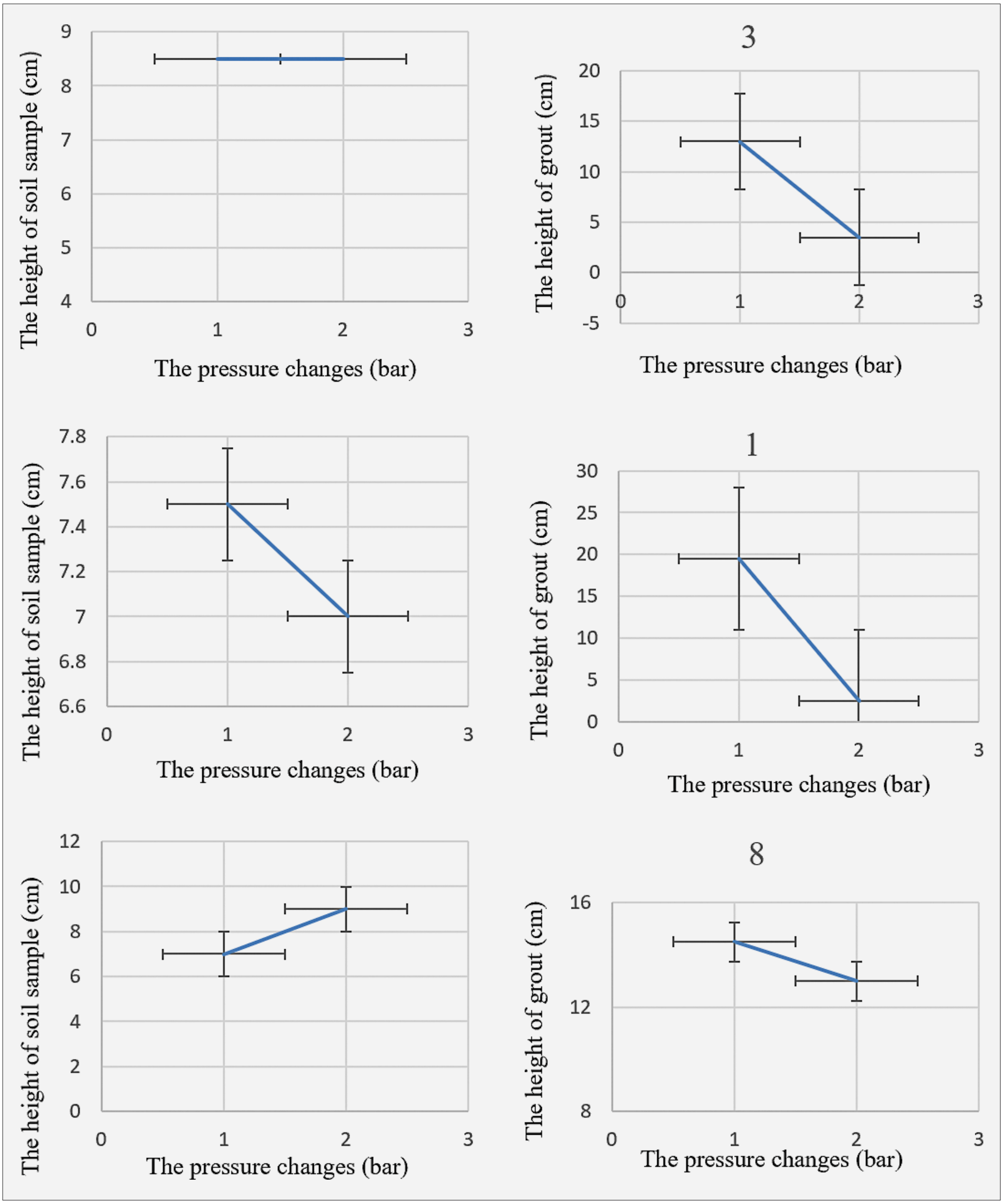

Figure 8. The changes in the height of grout and soil sample by decreasing the injection pressure for 3 Mixing designs.

research, soil from the project site was used, and the results may vary in other types of soil and conditions. Therefore, the limitations of the study include the mentioned factors. To expand knowledge and advance future studies and research, various types of soil with different classifications and other environmental factors can be utilized.

The results from both injection pressures highlight key insight regarding the behaviour of two-component grout in tunnelling applications. These findings are analyzed below, with justifications provided for the observed trends.

- **Effect of Sodium Silicate on Grout Performance**

Sodium silicate played a central role in influencing grout behaviour. As the amount of sodium silicate increased from 50 kg to 100 kg, the viscosity of the grout also increased, resulting in reduced grout penetration into the soil. The rapid-setting properties of sodium silicate cause the grout to gel quickly, which impedes its ability to flow into the surrounding soil and fill voids effectively. At 2 bars, the increased viscosity of the grout mixtures with higher sodium silicate content led to the grout remaining predominantly in the soil chamber without substantial penetration. For example, Mixing Design 8, which contained 90 kg sodium silicate, exhibited the highest resistance to washout, with 13 cm of grout remaining in the chamber. However, the corresponding soil sample height was only 9 cm, indicating limited penetration. This aligns with previous studies, such as **Sharghi et al. (2017)**, who found that higher sodium silicate content improved grout stability and resistance to washout but also reduced grout infiltration. The rapid setting of sodium silicate is a double-edged sword: while it helps prevent washout by quickly forming a stable gel, it also limits grout penetration, which can be problematic in tunnels requiring full void filling and soil stabilization. In practice, this means that while sodium silicate-based grout may be ideal for resisting washout under high water pressure, it may struggle to provide sufficient coverage in terms of filling voids behind tunnel segments.

- **Effect of Bentonite on Grout Behaviour**

Bentonite had a secondary but notable effect on grout penetration and resistance to washout. The addition of bentonite increased the grout's viscosity, making it less likely to flow into the soil, particularly in the presence of water flow. At 2 bars, the grout mixture with 60 kg of bentonite (Mixing Design 8) exhibited significantly less penetration, as the grout became thicker and less able to infiltrate the soil. This finding is consistent with **Yang et al. (2019)**, who demonstrated that bentonite, by increasing grout viscosity, can reduce the permeability of grout, enhancing washout resistance but also hindering its ability to penetrate the soil. Bentonite's effect is more pronounced in high-viscosity grouts. While it contributed to the washout resistance of the grout, it did so at the cost of grout mobility. Therefore, while bentonite is beneficial in preventing grout from being washed away by water flow, it must be used in a controlled manner to balance washout resistance with sufficient grout penetration.

- **Effect of Injection Pressure**

The injection pressure was a critical factor influencing grout penetration and performance. At 2 bars, higher injection pressures allowed for greater grout penetration, although the viscosity of the grout mixtures (influenced by sodium silicate and bentonite content) reduced the depth of penetration. In contrast, at 1 bar, even the low-viscosity grout (Design 1) failed to penetrate the soil, and all grout was displaced by water flow. The results highlight the importance of optimizing injection pressure based on grout composition. At lower pressures, particularly for high-viscosity grouts, grout penetration is significantly hindered. This suggests that in tunnel boring operations, especially in water-bearing conditions, a higher injection pressure may be necessary to ensure effective grout penetration, particularly when using grouts with higher sodium silicate content. In real-world tunnelling applications, where pressure variations can occur due to changes in water table levels and soil conditions, these findings emphasize the need for precise control over both grout composition and injection pressure. Grouts with higher sodium silicate and bentonite content may require higher injection pressures to ensure that the grout adequately fills the voids behind tunnel segments. This finding is consistent with the results of **Jorne & Henriques (2016)**, who demonstrated that higher injection pressures can improve grout flow but that grout viscosity must also be considered when determining the optimal injection pressure.

- **Practical Implications for Tunnel Boring Machines (TBMs)**

These findings have important implications for mechanized tunnelling projects, particularly those involving tunnel boring machines (TBMs) operating below the water table. The study shows that two-component grout mixtures with higher sodium silicate and bentonite content provide superior washout resistance, but at the expense of grout penetration. For TBM operations, this could mean that grout formulations need to be carefully balanced to achieve both effective void filling and washout resistance. In situations where washout is a primary concern (e.g. in water-saturated soils), grout mixtures with higher sodium silicate content may be preferable, but this needs to be coupled with an appropriately high injection pressure to ensure adequate soil stabilization. Conversely, in tunnels where full void filling and soil penetration are the primary objectives, grout compositions with moderate sodium silicate and bentonite content might be preferred, as these will allow for better flow and infiltration into the surrounding soil.

Compared to previous studies, our findings provide a deeper understanding of the interplay between sodium silicate, bentonite, and injection pressure in determining grout performance. For instance, **Sharghi et al. (2017)** found that increasing sodium silicate improved grout stability but at the expense of reduced fluidity. Similarly, **Rahmati et al. (2022)** reported that increasing bentonite content reduced grout permeability but also led to decreased pumpability. Our study corroborates these findings while providing additional insight into how water flow conditions further complicate grout performance, especially in coarse-grained soils below the water table.

While this study provides valuable insight into the performance of two-component grout in mechanized tunnelling, several areas remain where further research can extend or build upon these findings. Below are some potential avenues for future studies: exploration of grout composition variability, effects of soil type and composition, long-term grout behaviour under cyclic loading, field-scale testing and validation, grout injection under varying water flow conditions, environmental impact of grout additives and optimization of injection technology and techniques.

4. Conclusions

Injection behind the segments is a significant factor in controlling ground surface settlement and reducing permeability around the tunnel in mechanized excavation in coarse-grained environments below the water table. The failure of the brush in the equipment can lead to grout washout, which may cause ground surface settlement and structural damage. This study investigated the impact of increasing bentonite and sodium silicate to prevent grout washout and enhance the performance of injected grout in water-bearing environments. The experiments were conducted at injection pressures of one and two bars to analyze the effectiveness of different grout compositions.

Increasing the sodium silicate content significantly improves grout washout resistance but reduces penetration due to higher viscosity and rapid setting time. Bentonite contributes to viscosity and enhances resistance to grout flushing, but excessive amounts hinder grout penetration into the soil. The combination of sodium silicate and bentonite plays a crucial role in balancing stability and penetration for effective grout performance.

Injection pressure is a key parameter influencing grout penetration. At lower pressures of one bar, grout penetration was minimal, and washout resistance was reduced. Higher injection pressures of two bars improved grout penetration, but the extent was still affected by the viscosity resulting from sodium silicate and bentonite content. Proper pressure control is essential to optimize grout penetration while preventing excessive dilution in water-bearing environments.

The findings emphasize the importance of grout composition and injection pressure in achieving effective void filling behind tunnel segments. In projects with high water inflow, grout mixtures with increased sodium silicate and bentonite content provide better stability and washout resistance. Optimizing injection pressure is necessary to ensure effective grout penetration and minimize the need for secondary grouting, which can increase project costs.

Considering the height of the remaining grout in the injection chamber after conducting the grout penetration test and simulating water table flow during the injection process, the most resistant designs against washout were identified. Design 5, which included 125 kilograms of sodium silicate, Design 4, with 100 kilograms of sodium silicate, and Design 8, with 60 kilograms of bentonite, exhibited the highest resistance to washout. These findings provide valuable insight for optimizing grout formulations and injection parameters in mechanized tunnelling under challenging water-bearing conditions.

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SAŽETAK

Laboratorijsko ispitivanje učinkovitosti dvokomponentne smjese za injektiranje iza segmenta tunela u pjeskovitim tlima ispod razine podzemne vode

Sve veća uporaba TBM-a u urbanim područjima povećala je važnost injektiranja iza tunelskih segmenata. Ključni koncept strojnoga iskopa tunela jest primjena smjese za injektiranje iza segmenata tunela (potporni sustav) kako bi se spriječilo slijeganje tla. Cilj je ove studije istražiti veličinu ispiranja dvokomponentne smjese iza segmenata tunela. Ova studija također simulira prisutnost protoka vode u laboratorijskim testovima, što je razlikuje od drugih sličnih studija. Problemi kao što su curenje podzemne vode i ispiranje smjese iza segmenata tunela, posebice kada postoje nedostatci na četki za brtvljenje (uzrokovani raznim čimbenicima kao što su smanjena debljina dodira zbog trenja o segmentni prsten, neusklađenost štita zbog nepravilnoga sastavljanja ili oštećenja zglobnih potiskivača), mogu dovesti do nepotpunoga ispunjavanja prostora i uzrokovati površinsko slijeganje. Zbog toga je iznimno važno odabrati odgovarajuću smjesu za injektiranje u tim uvjetima. Studija provodi procjenu injektiranja dvokomponentne smjese s različitim količinama bentonita i natrijeva silikata. Simulirani su različiti pritisci injektiranja i vodonosni uvjeti kako bi se procijenilo prodiranje smjese u krupnozrnata tla. Ispitivanja injektiranja smjese za injektiranje pri tlaku od 1 i 2 bara pokazala su da povećanje sadržaja bentonita i natrijeva silikata u smjesi za injektiranje ne samo da smanjuje prodiranje u tlo, već i pomaže u sprječavanju ispiranja smjese uslijed protoka vode. Osim toga, važno je napomenuti da natrijev silikat ima veći učinak na spomenute procese od bentonita.

Ključne riječi:
strojno iskopavanje, ispiranje, brtvena četka, dvokomponentna injektirajuća smjesa, tlak injektiranja

Author's contribution

Samaneh Khodaei (PhD candidate of Mining Engineering) provided the paper and presentation of the results. **Erfan Khoshzaher** (PhD candidate of Mining Engineering) provided and wrote the paper. **Hamid Chakeri** (PhD, Associate Professor) proposed the idea and guided the research. **Shahla Miri Darmarani** (MSc graduate of Mining Engineering) proposed the idea and guided the research.
All authors have read and agreed to the published version of the manuscript.