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The Effect of Soil and Grout Mixture on the Ground Surface Settlement in Mechanized Excavation

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Abstract

Excavation with Tunnel Boring Machine (TBM) in urban environments can have risks, such as ground surface settlement. The empty space between the cutterhead and the segment should be filled with suitable grout during the excavation. Nowadays, using grout behind the segment and other fillers fill the empty space behind the segment and reduce the amount of ground surface settlement. Undoubtedly, using a grout with appropriate mechanical behavior can be a suitable substitute for excavated soil in mechanized tunneling. In this research, the mechanical behavior of the grout behind the segment during injection into the space between the soil and the segment and its mixture with the soil is studied. Also, the effect of mechanical properties of grout mixed with soil on the ground surface settlement is investigated using numerical modeling. The components of two-component grout of this study comprises Sufian type 2 cement with 28-day strength of 44 MPa and density of 3050 kg/m3, Salafchegan bentonite with density of 2132 kg/m3 and precipitator of liquid sodium silicate with density of the solution 1500 kg/m3. The results of the laboratory studies indicated that mixing the grout and soil increases the mechanical properties of grout significantly. Increasing the soil in the mixture of soil and grout up to 40% increases the uniaxial compressive strength up to 300%, the elasticity of modulus up to 156% and the cohesion of the mixture up to 100%. On the other hand, based on the results of numerical modeling, the proper injection pressure can significantly reduce the ground surface settlement. Increasing the injection pressure from 0 to 120 kPa has a 17% influence on the reduction of ground surface settlement.

1. Introduction

Nowadays, tunneling in urban environments is essential due to the extensive progress of urbanization. Tunnels excavated in urban environments are often placed at a shallow depth. Using the full-section boring methods with the EPB (earth pressure balance) machine in this type of ground has been progressively increased. Although using EPB has reduced the risk of ground surface settlement during tunnel excavation, ground surface settlement is still one of the significant risks in excavating with this type of machines. One of the most important parameters on ground surface settlement is the empty space behind the segment caused by the over-excavation of the cutterhead and the shield. This empty space should be filled with a suitable filler, which is mainly the injection grout. Improving the mechanical behavior of grout and its mixture with soil in this space could significantly reduce settlement risks. Most of the utilized grouts are cement-based because cement is readily available and cheap. Two-component grouts are increasingly used worldwide due to their many advantages and good compatibility with different types of soils. Quick hardening in these grouts reduces the settlement risk [1, 2].

Two-component grout comprises components A and B, pumped separately through separate pipes

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and mixed at the injection point. Component A is a cement mortar designed to be chemically and physically stable. This component usually comprises cement, water, bentonite, and retardant/plasticizer. Component B is an accelerator mixture added to component A just a few centimeters before the grout injection nozzle. Component B is usually made up of sodium silicate solution [2]. The two-component grout has a short gelation time and high initial strength and is generally used in water-rich layers. Nevertheless, producing this type of grout requires more advanced injection equipment. Hence, this type of grout's complex manufacturing and its preparation technology limits its wide application [3].

Various researchers have studied grout and its properties in mechanized excavation [4-10]. Anagnostopoulos [11] investigated the use of water-soluble polymers to improve the physical and mechanical properties of granular soil. The grouts were prepared using different percentages of cement, clay, and water, along with the amount of acrylic resin or methyl methacrylate copolymer emulsion. The experimental results show that adding latex to the thick pure cementous grout significantly enhances the physical and mechanical properties of the injected soil. Generally, Latex Modified Mortar (LMM) and Latex Modified Concrete (LMC) show a significant reduction in water absorption and water permeability due to the formation of polymer membranes or films that fill or seal the larger pores. In general, it can be concluded that combining such materials with cement for injection purposes and according to the W/C ratio significantly helps to improve the properties of the injected soil. Flores [12] and Todaro [13] stated in their research that the mechanical properties of the two-component grout change according to the type of mix design. Sharghi et al. [14] examined the effect of the two-component grout ingredients on different parameters. They showed that the main characteristics of grout depend on bleeding, fluidity, and the marsh funnel test results (grout pumping capability), set time, gelation time, and the grout compressive strength. When the bleeding is less, the grout mixture becomes more homogeneous, and the possible sedimentation of solids in the transfer path reduces. As a result, the risk of clogging of the grout pipes used for transportation will be less. One of the most important reasons for adding bentonite to the grout is to reduce the bleeding and maintain the grout's homogeneity.

Todaro et al. [15] conducted laboratory experiments focusing on shear strength. The short and long-term curing times were performed under drained conditions according to the direct shear test. The Mohr-Coulomb failure envelope model was chosen for this study. The results indicated that the direct shear test is not a correct test method for 1 hour of curing. According to the obtained results, the only method that can provide a reliable value for the shear strength is the undrained method. Oggeri et al. [16] conducted a detailed study of filler percentage's effect on the support system's behavior (lining and filler) using the convergence-adjacency analytical method and the Einstein-Schwartz method. In this research, a composite design of two-component grout was analyzed in detail. The unconfined compressive strength (UCS) and the oedometer tests were investigated at different curing ages. It can be recognized from this study that filler material has a significant effect on the stiffness of the support system in the convergence-adjacency method and, therefore, on the load imposed on the segmental lining. Alternatively, the filler material has reduced negligible effects on the overall stiffness of the support system in the Einstein-Schwartz method, which was used to implement the first segmental lining design.

Rahmati et al. [17] conducted laboratory experiments to examine the characteristics of two-component grout, such as flowability, bleeding, gelation time, and uniaxial compressive strength. The effect of lateral pressure on grout strength was studied according to the actual excavation conditions. The impacts of grout compositions and effective parameters such as bentonite and cement, water-cement ratio, accelerator amount (sodium silicate), and accelerator ratio were also investigated. The results indicated that increasing bentonite and cement leads to an increase in the marsh funnel time and, thus, a decrease in the flowability of grout. The w/c ratio had a direct relationship with the flowability of the grout. Increasing the bentonite and decreasing the w/c ratio decreased the bleeding of fresh grout. Increasing the amount of cement and sodium silicate (accelerator) and reducing the w/c ratio increased the amount of UCS. Bentonite also increased the short-term compressive strength but decreased it in the long term. Gelation time has a direct relationship with the amount of sodium silicate and an inverse relationship with its ratio (silicon dioxide/ silicon oxide). Increasing the dose of sodium silicate increased the gelation time. Decreasing the sodium silicate ratio increased the gelation time. The modulus of elasticity decreased with the increase of the w/c ratio. The final strength of grout increases with the increase of lateral pressure.

Fu et al. [18] investigated effects of transversely isotropic layers on failure mechanism of non-homogeny concrete-soil specimens. The results of their research showed that transversely isotropic layers can have an important effect on the behavior of non-homogeny concrete-soil samples, and changes in the properties of the layers can affect the failure mechanisms of concrete-soil structures. Sarfarazi et al. [19] modeled unreinforced and geogrid-reinforced soil foundations under surface strip footing loads by discrete element method. They investigated the effects of geogrid position, thickness, number and confining pressure on footing settlement. They also analyzed the interaction between the tunnel and the strip footing. The results showed that the use of geogrid can lead to an improvement in the performance of the strip footing. Fu et al. [20] studied deformation behavior of circular underground opening in hard soil using a 3D physical model and investigated the settlement of the tunnel due to excavation and surface loading in dense and loose soils. They showed that the highest amount of settlement occurs in the upper and adjacent layers of the tunnel arch.

Liu et al. [21] designed a new laboratory device to investigate grouts' deformation mechanism according to the injection material's behavior. The purpose of the laboratory tests was to visually analyze the grouting material's behavior and explore the grout stabilization mechanism caused by different proportions of grouts and earth pressure. The results showed that the grout strain increases nonlinearly with time while the increase rate decreases reversely. Higher earth pressure resulted in a more considerable ultimate strain (ε_0) for the same grout. The grout strain in low-permeability silt was smaller than in high-permeability sand. Barri et al. [22] investigated the risks of excavation in urban environments and the risks of improper injection in mechanized EPB excavation on the surface settlement of the ground. Experimental tests were performed with different grout injection pressures and the effect of grout pressure was investigated using physical modelling. The results of this study showed that a double increase in grout injection pressure causes a 30% increase in grout penetration depth.

In this study, the mixing of the grout with the soil around the tunnel and its effect on the mechanical properties of the grout and the settlement of the ground surface is investigated. For this purpose, at first, the effect of increasing the soil percentage on the mechanical properties of the grout is investigated by laboratory tests. Then, the impact of this mixture on the ground surface settlement is investigated by numerical modeling.

2. Introducing Tabriz Metro Line 2

Since the soil used in this research was prepared from Tabriz metro Line 2, it is briefly introduced. Tabriz metro Line 2 starts from the organic fertilizer factory in the west of Tabriz city and, by passing through the city center, ends at the Tabriz International Exhibition located in the Basij Square in the eastern part of the city. This line has 20 stations, and its length is approximately 22.4 km. A depot will be built in the western part of the route, and an underground parking will be constructed in the eastern region. Figure 1 shows general layout of Tabriz metro network.

Based on the studies conducted in this area, fine-grained alluvial and silty sediments have been observed. Among these fine-grained alluvial layers, there are also sandy deposits, but the tunnel route mostly passes through the fine-grained alluvial sediments. Figure 2 shows geology map of Tabriz metro line 2.

The EPB-TBM machine is excavating the route of the western part of line 2 of the Tabriz metro with a diameter of 9.49 m. The tunnel maintenance system is in the form of prefabricated concrete segments. The inner diameter of the tunnel concrete segment is 8.48 m, and the free space behind the segment is 15.5 cm. The grout injection system behind the segments is a two-part grout pumping from outside the tunnel according to the specifications of the TBM machine purchased for excavating line 2 of the Tabriz metro.

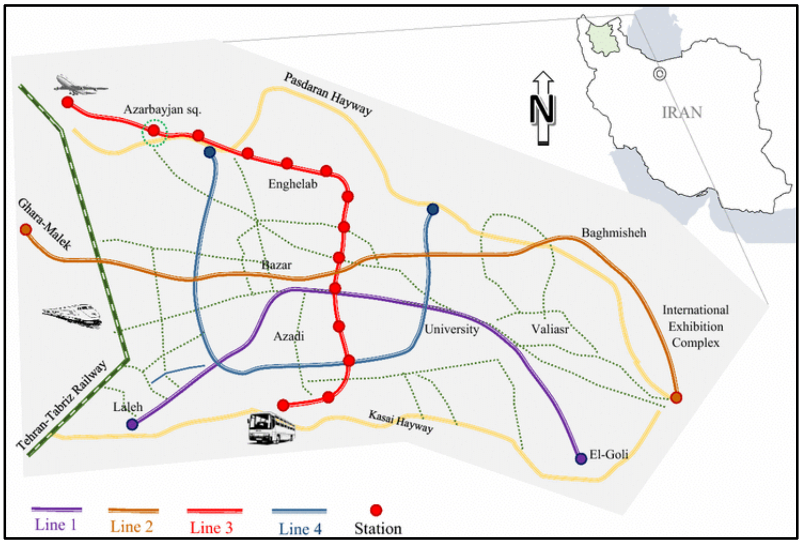


Figure 1. General layout of Tabriz metro network.

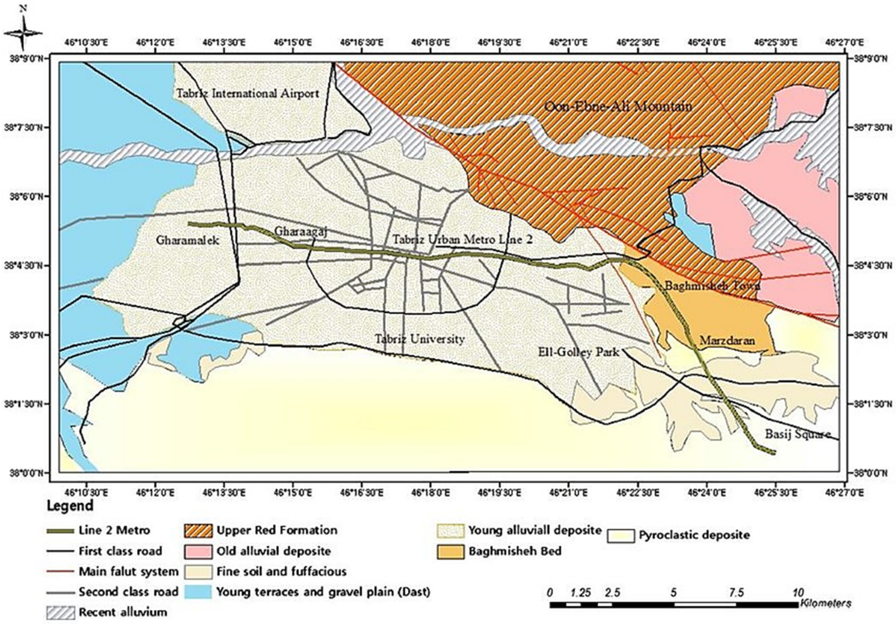


Figure 2. Geology map of Tabriz metro line 2 [23].

3. Laboratory studies

As mentioned earlier, components A and B ingredients include water, bentonite, cement, fillers, and additives. The water is the most essential element in the preparation of cement-based grout. The water used to prepare grouts must be free of organic substances and solid particles. The proper water for this purpose has a clear appearance. According to Kutzner [24], the quality of suitable water for preparing grout is relatively similar to that of drinking water with a bit of ignorance. The water used in this study is the drinking water of Sahand University of Technology.

The very favorable properties created after adding bentonite to the grout are such that it is the second most important ingredient after cement. The presence of these characteristics in the grout is significant, especially in the injection of waterproofing. Bentonite refers to clay minerals that absorb water and swell due to water absorption [24]. The utilized bentonite is an active bentonite brought from Salafchegan with a density of 2132 kg/m^3.

The most widely cement used in grout preparation is ordinary cement, introduced under the name of Portland cement. The most important characteristic of ordinary cement is the fineness and circulation of its particles because it strongly affects its stability, increase in fluidity, and penetration into the joints. Therefore, the functional quality of cement, the suspension water content, and its strength after hardening increases by reducing the dimensions of cement grains. The cement used in this research is Sufian type 2 cement with a density of 3050 kg/m^3.

Fillers increase the volume of grout without causing drastic changes in its properties. Basically, using fillers in grout is considered more as the economic aspect. The price of these materials is cheaper compared to cement and bentonite. Generally, these materials can be divided into three categories: coarse-grained pebbles, fine-grained soils, and miscellaneous materials [24]. This study used the soil of Tabriz metro line 2 (mainly fine-grained) as filler.

Additives are added to the grout to solve one or more specific complications. Additives are mostly chemical substances and compounds, and the amount used is often much less than the previous components [24]. This study used liquid sodium silicate with the brand name SA-161 and the density of the solution 1500 kg/m3 as a precipitator.

3.1. Determining the two-component grout mix design based on bleeding, Marsh funnel and gelation tests

Determining the two-component grout mix design was based on the laboratory results. Therefore, a suitable mix design was selected in the laboratory based on the flow chart presented in Figure 3 for the subsequent experiments. The final mix design was determined by conducting laboratory tests to determine the suitable two-component grout mix design. The considered mix designs and the results regarding their approval or rejection are presented in Table 1.

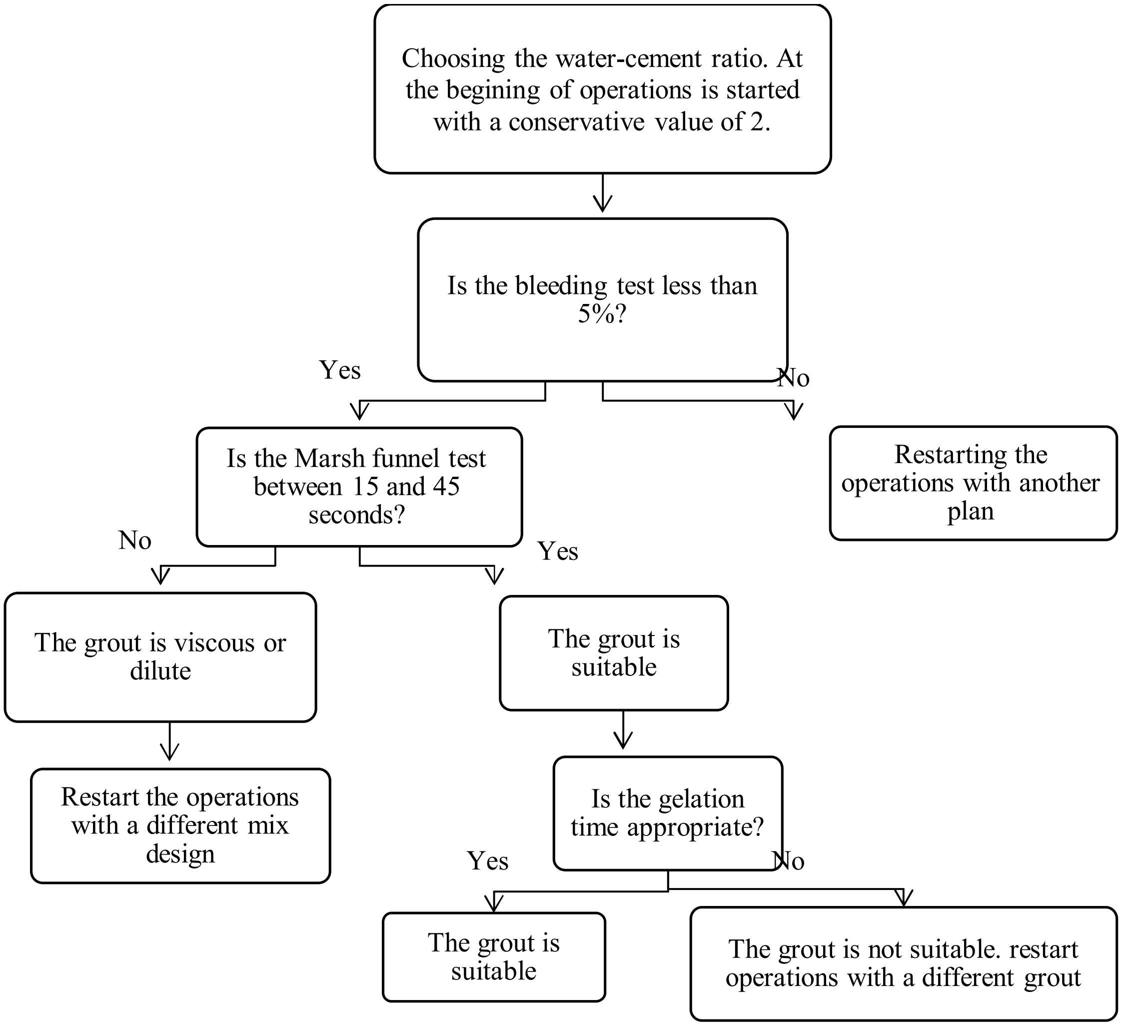


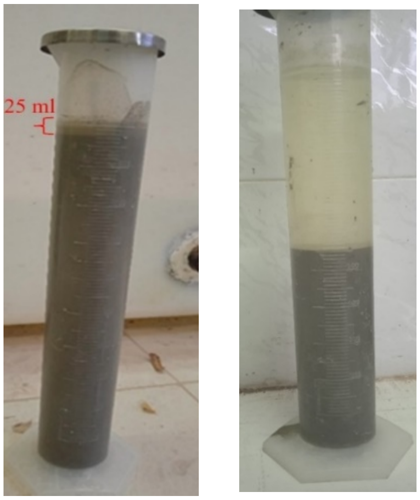
Figure 3. Flowchart of choosing the suitable mix design for grout.

Table 1. Utilized mix designs in the laboratory to determine the suitable mix design.

Design No.	Cement (Kg)	Water (L)	Bentonite (Kg)	Retarder (Kg)	Accelerator (Kg)	SiO_2/Na_2O ratio	W:C
1	360	799	40	0	90	3.1	2.22
2	400	798	15	0	90	3.1	1.98
3	440	770	40	0	90	3.1	2.16
4	400	744	40	0	150	3.1	1.81
5	440	778	40	0	90	3.1	1.76
6	380	816	40	0	50	3.1	2.15
7	400	794	30	0	90	3.1	2.29
8	350	863	40	3.5	90	3.1	2.46
9	350	866	35	3.5	90	3.1	2.47
10	350	868	30	3.5	90	3.1	2.48
11	380	856	35	3.8	90	3.1	2.25
12	380	858	30	3.8	90	3.1	2.25
13	400	852	30	4	9	3.1	2.13
14	425	844	30	4.25	90	3.1	1.98
15	425	846	25	4.25	90	3.1	1.99
16	445	838	28	4.25	90	3.1	1.88
17	445	840	23	4.25	90	3.1	1.88
18	460	836	21	4.6	90	3.1	1.81
19	460	839	16	4.6	90	3.1	1.82

In this research, bentonite is kept in a suitable place for 24 hours at first with a certain amount of water, which causes the bentonite particles bloom and absorb water, and then the required bentonite is mixed with 85% of the mix design water with the help of a high-speed mixer; mixing bentonite with water takes about 30 minutes and is done until the mixture is free of bentonite lumps; then other constituents of the component A of the grout including cement and the rest of water are added and mixed for a few minutes by a high-speed mixer to obtain a uniform grout with high fluidity. Three different specimens were prepared for each experiment at each age.

The standard C940 [25] was applied to perform the bleeding test for the grout. The results of the bleeding test for the two designs are illustrated in Figure 4. The amount of water injection in mix design one, selected as the final mix design in this research, is about 25 mm, equivalent to 2.5%. This amount is within the allowed range based on the standard used. The second mix design with water injection above 5% is unacceptable. Table 2 and Figure 5 shows the bleeding of the investigated designs; those out of the standard range have been eliminated. Mix designs 1, 4, 5, 8-17 are acceptable regarding bleeding, so that the subsequent tests will be performed only on these thirteen designs. The design numbers 2, 3, 6, 7, 18 and 19 are unacceptable, due to more than 5% bleeding, and will be eliminated from the testing process. Figure 6 shows the effect of retarder and water-to-cement ratio on bleeding in different mix designs.



(a) (b)

Figure 4. a) Bleeding of mix design 1, b) Bleeding of mix design 2.

Table 2. Choosing suitable mix design based on bleeding, Marsh funnel and gelation tests.

Design No.	Bleeding (%)	Is the bleeding test less than 5%?	Marsh funnel time (s)	Is the Marsh funnel test between 15 and 45 seconds?	Gelation time (s)	Final status
1	4	Acceptable	36	Acceptable	30	Acceptable
2	25	Rejected				Rejected
3	5.3	Rejected				Rejected
4	3.9	Acceptable	46	Rejected		Rejected
5	3	Acceptable	44	Acceptable	35	Rejected
6	5.4	Rejected				Rejected
7	7	Rejected				Rejected
8	1	Acceptable	42	Acceptable	26	Rejected
9	2	Acceptable	39	Acceptable	20	Rejected
10	2	Acceptable	38	Acceptable	29	Rejected
11	1.7	Acceptable	41	Acceptable	13	Rejected
12	2.6	Acceptable	39	Acceptable	20	Rejected
13	1.8	Acceptable	46	Rejected		Rejected
14	2	Acceptable	49	Rejected		Rejected
15	2.9	Acceptable	43	Acceptable	14	Rejected
16	2.5	Acceptable	52	Rejected		Rejected
17	3	Acceptable	48	Rejected		Rejected
18	5	Rejected				Rejected
19	9.3	Rejected				Rejected

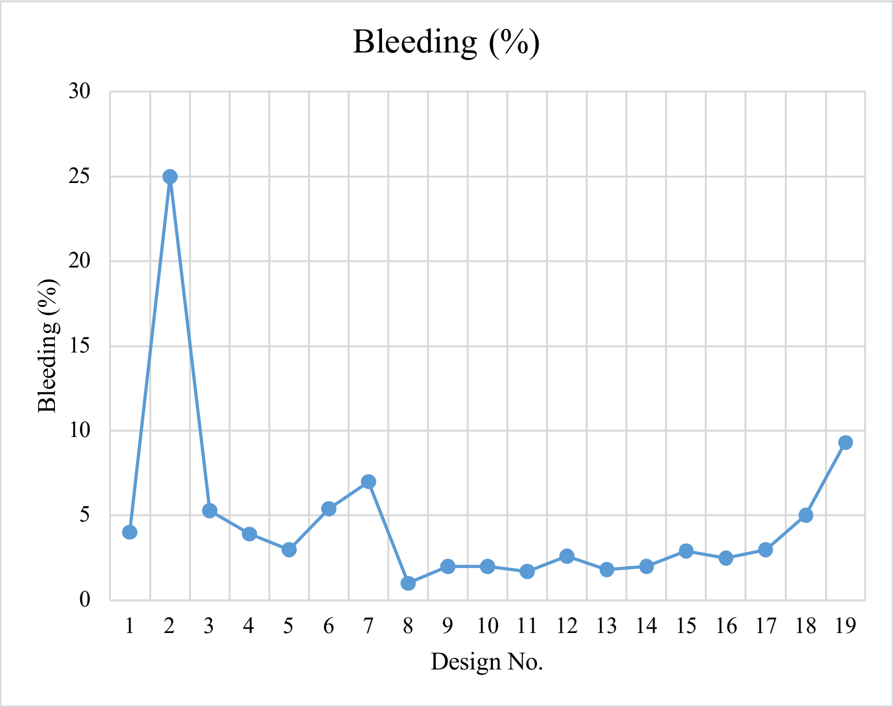


Figure 5. Bleeding of different mix designs.

The next control to be performed is the flowability test. The best method for this test is the Marsh funnel test. Based on the ASTM D6910 [26] standard, the allowed time range for the grout to pass through the Marsh funnel is between 35 and 45 seconds. With the shorter time of the Marsh funnel, the higher flow rate, the grout bleeding increases. This is not suitable from a technical point of view, and on the contrary, with the longer time of the Marsh funnel, the lower flow rate, the bleeding and pumping ability will decrease. Table 2 and Figure 7 shows the flow time for different mix designs. As can be seen, design numbers 1, 5, 8-12 and 15 have a flow time between 35 and 45 seconds, but design numbers 4, 13, 14, 16 and 17 will be unacceptable due to having a flow time of more than 45 seconds. Figure 8 shows the effect of retarder and water-to-cement ratio on Marsh funnel time in different mix designs.

The final control to be performed is the gelation time test. Table 2 indicates the gelation time for different mix designs. Based on Tables 1 and 2, design number 1 can be suitable for the subsequent tests (uniaxial strength) due to its lower gelation time, not having a retarder and less cement consumption.

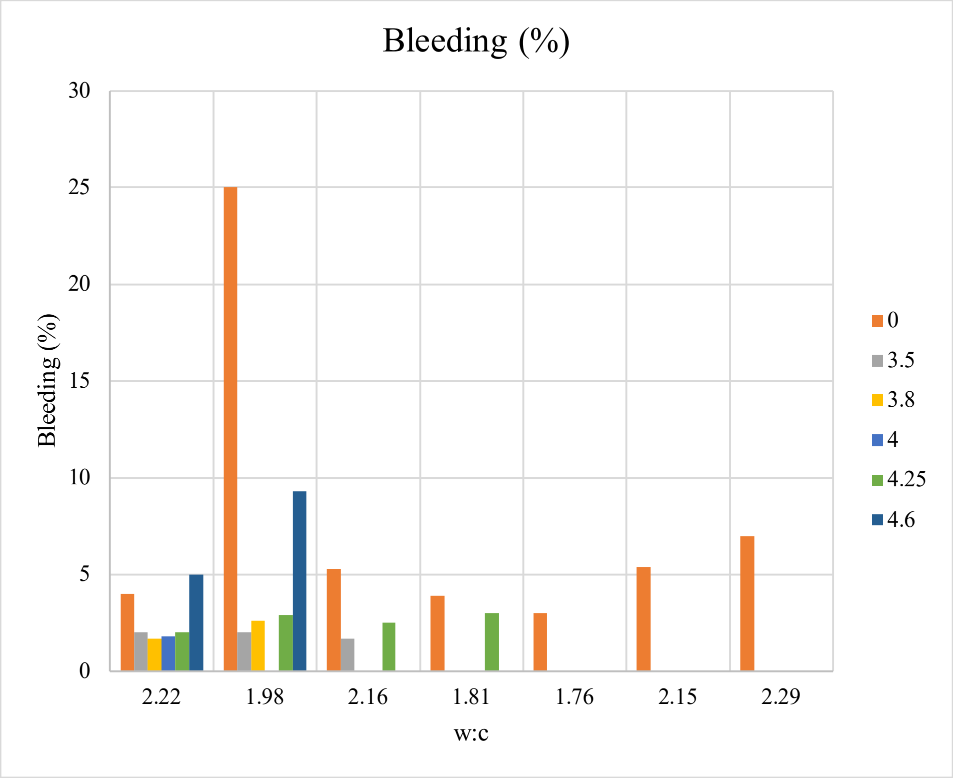


Figure 6. Effect of retarder and water-to-cement ratio on bleeding in different mix designs.

3.2. The effect of soil and grout mixture on the mechanical properties of grout

The initial steps of preparing the specimens to perform the uniaxial compressive strength test are the same as the gelation time test, with the only difference that after a few seconds of mixing the two components of grout and ensuring the correct and homogeneous mixing, the mixture is immediately placed in a cylindrical mold with a length to diameter ratio of 2 (ASTM C109 [27]). The excess material is smoothed on the specimens. Then, the specimens are covered to prevent evaporation. The specimens are tested 2, 4, and 24 hours after being taken out of the mold, but the 7 and 28-day specimens are taken out of the mold after 24 hours and placed in the concrete curing basins. The compressive strength is measured in two different ways according to the characteristics, age, and curing of specimens:

- Short-term (initial hours): in less than 24 hours or strength below 1 MPa.
- Long-term: for times longer than 24 hours or strength greater than 1 MPa.

The specimens evaluated for compressive strength include 2-hour, 24-hour, 1-day, 7-day, and 28-day specimens. Three specimens were prepared for each time frame, and a uniaxial test was conducted. The results of compressive strength tests for the mix design number 1 are presented in Table 3. Figure 9 also shows the two-hour specimen after the uniaxial test.

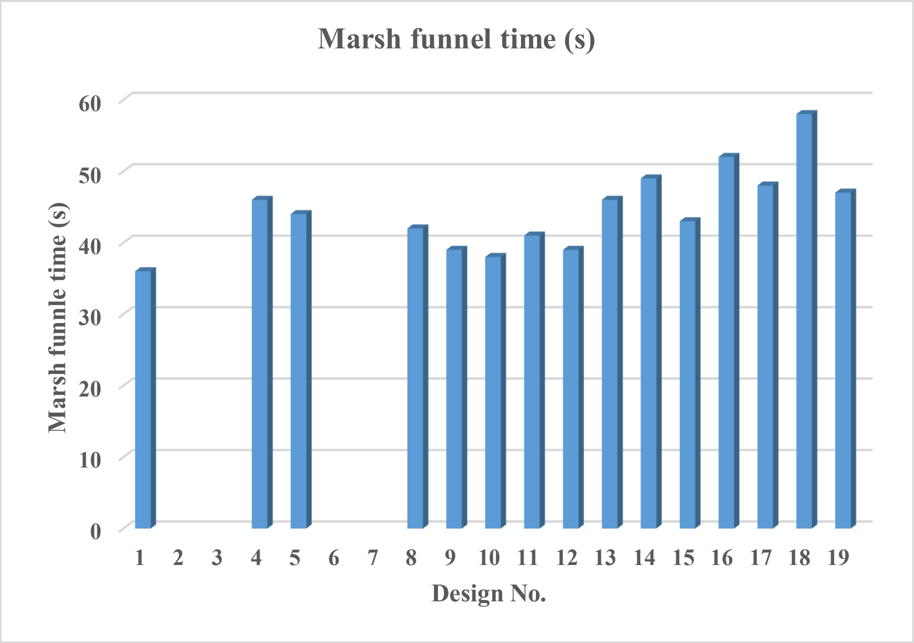


Figure 7. Marsh funnel time for different mix designs.

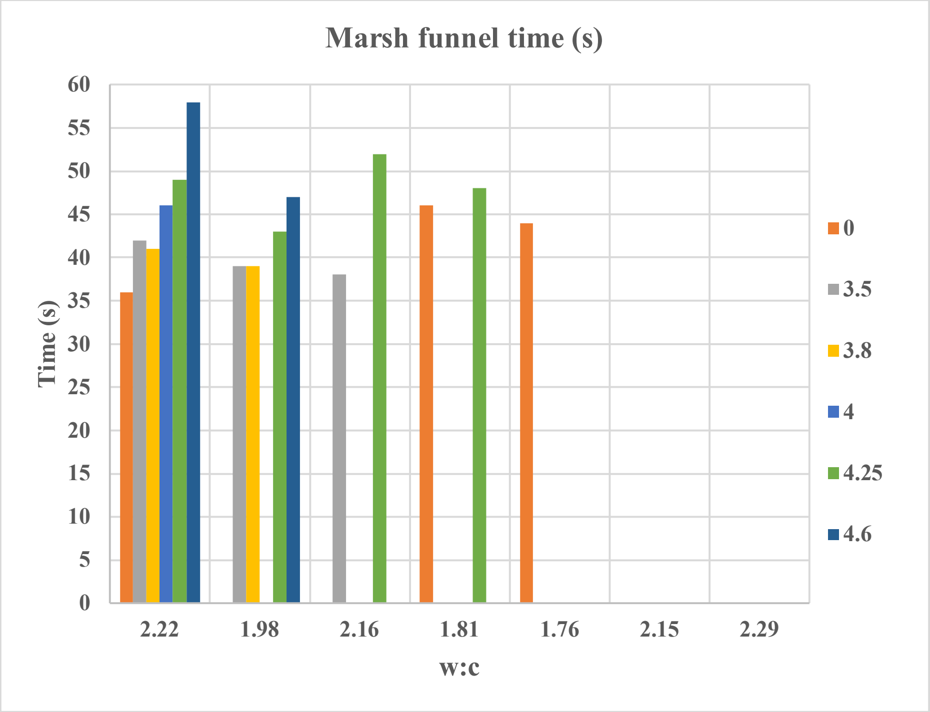


Figure 8. Effect of retarder and water-to-cement ratio on Marsh funnel time in different mix designs.

Table 3. Simple grout strength in different time intervals.

Grout age	2-hour	4-hour	1-day	7-day	28-day
Strength (MPa)	0.02003	0.0595	0.189	0.283	0.3633

Generally, in the studies of grout behind the segment, the strength of grout mixed with soil is investigated. Therefore, the strength of the grout and the grout mixed with soil is investigated in this section to evaluate the effect of these parameters on the amount of ground settlement; for this purpose, the compressive strength test is performed on the mixtures of grout and soil with different percentages. The mix design specifications in various models are prepared and listed in Table 4.

Figure 9. 2-hour specimen for the mix design number 1 after performing the uniaxial test.

Table 4. Utilized mix designs.

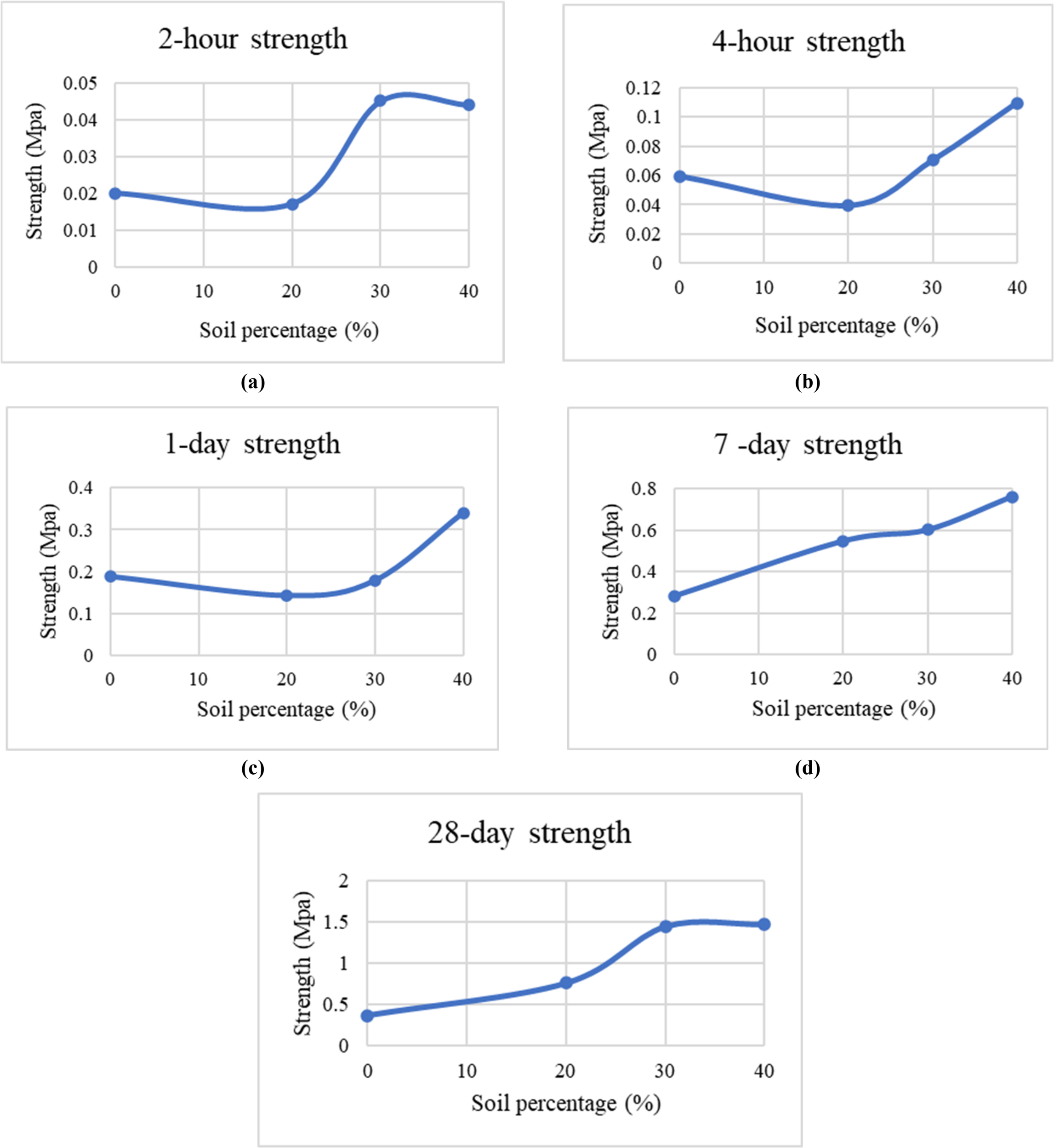
Design No.	Cement (Kg)	Water (L)	Bentonite (Kg)	Accelerator (Kg)	SiO_2/Na_2O ratio	W:C	Soil (%)
1	360	799	40	90	3.1	2.22	20
2	360	799	40	90	3.1	2.22	30
3	360	799	40	90	3.1	2.22	40

As shown in Table 4, the grout has mixed with different percentages of soil (20, 30, and 40 percent) in the mix design number 1 of the previous experiments. In these experiments, it has been tried to investigate the effect of soil on the short-term (early hours) and long-term (28-day) strengths of the grout. The results obtained in the laboratory and the percentage of soils used in the experiments are presented in Table 5. As evident in this table, the weight of the specimens and the uniaxial strength of 1, 7, and 28 days increase with the amount of soil in the grout.

Table 5. Uniaxial compressive strength of different mix designs.

Design No.	The average weight of the specimens in grams and the strength in MPa with varying amounts of soil									
	2-hour		4-hour		1-day		7-day		28-day	
	Weight (gr)	Strength (MPa)	Weight (gr)	Strength (MPa)	Weight (gr)	Strength (MPa)	Weight (gr)	Strength (MPa)	Weight (gr)	Strength (MPa)
1	368.2	0.01245	384.6	0.03964	404.0	0.13110	399.3	0.52860	411.9	0.74330
	380.8	0.01851	395.0	0.04012	403.6	0.14380	385.5	0.54740	408.3	0.73980
	408.1	0.02040	408.6	0.03910	401.1	0.15590	400.0	0.56600	404.8	0.78770
2	433.1	0.04040	430.7	0.06684	433.4	0.17070	424.5	0.59150	459.6	1.41182
	431.2	0.04589	433.0	0.06986	434.5	0.17850	426.0	0.61050	455.2	1.44310
	429.0	0.04927	435.3	0.07453	435.6	0.18880	425.6	0.60250	458.9	1.48140
3	445.4	0.03530	447.3	0.09310	433.3	0.32200	451.1	0.74010	458.1	1.42670
	444.9	0.04700	445.8	0.11250	450.8	0.34580	449.3	0.76610	455.1	1.48930
	449.6	0.05000	449.5	0.12250	458.4	0.35200	447.5	0.77760	452.1	1.50277

Figure 10 shows the uniaxial strength obtained from tests for all three selected designs with 20, 30, and 40 percent of soil. Based on the results presented in Table 5 and illustrated in Figure 10, the strength increases as the amount of soil increases. The process of this increase differs for the short-term and long-term tests. The short-term strengths have not changed much in low percentages of soil. The changes in short-term strengths are evident only in higher rates of soil, but there are also significant changes in the grout strength regarding the long-term strengths in the low percentages of soil. This can be attributed to the short-term lack of sufficient adhesion between soil particles and grout. On the other hand, as it is apparent in the figure, the 28-day strength of the grout has not changed much with the increase to more than 30%, but the short-term strength has had good changes for the soil percentage increase of more than 30%. Therefore, it can be said that it is better to mix the grout with a high percentage of soil if the short-term strength is essential; otherwise, 30% of this type of soil is suitable for the 28-day strength. Figure 11 shows several specimens after the uniaxial experimental tests.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 10. Uniaxial compressive strength of grout mixed with different percentages of soil a) 2-hour, b) 4-hour, c) 1-day, d) 7-day, e) 28-day

When a sample is subjected to compressive stress, its length decreases in the direction of stress (axial strain). At the same time, the sample shows a positive deformation in the perpendicular direction of the stress, and its dimensions increase in this direction. The ratio of lateral strain to axial strain is called Poisson's ratio. The Poisson's ratio was obtained between 0.3 and 0.35 based on the experiments conducted in this research using cylindrical samples to design used mixtures.

The modulus of elasticity is the ratio of stress to strain. The factors affecting the strength can also affect the modulus of elasticity, which can be monitored by factors such as the amount of cement, quick setting, and the water-to-cement ratio. Figure 12 shows the modulus of elasticity for different mix designs at different times.

Also, it is possible to classify the average density of the grout for different mix designs based on the soil variations. The results of density are given in Table 6, and as expected, the density of grout increased in both the short-term and long-term with the increase in soil percentage.

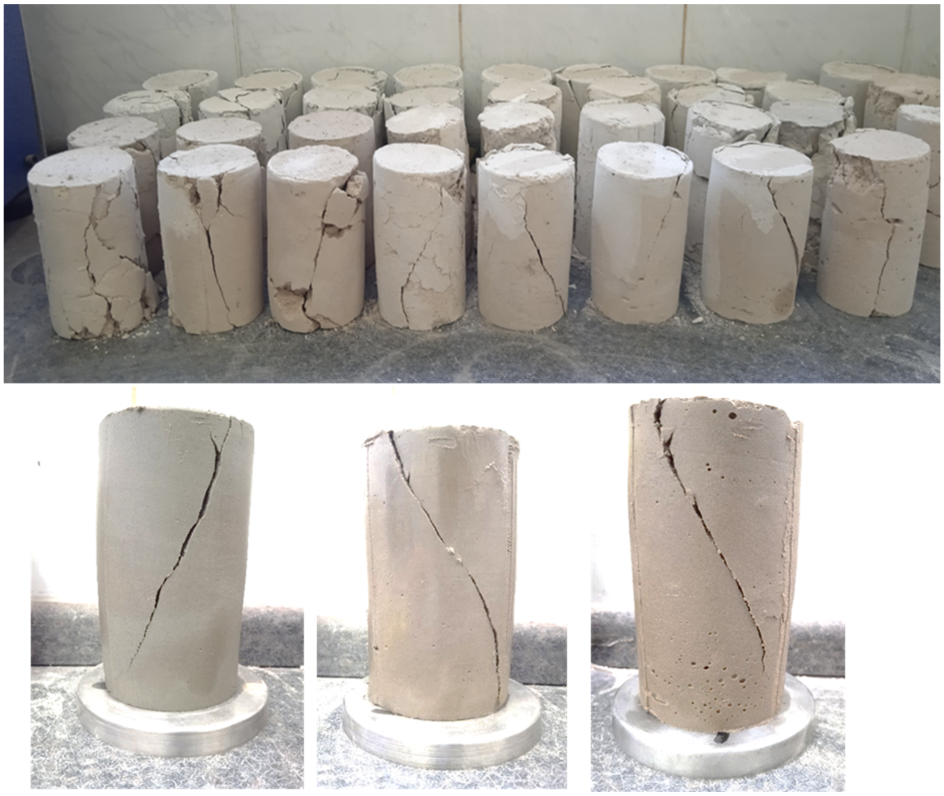


Figure 11. Broken specimens in different time intervals with varying percentages of soil.

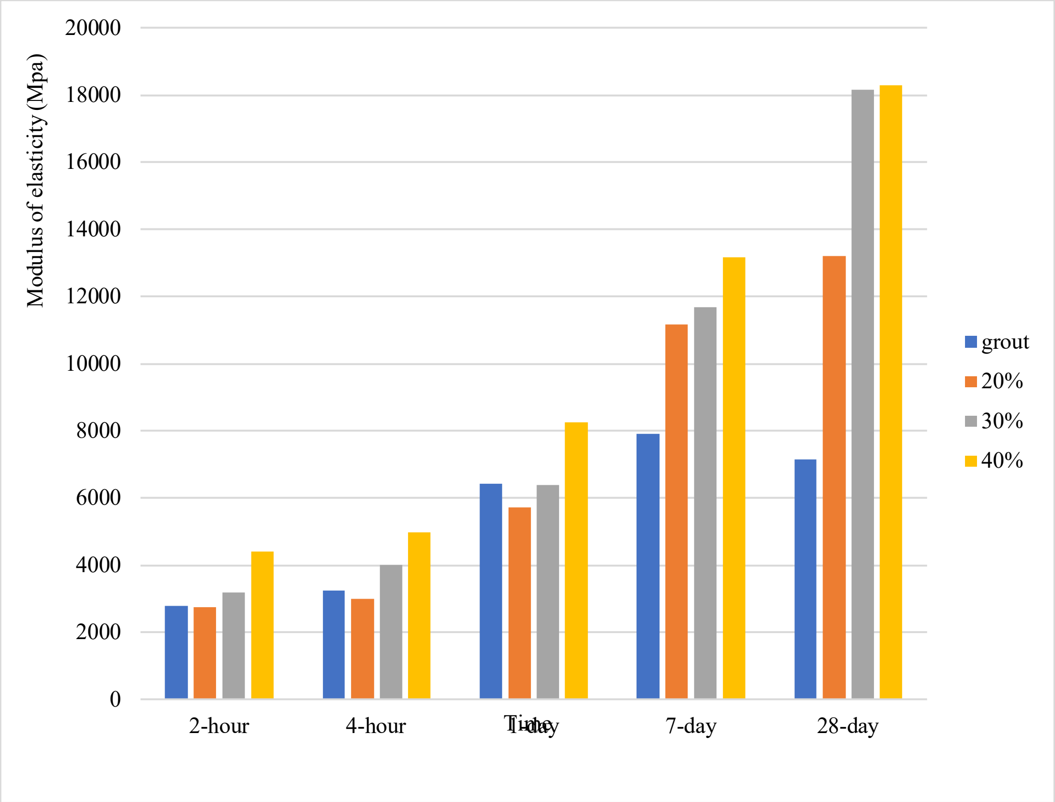


Figure 12. Modulus of elasticity changes over time.

Table 6. Density changes with various soil.

Density changes with amount of soil (kg/m^3)					
Amount of Soil (%)	**Age of specimen**				
	2 hours	**4 hours**	**1 day**	**7 days**	**28 days**
0	1308.56	1292.09	1277.02	1315.83	1320.82
20	1385.89	1422.55	1432.07	1432.32	1435.78
30	1497.80	1538.48	1539.15	1514.85	1603.15
40	1566.17	1573.03	1598.17	1589.53	1602.07

A direct soil cutting machine with box jaws of 10 × 10 cm and the ASTM D3080 standard [28] were used in this research to perform the direct shear tests for the soil and grout mixture. The height of each box is 2.5 cm, and gauge measurements have an average accuracy of 0.01 mm.

Nine tests were performed to study the shear behavior of the soil-grout mixture. There are three tests of grout without soil and six tests of grout mixture with different percentages of soil (20 and 40 percent), which were carried out with the pressures of 30, 50, and 70 kg overburden and are listed in Table 7. Figure 13 shows diagrams of normal stress versus shear stress and horizontal displacement versus shear stress for different mixing designs. The results of shear tests indicate that increasing the percentage of soil up to 20% causes a significant increase in the internal friction angles of the grout. Increasing the amount of soil up to 40% also improves the cohesion and the internal friction angle significantly compared to the mere grout.

Table 7. Specifications of shear tests.

Design No.	Design type	Vertical pressure (kg)	C ($\frac{kg}{cm^2}$)	φ (°)
1	grout	30	0.34	4
2		50		
3		70		
4	Grout mixed with 20 % soil	30	0.17	52
5		50		
6		70		
7	Grout mixed with 40 % soil	30	0.68	57
8		50		
9		70		

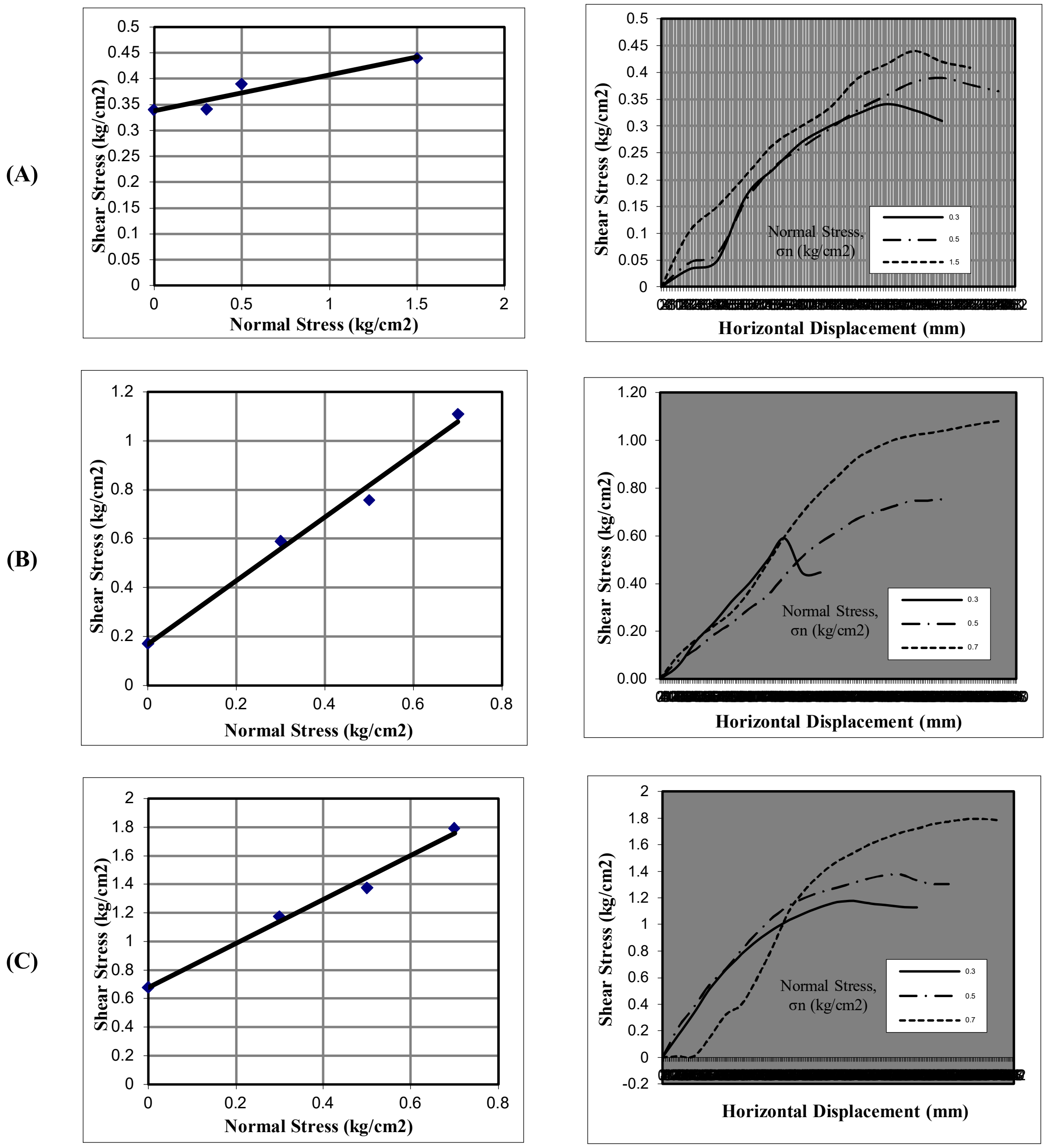


Figure 13. Diagrams of normal stress versus shear stress and horizontal displacement versus shear stress for different mixing designs of shear tests: A) 0% soil, B) 20% soil, C) 40% soil.

4. The effect of soil and grout mixture on the ground surface settlement

The effect of soil and grout mixture on the ground surface settlement was investigated using Numerical modeling with PLAXIS^{3D} software. PLAXIS^{3D} software can be used for analysis in soil environments. This software is based on the Finite Element Method (FEM).

According to the settlement measuring provided for Tabriz metro Line 2 at the chainage 3+550 km–west direction, the settlement amount was 12 mm after the tunnel excavation. The rapid increase in the strength of the two-component grout reduces the deformations of the surroundings and adjacent soil towards the ring-shaped empty space. Since the short-term strength of injection grout is an important issue in the injection process, numerical models with different characteristics of injection grout (mentioned in previous section) were created in this research. The first 4 models were created by changing the composition of the grout. In these models, the injection pressure was 120 kPa. 3 models were also created with the specifications of the first model and only changing the injection pressure at injection pressures of 0, 50 and 120 kPa. The specifications of these models are listed in Table 8.

The applied characteristics for the different layers based on the Mohr-Coulomb behavioral model in 7 different models are given in Table 9. These characteristics are presented based on the borehole drilled in the area of station 5, Tabriz metro line 2.

Table 8. Specifications of different models designed in numerical analysis.

Designed model	Grout specifications	υ	E (MPa)	G (MPa)	K (MPa)	Injection pressure (kPa)
1	Weak grout	0.3	320.47	123.26	267.06	120
2	Primary grout		9614.32	3697.81	8011.94	120
3	Grout mixed with 20 % soil		13211.42	5081.31	11009.51	120
4	Grout mixed with 30 % soil		18161.54	6985.21	15134.62	120
5	Primary grout with an injection pressure of 0 kPa		320.47	123.26	267.06	0
6	Primary grout with an injection pressure of 50 kPa					50
7	Primary grout with an injection pressure of 120 kPa (the same as the first model)					120

Table 9. Applied characteristics for the layers in 7 different models based on the borehole drilled in the area of station 5, Tabriz metro line 2.

Layer	Unified Soil Classification System (USCS)	Layer thickness (m)	E (MPa)	Density ($\frac{kg}{m^3}$)	φ (°)	C (kPa)	υ
1	SC-SM	6	40	1650	26	10	0.31
2	ML-CL	8	60	1540	24	20	0.35
3	SM	6	70	2060	28	15	0.30
4	ML-CL	16	80	1940	24	30	0.44
5	Marl	19	80	2150	22	50	0.37

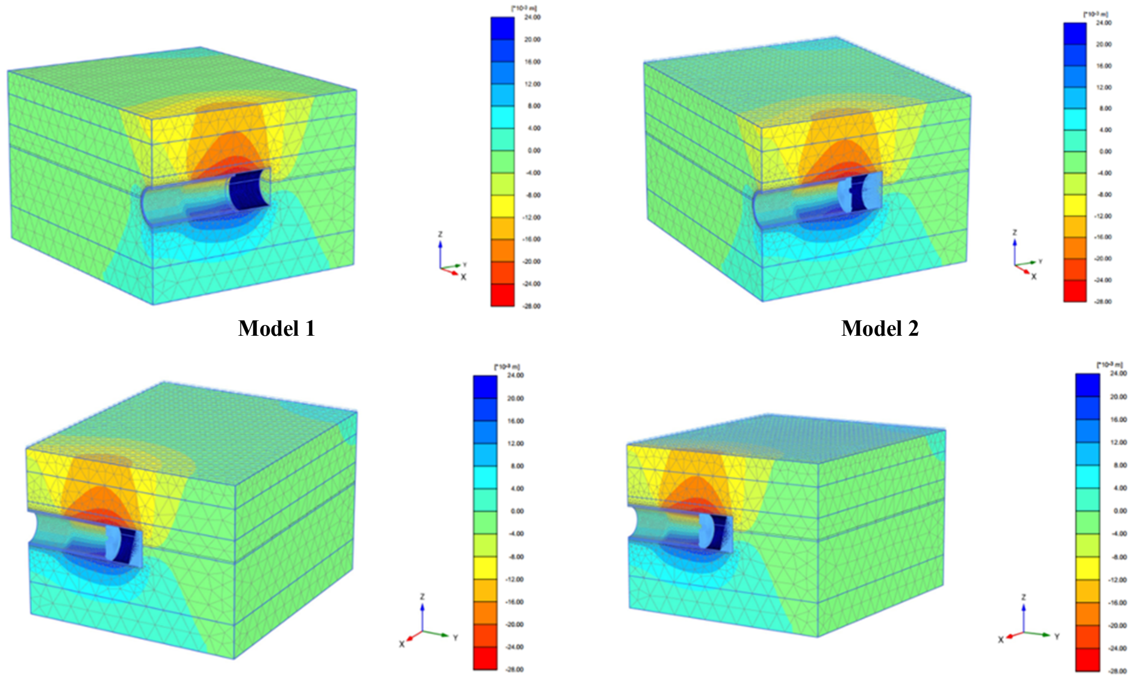
The reduction of surface settlements due to the increase in grout strength is shown in Table 10 and Figure 14. It can be concluded by comparing the results of modeling with the results of settlement measures of Tabriz metro line 2 in the west direction at the chainage 3+550 km that the numerical modeling has provided an acceptable solution. Based on the modeling results, the amount of ground deformations and surface settlements related to the range of empty space behind the tunnel segmental cover has decreased by increasing the properties of the grout and its strength.

The vertical displacement contours in the perpendicular direction to the tunnel axis is shown in Figure 15 for all four chosen designs. The results indicate that there are not many changes in the amount of ground settlement in the case of injecting grout with soil (design numbers 1, 2, 3, and 4); therefore, the combination of grout with soil to increase the mechanical properties of the grout in terms of settlement cannot be significant. However, it seems that it is possible to reduce the permeability and the ground surface settlement by increasing the pressure and penetration of the grout in the surrounding soil. On the other hand, the results obtained from the numerical modeling indicates that increasing the injection pressure from 0 to 120 kPa would have a 17 percent influence on the reduction of ground surface settlement. Figure 16 shows vertical displacement contours in models 5, 6 and 7 with injection pressures of 0, 50 and 120 kPa respectively.

Table 10. Comparison of maximum settlement in different models and maximum measured settlement.

Designed model	Maximum settlement in numerical modeling (mm)	Maximum measured settlement (mm)
1	-14.9	
2	-14.6	-12
3	-14.5	
4	-14.5	
5	-17.1	
6	-15.5	
7	-14.6	

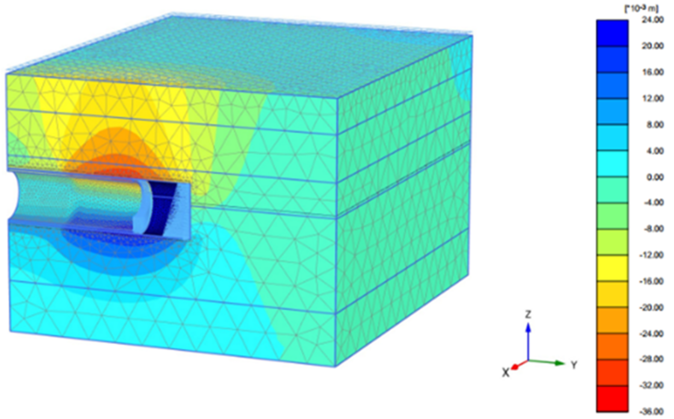
Figure 14. Maximum settlement diagram in different designs.



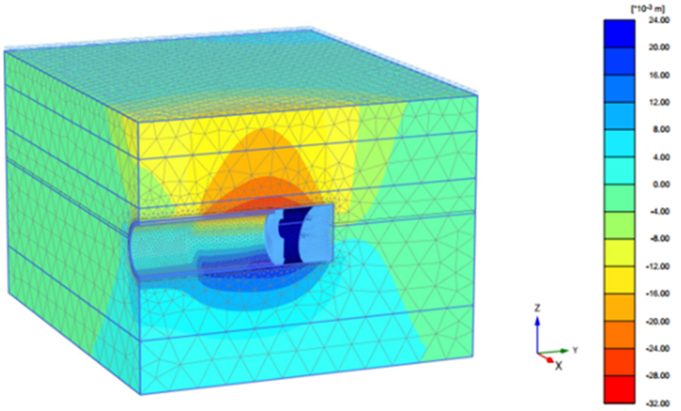
Model 1 **Model 2**

Model 3 **Model 4**

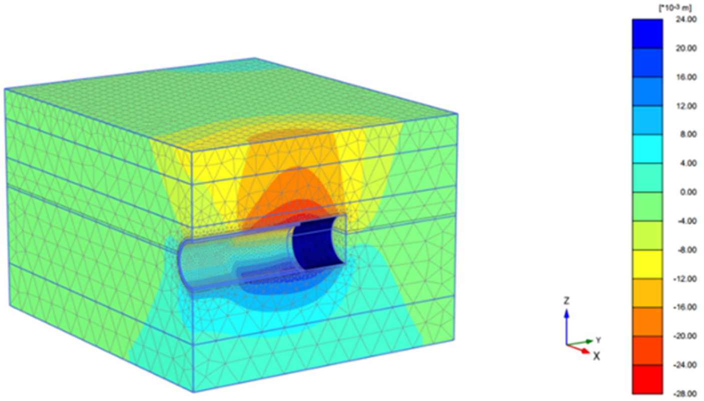
Figure 15. Vertical displacement contours in the models 1, 2, 3 and 4 with different grout specifications and with an injection pressure of 120 kPa.



Model 5



Model 6



Model 7

Figure 16. Vertical displacement contours in models 5, 6 and 7 with injection pressures of 0, 50 and 120 kPa respectively.

5. Conclusions

The study of mechanical properties of the grout injected behind the segment is essential in mechanized excavation with EPB machines in urban environments to control the ground surface settlement. For this purpose, in this research, various laboratory experiments with different mix designs were done to investigate the influence of mixture of the grout and soil on the ground surface settlement. The results of these studies are as follows:

1. Increasing the amount of soil mixed with the grout leads to an increase in the uniaxial compressive strength, the modulus of elasticity, cohesion and internal friction angle of the grout. Increasing the soil in the mixture of soil and grout up to 40% increases the uniaxial compressive strength up to 300% and the cohesion of the mixture up to 100%.

2. Increasing the soil percentage increases the weight of the sample and density of samples both in the short-term and long-term. By increasing the amount of soil up to 40% in the mixture of soil and grout, the density of the 28-day sample increases up to 21.3%.
3. Based on the results of numerical modeling, the proper injection pressure can significantly reduce the ground surface settlement. Increasing the injection pressure from 0 to 120 kPa showed a 17 percent influence on the reduction of ground surface settlement.
4. If there is a need to reduce the permeability of the soil around the tunnel especially in the entrance parts of the machine to the station, the proper combination of grout with soil reduces the permeability and the ground surface settlement by increasing the pressure and penetration of the grout in the surrounding soil.

References

[1]. Sharghi, M., Chakeri, H., & Ozcelik, Y. (2017). Investigation into the effects of two component grout properties on surface settlements. *Tunnelling and Underground Space Technology, 63,* 205-216.

[2]. André, L., Bacquié, C., Comin, G., Ploton, R., Achard, D., Frouin, L., & Cyr, M. (2022). Improvement of two-component grouts by the use of ground granulated blast furnace slag. *Tunnelling and Underground Space Technology, 122,* 104369.

[3]. Song, W., Zhu, Z., Pu, S. h., Wan, Y., Huo, W., & Peng, Y. (2022). Preparation and engineering properties of alkali-activated filling grouts for shield tunnel. *Construction and Building Materials, 314,* 125620.

[4]. Bezuijen, A., & Talmon, A. M. (2008). Processes around a TBM. *Geotechnical Aspects of Underground Construction in Soft Ground, Shanghai, China,* 1–11.

[5]. Dias, T. G. S., & Bezuijen, A. (2015). TBM Pressure Models - Observations, Theory and Practice. *15th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Buenos Aires, Argentina,* 347–374.

[6]. Zheng, G., Zhang, T., & Diao, Y. (2015). Mechanism and countermeasures of preceding tunnel distortion induced by succeeding EPBS tunnelling in close proximity. *Computers and Geotechnics*, *66 (5),* 53–65.

[7]. Ding, W., Duan, C., Zhu, Y., Zhao, T., Huang, D., & Li, P. (2019). The behavior of synchronous grouting in a quasi-rectangular shield tunnel based on a large visualized model test. *Tunnelling and Underground Space Technology, 83,* 409–424.

[8]. He, S., Lai, J., Wang, L., & Wang, K. (2020). A literature review on properties and applications of grouts for shield tunnel. *Construction and Building Materials, 239,* 117782.

[9]. Mao, J. H., Yuan, D. J., Jin, D. L., & Zeng, J. F. (2020). Optimization and application of backfill grouting material for submarine tunnel. *Construction and Building Materials, 265,* 120281.

[10]. Oreste, P., Sebastiani, D., Spagnoli, G., & Lillis., A. (2021). Analysis of the behavior of the two-component grout around a tunnel segmental lining on the basis of experimental results and analytical approaches. *Transportation Geotechnics, 29,* 100570.

[11]. Anagnostopoulos, C. A. (2005). Laboratory study of an injected granular soil with polymer grouts. *Tunnelling and Underground Space Technology, 20 (6),* 525-533.

[12]. Flores, A. Q. (2015). *Physical and mechanical behavior of a two-component cement-based grout for mechanized tunneling application*. MSc Thesis, Universidad Federal do Rio de Janeiro, Brazil.

[13]. 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 WTC 2019 ITA-AITES World Tunnel Congress (WTC 2019), Naples, Italy.*

[14]. Sharghi, Mohammad, Chakeri, H., Afshin, H., & Ozcelik, Y. (2018). An experimental study of the performance of two-component backfilling grout used behind the segmental lining of a tunnel-boring machine. *Journal of Testing and Evaluation*, *46 (5),* 2083-2099.

[15]. Todaro, C., Carigi, A., Martinelli, D., & Peila, D. (2021). Study of the shear strength evolution over time of two-component backfilling grout in shield tunnelling. *Case Studies in Construction Materials, 15,* e00689.

[16]. Oggeri, C., Oreste, P., & Spagnoli, G. (2021). The influence of the two-component grout on the behaviour of a segmental lining in tunnelling. *Tunnelling and Underground Space Technology, 109,* 103750.

[17]. Rahmati, S., Chakeri, H., Sharghi, M., & Dias, D. (2022). Experimental study of the mechanical properties of two-component backfilling grout. *Proceedings of the Institution of Civil Engineers-Ground Improvement,175 (4),* 277–289.

[18]. Fu, J., Haeri, H., Sarfarazi, V., Mehri, M., Asgari, K., & Fatehi Marji, M. (2022). Effects of transversely isotropic layers on failure mechanism of non-homogeny concrete-soil specimens. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 8, 163.*

[19]. Sarfarazi, V., Tabaroei, A., & Asgari, K. (2022). Discrete element modeling of strip footing on geogrid-reinforced soil. *Geomechanics and Engineering, 29,* 435–449.

[20]. Fu, J., Safaei, M. R., Haeri, H., Sarfarazi, V., Fatehi Marji, M., Xu, L., & Arefnia, A. (2022).

Experimental investigation on deformation behavior of circular underground opening in hard soil using a 3D physical model. *Journal of Mining and Environment, 13,* 727-749.

[21]. Liu, W., Liang, J., & Xu, T. (2023). Tunnelling-induced ground deformation subjected to the behavior of tail grouting materials. *Tunnelling and Underground Space Technology, 140,* 105253.

[22]. Barri, F., Chakeri, H., Haghkish, H., & Manafi, M. (2024). Investigation of the Feasibility of Increasing the Tail-grouting Zone during Mechanized Tunneling in Sandy Soils. *Periodica Polytechnica Civil Engineering, 68 (2)*.

[23]. Ghobadi, M.H., Firuzi, M., & Asghari, E. (2016). Relationships between geological formations and ground water chemistry and their effects on concrete lining of tunnels (case study: Tabriz metro line 2). *Environmental Earth Science, 75,* 2–14.

[24]. Kutzner, Ch. (1996). *Grouting of rock and soil.* CRC Press, London.

[25]. American Society for Testing and Materials. (1999). *Standard test method for expansion and bleeding of freshly mixed grouts for preplaced-aggregate concrete in the laboratory* (ASTM C940).

[26]. American Society for Testing and Materials. (2004). *Standard test method for marsh funnel viscosity of clay construction slurries* (ASTM D6910).

[27]. American Society for Testing and Materials. (2008). *Standard test method for compressive strength of hydraulic cement mortars* (ASTM C109).

[28]. American Society for Testing and Materials. (2011). *Standard test method for direct shear test of soils under consolidated drained conditions* (ASTM D3080).

تأثیر مخلوط خاک و دوغاب بر نشست سطح زمین در حفاری مکانیزه

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چکیده:

حفاری با ماشین حفاری تونل (TBM) در محیط‌های شهری می تواند خطراتی مانند نشست سطح زمین داشته باشد. در حین حفاری، باید فضای خالی بین کله حفار و سگمنت با دوغاب مناسب پر شود. امروزه با استفاده از دوغاب پشت سگمنت و سایر پرکننده‌ها، فضای خالی پشت سگمنت پر شده و میزان نشست سطح زمین کاهش می‌یابد. بدون شک استفاده از دوغاب با رفتار مکانیکی مناسب می‌تواند جایگزین مناسبی برای خاک حفاری شده در تونل سازی مکانیزه باشد. در این تحقیق، رفتار مکانیکی دوغاب پشت سگمنت در خلال تزریق به فضای بین خاک و سگمنت و مخلوط آن با خاک مطالعه شده است. همچنین اثر خواص مکانیکی دوغاب مخلوط با خاک بر نشست سطح زمین با استفاده از مدل‌سازی عددی بررسی شده است. اجزاء دوغاب دو جزئی این تحقیق شامل سیمان صوفیان تیپ ۲ با مقاومت ۲۸ روزه، ۴۴ مگاپاسکال و دانسیته $۳۰۵۰\ kg/m^3$، بنتونیت سلفچگان با دانسیته $۲۱۳۲\ kg/m^3$ و زودگیر سیلیکات سدیم مایع با دانسیته محلول $۱۵۰۰\ kg/m^3$ می‌باشند. نتایج مطالعات آزمایشگاهی نشان داد که اختلاط دوغاب و خاک باعث افزایش قابل توجه خواص مکانیکی دوغاب می‌شود. افزایش خاک در مخلوط خاک و دوغاب تا ۴۰ درصد، مقاومت فشاری تک محوری را تا ۳۰۰ درصد، مدول الاستیسیته را تا ۱۵۶ درصد و چسبندگی مخلوط را تا ۱۰۰ درصد افزایش می‌دهد. از سوی دیگر، بر اساس نتایج مدل‌سازی عددی، فشار تزریق مناسب می‌تواند نشست سطح زمین را به میزان قابل توجهی کاهش دهد. افزایش فشار تزریق از ۰ تا ۱۲۰ کیلو پاسکال، ۱۷ درصد بر کاهش نشست سطح زمین تأثیر دارد.

کلمات کلیدی: حفاری مکانیزه، دوغاب، نشست سطح زمین، خواص مکانیکی، روش المان محدود.
