RGNZ/MGPB

# Laboratory investigation of the effect of sodium silicate and bentonite on the mechanical properties of the grout behind the segment in mechanized excavation

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 622.2
DOI: 10.17794/rgn.2024.2.5

Original scientific paper

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## Abstract

Nowadays, the use of Tunnel Boring Machines (TBM) in tunnelling has increased in urban environments. One of the effective parameters in the excavation process is the use of grout behind the segments to prevent ground settlement and penetration into the tunnel. The investigation of the effects of two-component grout (bentonite and sodium silicate) on the mechanical properties of the grout plays a crucial role in mechanized excavation. Therefore, this article aims to investigate the effect of various parameters on the properties of the two-component grout. Eight different mixing designs were considered in this research. Gel-time tests, viscosity test, water bleeding test, uniaxial compressive strength tests (UCS), and direct shear tests were conducted for each mixing design. The UCS tests were performed for eight mixing designs and at four different ages of the grout, while the direct shear test was conducted for five mixing designs at the age of one day. The results showed that increasing the sodium silicate content from 4% to 9.4% reduced the Gel-time to 7 seconds, and increasing the bentonite content from 2.3% to 4.58%, increased the marsh funnel time to 12 seconds. The uniaxial compressive strength of the grout increased to 0.682 MPa at the age of 28 days. Finally, by conducting the direct shear test on the grout and obtaining the parameters of cohesion and internal friction angle, it was determined that these two parameters depend on the values of bentonite and sodium silicate, and they change with the increase or decrease of these grout components.

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**Keywords:**
mechanized excavation; two-component grout; bentonite; sodium silicate; Gel-time; uniaxial strength

## 1. Introduction

There are various methods available for tunnelling in urban environments. One of the methods used for tunnelling in soft ground is the Full-Face excavation by the Earth Pressure Balancing Machine (EPB). With the increasing use of tunnel boring machines in urban tunnelling industry, the importance of grouting behind the segments becomes crucial. Injecting the two-component grout into the area behind the segments inside the tunnel enhances the strength and stability of the tunnel, protects it from water penetration, strengthens the surrounding soil, and reduces ground settlement.

**Pila et al. (2011)** conducted a study analysing different types of grouts, particularly two-component grout, and presented the laboratory test results. This study provides the results of a series of experiments regarding the physical and mechanical behaviour of the injected two-component grout for filling the space behind the segments. According to the obtained results, the strength of the grout increases with time and age, and if the sample loses its natural water content, it also loses its mechanical properties.

**Sharghi et al. (2017)** conducted a study to investigate the effect of each constituent material of two-component grout on the parameters and the suitable range of compressive strength for grout behind the segment, following the determination of the mechanical properties of two-component grout with specific mixing designs. The results of this study showed that exceeding the grout strength beyond a specific limit only incurs additional costs and does not have a significant impact on settlements. Additionally, reducing the water-to-cement ratio, increasing the amount of bentonite and cement, all contribute to an increase in the viscosity of fresh grout and consequently increase the marsh funnel viscosity time, reduce grout pumpability, and decrease the bleeding of grout. On the other hand, increasing the amount of cement and sodium silicate leads to an increase in the apparent compressive strength of the grout in both short-term and long-term durations.

**Yang et al. (2019)** examined the effect of bentonite on the pore structure and permeability of cementitious mor-

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tar. In this study, bentonite was added to the mortar as a swelling clay with 0%, 4%, and 8% by weight of cement. The compressive strength, flexural strength, and permeability of the cement mortar with bentonite were determined and compared with samples of plain cementitious mortar. The test results demonstrate that adding 8% bentonite can increase compressive strength, flexural strength, and permeability by 61.48%, 42.09%, and 76.47%, respectively.

**Di Giulio et al. (2020)** conducted a study on two-component grouts typically injected behind segments by a tunnel boring machine. The purpose of this study was to contribute to the understanding of the chemical factors and influential factors on the performance of the mixing design and standardization of testing methods for their measurement. The results of this research show that the properties of bentonite have an impact on bleeding and viscosity depending on the hydration time. The Gel-Time increases with the increase in the accelerator percentage. Increasing the accelerator percentage leads to an increase in the strength of the grout. The Gel-Time is longer when a non-alkaline accelerator is used. The strength of samples prepared using the mixing system method is more than twice that of manual samples.

**Todaro et al. (2021)** conducted a study to investigate the uniaxial compressive strength as the primary parameter for assessing the compatibility of a specific grout with specific technical requirements. This research was carried out based on the focus on shear strength and its evolution during the aging (curing) of the grout. These researchers demonstrated that shear strength, in addition to uniaxial compressive strength, plays an important role in tunnel lining stability. The values obtained for the friction angle and cohesion of the grout at different ages are a function of the mixing design. For the 1-hour sample, direct shear testing cannot be performed. Paying attention to the friction angle and cohesion during the curing process of the grout at different ages is crucial for the design and stability phase of tunnel lining.

**Rahmati et al. (2022)** conducted a study that focused on examining the uniaxial and triaxial compressive strength of various mixing designs of grout after investigating the mechanical properties of the grout. This research demonstrated that increasing the amount of bentonite and cement led to an increase in marsh funnel viscosity and viscosity overall. Increasing the amount of bentonite resulted in a reduction in bleeding and increased grout strength. The addition of sodium silicate in the grout led to a decrease in Gel-Time and increased in grout strength. Furthermore, increasing the water-to-cement ratio exhibited a decreasing trend in the modulus of elasticity, while increasing the amount of cement increased the cohesion and decreased the internal friction angle. Both the uniaxial and triaxial compressive strength increased with the addition of bentonite and sodium silicate in the grout.

**Todaro et al. (2022)** conducted studies on the characterization of two-component grout and its application in tunnel construction. These studies showed that bentonite plays a significant role in the technology of two-component grout and affects the behaviour of both grout components and set grout, even if the bentonites are diverse. The role of bentonite in stabilizing the first component and its impact on reducing bleeding was confirmed, even when the effect of activation time could not be ignored. The liquid limit test of Atterberg is a valuable experiment that can be used for the initial selection of the best bentonite for a specific application.

**Barri et al. (2023)** studied the effect of the grout penetration depth on surface settlement to determine the adequate amount of grout injection pressure. The results indicated that the amount of penetration in the implemented granulation has increased due to the increase in pressure, so doubling the pressure causes a 30% increase in grout penetration in the surrounding soil.

**Abdolghader et al. (2023)** investigated the optimal content of the main factors affecting the properties of the grout. In this research, bentonite, cement, and fluidizer were present in the grout structure. In this experiment, the water-to-cement ratio ranged from 0.36 to 0.58, while the amount of bentonite and fluidizer ranged from 0% to 6% and 0% to 8%, respectively. The results indicate that the spreading of the grout increases with an increase in the amount of fluidizer and water-to-cement ratio, but decreases with an increase in the amount of bentonite. On the other hand, the strength of the grout decreases with an increase in the amount of fluidizer and water, but increases with an increase in the amount of bentonite.

**Gomez et al. (2023)** conducted a comprehensive study on the characteristics of cement-based grout. Cement grout is typically composed of cement, water, and sand, and it is optimized by adding additives. According to this research, the grout needs to have enough fluidity without losing its cohesion. The stability of the consistency is mainly influenced by the amount of water. Excessive water in the grout leads to sedimentation, increased porosity, and reduced strength. Excessive bleeding of the grout not only decreases its mechanical strength but also disrupts its permeability. Furthermore, according to the results, silica increases early fluidity, long-term strength, reduces viscosity, bleeding, and porosity. However, a high amount of silica in the grout mixture can impair its flowability and efficiency.

**Xinran et al. (2023)** conducted a study on the mechanical behaviour of the ground after injecting grout into the soil surrounding a tunnel boring machine (TBM) excavation site, and they simulated the changes using a three-dimensional model. In this study, the effects of various injection parameters, including the water-to-cement ratio, injection pressure, spacing of grout holes, etc., were examined and analysed. According to the results, the water-to-cement ratio had the most significant impact on the quality of the injection. Additionally, increasing the injection pressure from 2 to 4 megapascals increased the volume of injected grout.

This study aimed to investigate the influence of critical parameters on the properties of two-component grout. The effect of bentonite and sodium silicate in the composition of the two-component grout on the uniaxial strength and particularly the shear parameters were examined experimentally in the laboratory.

## 2. Materials and methods

The two-component grout consists of water, cement, and bentonite as the first component and sodium silicate as the second component. In this study, sodium silicate was used as the accelerator. The water used in this study is drinking water from Sahand University of Technology. The cement used is Sofian Type 2 cement with a density of 3050 kg/m$^3$ and strength class of the Sofian Type 2 cement is 42 MPa. The bentonite used is an active type of bentonite (Active bentonite is a material from the family of swelling clays and minerals. Active bentonite clay is a type of aluminum polysilicate based on clay, at least 85 to 90% of which is montmorillonite) with a specific weight of 2132 kg/m$^3$ from Salafchegan. A liquid sodium silicate with the trade name SA-161 and a specific solution weight of 1500 kg/m$^3$ was used as the accelerator.

### 2.1 Introduction of the mixing designs used to make grout

To achieve the objectives of this research and produce different types of grouts, eight different mixing designs were used. The most significant difference between the designs lies in the amount of bentonite and sodium silicate. The specifications of the mixing designs used are presented in **Table 1**. In the other designs, while keeping the values of other components constant, only the values of sodium silicate or bentonite were varied.

**Table 1:** Mixing designs used to make grout

| Mixing Design No. | Sodium Silicate | | Bentonite | | Cement | Water |
|---|---|---|---|---|---|---|
| | kg | Percent in Weight | kg | Percent in Weight | kg | kg |
| **1** | 50 | 4 | 40 | 3.2 | 360 | 799 |
| **2** | 75 | 5.88 | 40 | 3.13 | 360 | 799 |
| **3** | 90 | 6.98 | 40 | 3.1 | 360 | 799 |
| **4** | 100 | 7.69 | 40 | 3.07 | 360 | 799 |
| **5** | 125 | 9.4 | 40 | 3.02 | 360 | 799 |
| **6** | 90 | 7.03 | 30 | 2.34 | 360 | 799 |
| **7** | 90 | 6.9 | 50 | 3.84 | 360 | 799 |
| **8** | 90 | 6.87 | 60 | 4.58 | 360 | 799 |

## 3. Results and Discussion

In this study, tests were carried out on grout samples prepared using 8 different mixing designs. The conducted tests include gelation time, marsh funnel test, bleeding test, uniaxial compressive strength, and direct shear tests.

### 3.1. Gel-Time Test

Firstly, the grout test is conducted on recently mixed grout. To begin, the initial component of the grout is prepared, and then an exact measurement of sodium silicate, which is the second component, is stored in a separate container. Bentonite is combined with 80% of the specified water content one day prior to the test to enhance water absorption by the bentonite material. Once both grout components are ready in their respective containers, they are merged together by adding the second component to the first one. Following this step, an accelerator is incorporated into the first component before swiftly transferring and pouring out from one container. This time is referred to as the gelation time. The results of the Gel-Time for the selected eight mixing designs are presented in **Table 2**.

Changes in Gel-Time based on different values of bentonite and sodium silicate are presented in **Figures 1** and **2**.

According to the results obtained from the Gel-Time test for the 8 different mixing designs, where the amounts of bentonite and sodium silicate vary, it was observed that increasing the amount of bentonite in the grout mixture has a significant effect on reducing the gelation time. Specifically, with an increase in bentonite content from 30 to 60 kilograms, while keeping the sodium sili-

**Table 2:** Gel-Time for eight mixing designs

| Mixing Design No. | Sodium Silicate (kg) | Bentonite(kg) | Gel-Time(s) |
|---|---|---|---|
| 1 | 50 | 40 | 12 |
| 2 | 75 | 40 | 12 |
| 3 | 90 | 40 | 8 |
| 4 | 100 | 40 | 7 |
| 5 | 125 | 40 | 5 |
| 6 | 90 | 30 | 9 |
| 7 | 90 | 50 | 7 |
| 8 | 90 | 60 | 5 |

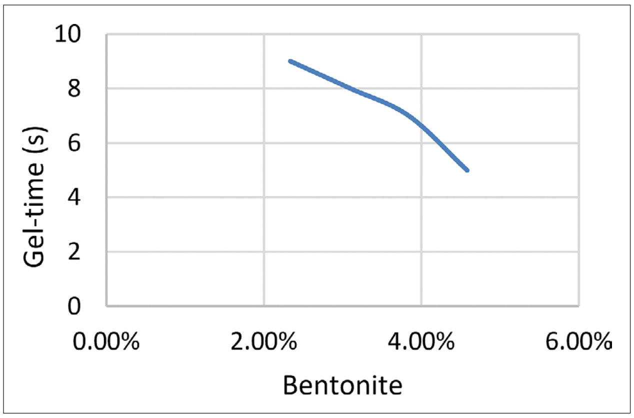

**Figure 1:** The chart of changes in Gel-Time with increasing amounts of bentonite in the mixing design with a fixed amount of sodium silicate (90 kg).

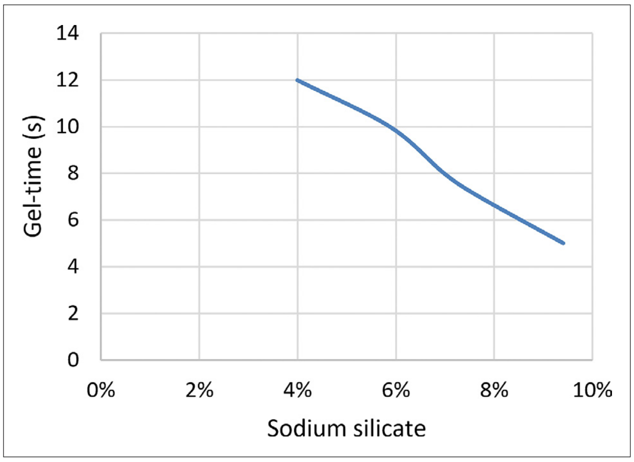

**Figure 2:** The chart of Gel-Time changes with increasing amounts of sodium silicate in mixing design with a fixed amount of bentonite (40 kg)

cate constant at 90 kilograms, the Gel-Time decreases from 9 seconds to 5 seconds due to the water-absorbing properties of bentonite.

As expected, increasing the amount of sodium silicate results in a reduction in gelation time. Specifically, with increased sodium silicate content from 50 to 125 kilograms, while keeping the bentonite constant at 40 kilograms, the Gel-Time decreases from 12 seconds to 5 seconds.

## 3.2. Marsh funnel viscosity Test

This test is performed on the first component of freshly mixed grout according to the **ASTM D6910 (2004)** standard. The procedure for conducting the test is as follows: firstly, one liter of the prepared first component of the grout is measured, and after blocking the outlet of the

**Table 3:** The Marsh time for each mixing design

| Mixing Design No. | Bentonite (kg) | Marsh time (s) |
|---|---|---|
| 3 | 40 | 40 |
| 6 | 30 | 38 |
| 7 | 50 | 50 |
| 8 | 60 | - |

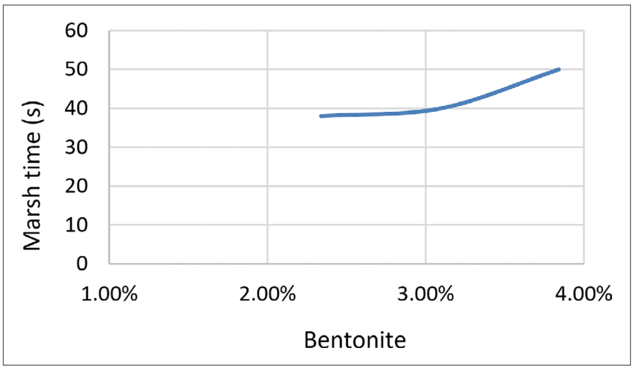

**Figure 3:** Marsh funnel time change chart with an increasing amount of bentonite in the first component of the mixing design

**Table 4:** Amount of bleeding for mixing designs

| Mixing Design No. | Bentonite (kg) | Bleeding (%) | Result |
|---|---|---|---|
| 6 | 30 | 6.5 | unacceptable |
| 3 | 40 | 2.3 | acceptable |
| 7 | 50 | 2 | acceptable |
| 8 | 60 | - | unacceptable |

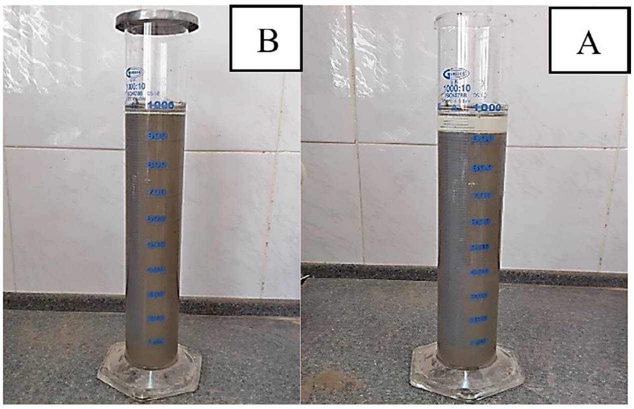

**Figure 4:** A) The amount of bleeding of mixing design number 6; B) bleeding of design number 7

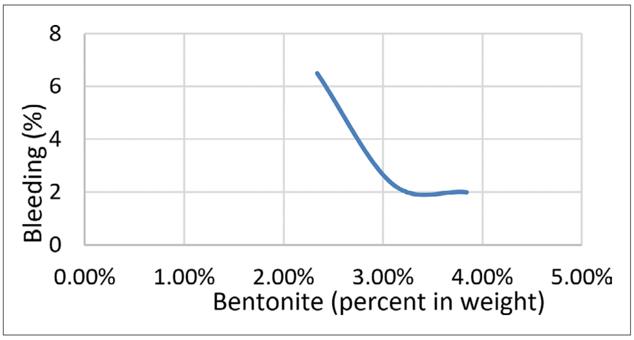

**Figure 5:** The chart of bleeding changes with increasing the bentonite in the mixing design

**Figure 6:** The tested samples

**Figure 7:** The fractured sample under uniaxial load

**Table 5:** Results of UCS (MPa)

| Mixing Design No. | The uniaxial compressive strength (MPa) | | | |
|---|---|---|---|---|
| | 2 hours | 1 day | 7 days | 28 days |
| **1** | 0.0025 | 0.24 | 0.56 | 0.68 |
| | 0.0027 | 0.19 | 0.50 | 0.61 |
| | 0.0026 | 0.25 | 0.62 | 0.72 |
| **2** | 0.068 | 0.22 | 0.4 | 0.7 |
| | 0.066 | 0.27 | 0.61 | 0.701 |
| | 0.064 | 0.255 | 0.64 | 0.73 |
| **3** | 0.10 | 0.46 | 0.59 | 0.7 |
| | 0.13 | 0.41 | 0.74 | 0.86 |
| | 0.135 | 0.41 | 0.57 | 0.7 |
| **4** | 0.13 | 0.49 | 0.45 | 0.14 |
| | 0.14 | 0.24 | 0.63 | 1/04 |
| | 0.14 | 0.42 | 0.64 | 1/01 |
| **5** | 0.133 | 0.496 | 0.57 | 0.88 |
| | 0.142 | 0.51 | 0.89 | 1.19 |
| | 0.159 | 0.48 | 0.87 | 1.08 |
| **6** | 0.092 | 0.35 | 0.37 | 0.51 |
| | 0.15 | 0.34 | 0.59 | 0.87 |
| | 0.13 | 0.22 | 0.43 | 0.67 |
| **7** | 0.17 | 0.57 | 0.9 | 1.25 |
| | 0.1 | 0.52 | 0.86 | 1.20 |
| | 0.21 | 0.50 | 0.7 | 1.15 |
| **8** | 0.21 | 0.515 | 0.8 | 1.14 |
| | 0.24 | 0.59 | 0.987 | 1.43 |
| | 0.29 | 0.60 | 0.941 | 1.30 |

funnel, the grout is poured from the mesh section into the funnel. Then, the funnel is placed on a graduated cup, and the outlet is opened to allow the grout to flow from the funnel into the graduated cup until a specified amount, equivalent to 946 milliliters, is reached in the cup. The time from opening the funnel's outlet until the specified amount in the cup is filled is recorded. This time represents the marsh funnel time for each mixing design. This test is also known as the viscosity test. The results obtained from the marsh funnel viscosity tests on the selected eight mixing designs are presented in **Table 3**.

Due to the fact that the first component (water + cement + bentonite) of mixing designs number 1 to 5 is composed of the same compounds and amounts, the recorded time for each of the five designs is the same. The marsh funnel viscosity tests for mixing design number 8, which has 60 kilograms of bentonite, was not executable due to its high viscosity (stiffness of the grout). It should be noted that the bentonite in different designs was mixed with 80% of the specified water content 24 hours before conducting the test. The chart illustrating the changes in Marsh time with increasing bentonite content in the first component of the mixing design is presented in **Figure 3**.

According to the results obtained from the Marsh funnel viscosity test, it is observed that increasing the amount of bentonite in the composition of the first component of the grout leads to an increase in the Marsh

**Table 6:** Final results for UCS

| Mixing Design No. | The uniaxial compressive strength (MPa) | | | |
|---|---|---|---|---|
| | 2 hours | 1 day | 7 days | 28 days |
| **1** | 0.0026 | 0.245 | 0.56 | 0.67 |
| **2** | 0.066 | 0.248 | 0.625 | 0.71 |
| **3** | 0.121 | 0.426 | 0.633 | 0.753 |
| **4** | 0.136 | 0.455 | 0.635 | 1.025 |
| **5** | 0.144 | 0.495 | 0.88 | 1.135 |
| **6** | 0.124 | 0.303 | 0.463 | 0.683 |
| **7** | 0.16 | 0.53 | 0.82 | 1.2 |
| **8** | 0.246 | 0.568 | 0.964 | 1.365 |

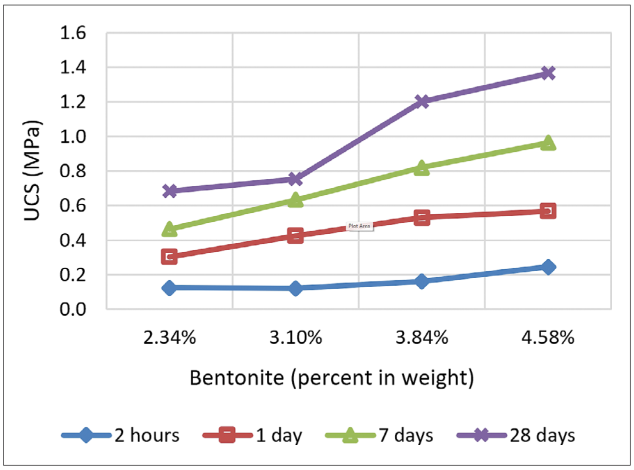

**Figure 8:** The chart of UCS changes with an increase in the amount of bentonite in different ages

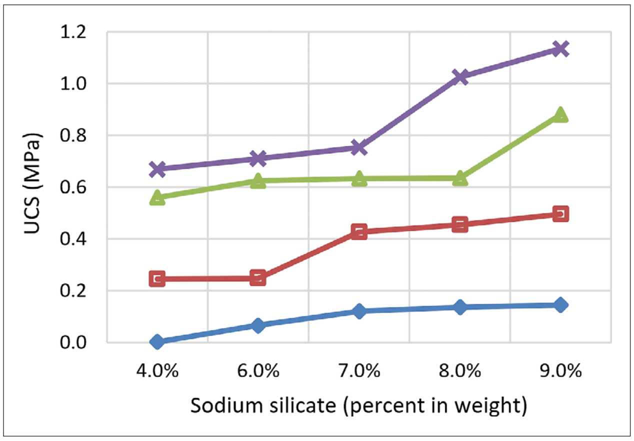

**Figure 9:** The chart of UCS changes with an increase in the amount of sodium silicate in different ages

**Figure 10:** Direct shear system

time. This is due to the water-absorbing properties of bentonite and the reduction in the water-to-cement ratio in the mixing design. The acceptable time range for grout in the Marsh funnel viscosity test is between 35 and 45 seconds. If the Marsh time is less than the acceptable range, it indicates the fluidity of the grout, which results in excessive water bleeding and is unsuitable for proper injection. If the Marsh time exceeds the acceptable range, the grout becomes highly viscous, and its pumpability and injectability decrease, making it unsuitable for proper injection.

## 3.3. Water Bleeding Test

This test, similar to the Marsh funnel viscosity test, is performed on the freshly mixed first component of the grout and is conducted according to the **ASTM C940-16 (1999)** standard. As per the procedure, the bentonite used for each mixing design is mixed with 80% of the specified water content for that design 24 hours prior to conducting the test. The test procedure is as follows: firstly, one liter of the prepared first component of the grout is measured, and after ensuring thorough mixing and uniformity, the mixture is poured into a graduated cylinder up to a specified grading of 1000 milliliters. The cylinder is then covered to prevent evaporation and placed on a smooth and vibration-free surface to remain undisturbed. After 24 hours, the amount of water accumulated on top of the grout is measured to determine the water bleeding for each mixing design. The results obtained from the water bleeding test for the selected designs are presented in **Table 4**.

Uniformity in the water bleeding rate for the first five mixing designs is due to the identical composition of the first component (consisting of water + bentonite + cement). In mixing design number 8, no water bleeding was observed due to the high amount of bentonite in the grout mixture and its water-absorbing properties. The water bleeding of the grout, after 24 hours according to the mentioned standard, should not exceed 5%. In **Figure 4**, the water bleeding rates of mixing designs number 6 and 7 are compared with each other.

**Table 7:** Recorded data for shear stress with increasing normal stress

| $\sigma_n$ (*kPa*) | $\tau$ (*kPa*) | | | | |
|---|---|---|---|---|---|
| | **Mixing design 3** | **Mixing design 5** | **Mixing design 1** | **Mixing design 6** | **Mixing design 8** |
| **29.42** | 33.44 | 34.52 | 20.00 | 29.41 | 38.63 |
| **49.03** | 38.25 | 42.19 | 17.65 | 38.53 | 43.44 |
| **68.65** | 43.15 | 46.39 | 21.57 | 43.15 | 69.43 |

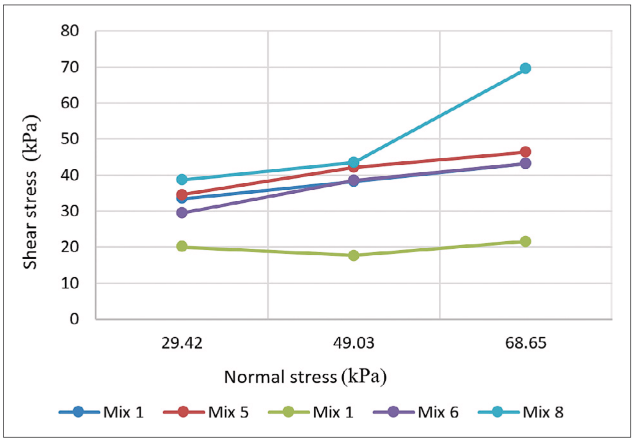

**Figure 11:** The variations of maximum shear stress with an increase in normal stress for 5 mixing designs

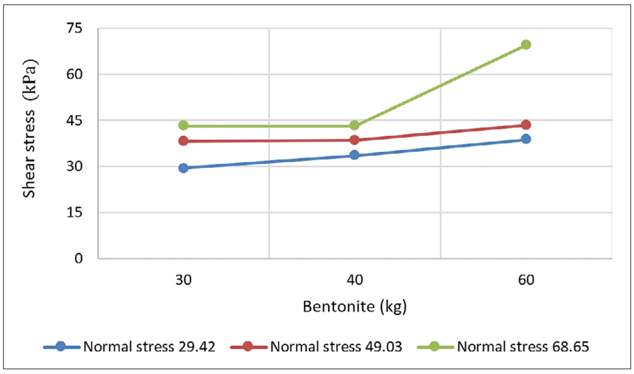

**Figure 12:** The chart of investigating the effect of increasing bentonite on the maximum shear stress for 3 different normal stresses

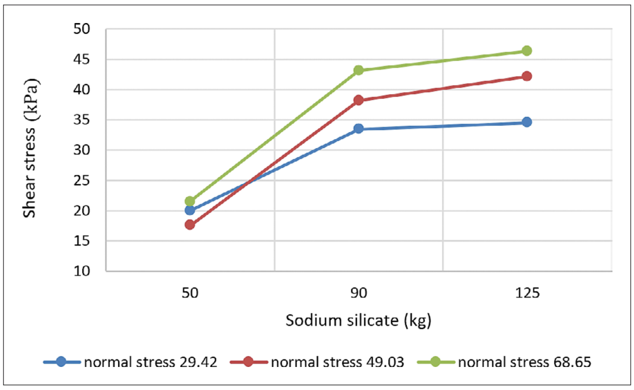

**Figure 13:** The chart of investigating the effect of increasing sodium silicate on the maximum shear stress for 3 different normal stresses

According to the results obtained from the water bleeding measurements of the eight mixing designs, it is observed that increasing the amount of bentonite in the composition of the first component of the grout plays a significant role in reducing water bleeding. Specifically, the 30 kg and 60 kg bentonite additions yield unacceptable water bleeding results. The chart depicting the water bleeding with variations in the amount of bentonite is presented in **Figure 5**.

## 3.4. Uniaxial Compressive Strength Test

This test is performed on hardened grout and is conducted according to the **ASTM C109-99 (2005)** standard. The test procedure follows: after preparing the two-component grout, the grout is poured into cylindrical molds with a length-to-diameter ratio of 2. The surface of the samples is levelled and covered. The samples are removed from the molds at the desired ages and placed in the uniaxial compressive strength testing machine. In this study, the uniaxial compressive strength test was conducted on 8 mixing designs at 4 different ages: 2 hours, 1 day, 7 days, and 28 days. Since three samples were prepared for each age of the grout, 96 cylindrical samples were subjected to the uniaxial compressive strength test to conclude the test and obtain the results (see **Figure 6**).

In each mixing design of the grout, the 2-hour samples are removed from the molds after 2 hours and transferred directly to the testing machine. The 1-day samples are also removed from the molds after 24 hours and transferred to the testing machine. However, for the 7-day and 28-day samples, after 24 hours, they are transferred to the concrete curing tank and remain there until the 7th and 28th day, respectively. Then they are removed from the curing tank and transferred to the testing machine. As mentioned before, three samples were prepared for each age of the mixing designs, and the average strength of the samples was used. In **Figure 7**, an example of a fractured sample in the laboratory is presented.

**Table 5** provides the results of the uniaxial compressive strength test for all mixing designs.

After normalizing the data in **Table 5** and removing the samples that showed significant differences in strength values, the remaining strengths were averaged. The final data for the uniaxial compressive strength of the grout mixing designs at 4 different ages are presented in **Table 6**.

**Figure 14:** The fractured samples under shear stress in the direct shear apparatus

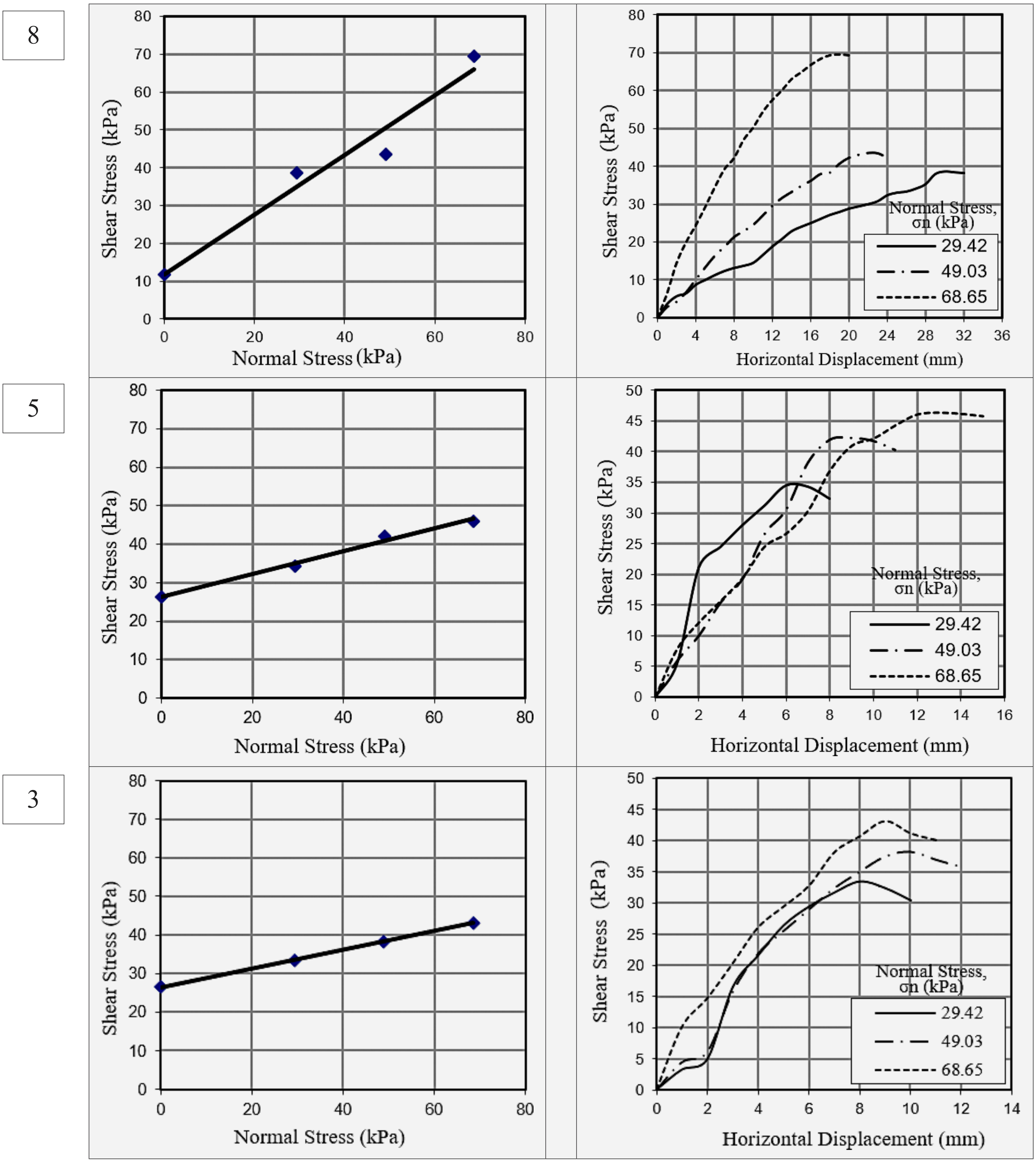

**Figure 15:** Calculating the cohesion and internal friction angle

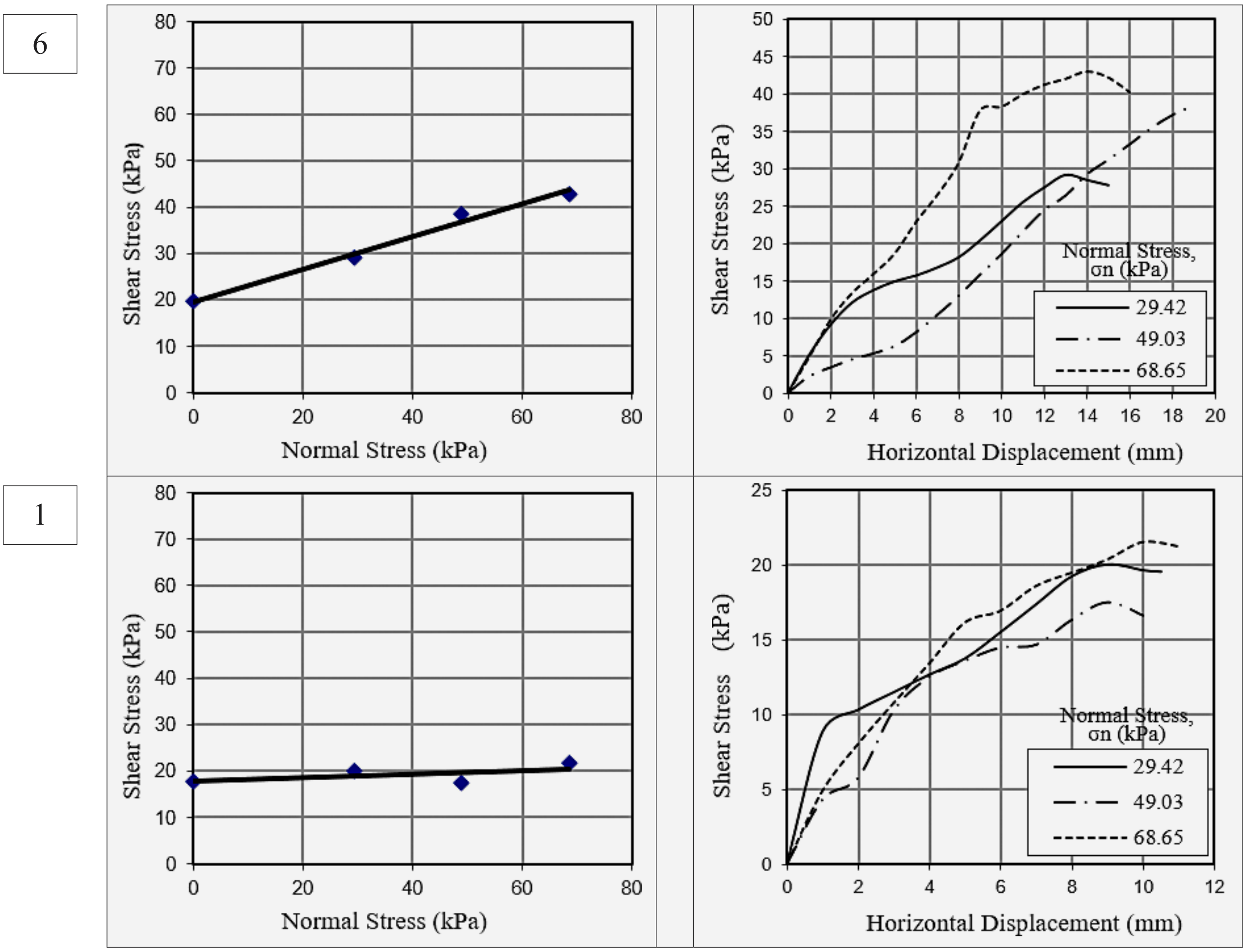

**Figure 15:** Calculating the cohesion and internal friction angle (continued)

**Table 8:** Results for cohesion and friction angle for 5 mixing designs

| Mixing Design No. | C (*kPa*) | φ (degree) |
|---|---|---|
| **3** | 26.48 | 14 |
| **5** | 26.48 | 17 |
| **1** | 17.65 | 2 |
| **6** | 19.61 | 19 |
| **8** | 11.77 | 38 |

The results of the uniaxial compressive strength test based on variations in the amounts of bentonite and sodium silicate at different ages are shown in **Figures 8** and **9**. As can be observed from these charts, increasing the amounts of bentonite and sodium silicate in the grout mixture leads to an increase in uniaxial compressive strength. Additionally, the age of the grout also plays a significant role in the strength development and increase in compressive strength. The increase in bentonite at 50 and 60 kilograms has a more significant impact on the strength. On the other hand, adding sodium silicate at 100 and 125 kilograms significantly increases the uniaxial compressive strength.

## 3.5. Direct shear test

The direct shear test is a standard method for measuring the mechanical properties of soils, which can also be used to investigate the properties of grouts. In this test, the grout samples are placed in the shear box apparatus (see **Figure 10**), the samples are placed in square molds with dimensions of 10×10×2 cm for direct shear test and vertical and horizontal forces are sequentially applied to the sample to obtain various parameters such as internal friction angle and cohesion. This test can be used as one of the methods to assess the stability of grouts.

### 3.5.1. The test procedure

Initially, the bentonite used in each mixing design was prepared 24 hours before conducting the test. Then, the first component of the grout was prepared according to the specified values for each design. Cubic molds were greased and tightly sealed to prevent grout from leaking out. Sodium silicate was added to the grout and poured into the molds. Three samples were required for each mixing design to apply different loads. After molding the samples, they were covered and, after 24 hours, removed from the molds and placed inside the shear box

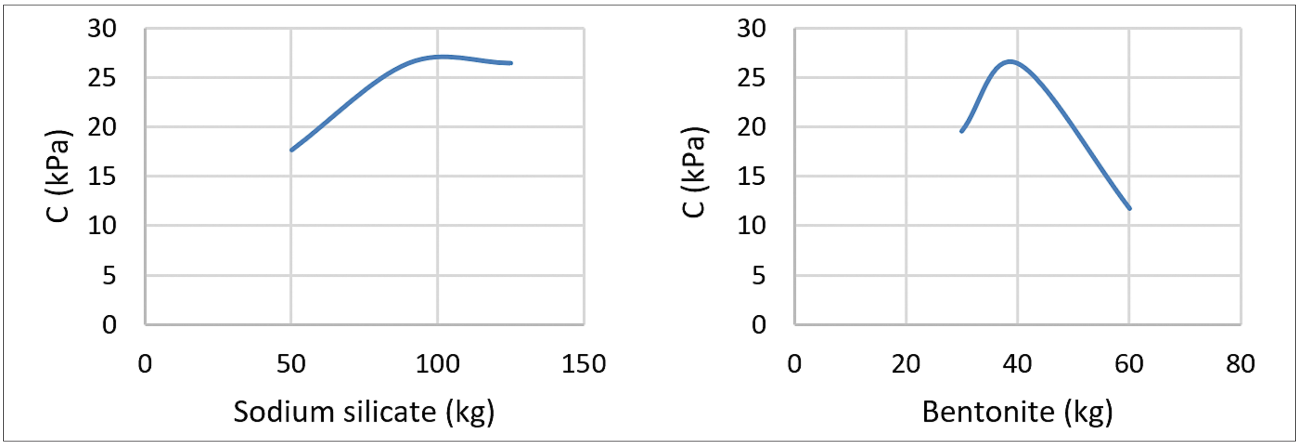

**Figure 16:** The chart of changes in the amount of cohesion in 5 mixing designs with increasing amounts of bentonite and sodium silicate

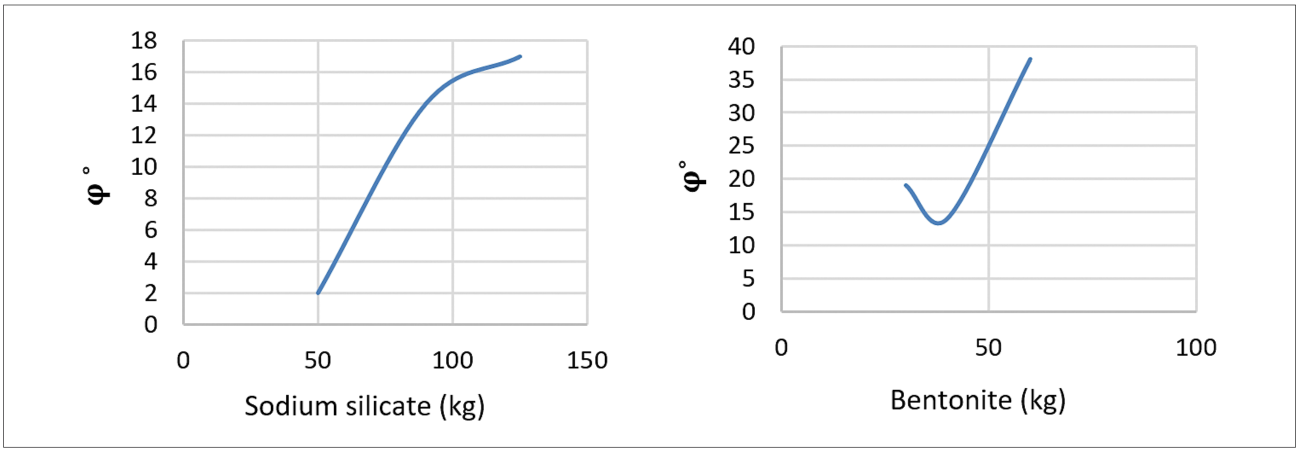

**Figure 17:** The chart of changes in the amount of frictional angle in 5 mixing designs with increasing amounts of bentonite and sodium silicate

apparatus. The direct shear test was performed under three different normal stresses. The results of the direct shear test for the selected five mixing designs are presented in **Table 7**.

The chart showing the variations of maximum shear stress with an increase in normal stress for each of the five selected mixing designs is presented in **Figure 11**.

In the chart of **Figure 12**, the effect of bentonite on the variations of maximum shear stress with an increase in normal stress is examined. In this comparison, mixing designs numbered 6, 3, and 8, corresponding to bentonite values of 30, 40, and 60 kilograms, respectively, are used. As observed, with an increase in bentonite to 60 kilograms, the maximum shear stress significantly increases at a normal stress of 68.65 (*kPa*).

In the chart of **Figure 13**, the effect of increasing sodium silicate content on the variations of maximum shear stress with an increase in normal stress is examined. The maximum shear stress increases by up to 2.5 times with increased sodium silicate content.

The samples tested after the experiment are presented in **Figure 14**.

The main objective of conducting the direct shear test on the grouts in the five mixing designs was to determine the cohesion and internal friction angle of these designs. Therefore, the following charts related to each design for obtaining the cohesion and internal friction angle are presented in **Figure 15**. Based on the charts in **Figure 15**, the cohesion and internal friction angle for each of the five designs are provided in **Table 8**. **Figures 16** and **17** examine the influence of increasing bentonite and sodium silicate on the variations of cohesion and internal friction angle for the tested mixing designs.

Both bentonite and sodium silicate are added to the grout mixture based on the injection objectives and the type of grout, resulting in the improvement of its properties, including stability and cohesion. The direct shear test also demonstrates the influence of bentonite and sodium silicate on increasing the cohesion and internal friction angle. As observed in **Figure 16**, an increase in bentonite from 30 to 40 kilograms leads to an increase in grout cohesion, but a further increase in bentonite reduces cohesion. However, the situation is opposite for the internal friction angle; that is, the angle decreases with an increase in bentonite up to 40 kilograms and then increases. Regarding the effect of sodium silicate that both cohesion and internal friction angle increase with an increase in sodium silicate.

As mentioned, the direct shear test is commonly used to investigate the mechanical properties of soils. However, in this study, an effort has been made to perform this test on grouts to determine the desired parameters. The test was conducted on mixing designs numbered 3, 5, 1, 6, and 8, which correspond to the main mixing design, the mixing design with the highest amount of sodium silicate, the mixing design with the lowest amount of sodium silicate, the mixing design with the lowest amount of bentonite, and the mixing design with the highest amount of bentonite, respectively. It should be noted that all samples with each mixing design were tested at an age of 1 day. Three samples were prepared for each mixing design and subjected to three different vertical stresses (29.42, 49.03 and 68.65 (*kPa*).

## 4. Conclusion

The main objective of this research was to evaluate the effect of different parameters on the properties of the two-component grout used for injection behind segments. The influence of bentonite and sodium silicate in the grout mixture was investigated. One of the key innovations of the present research lies in its focus on optimizing a two-component grout mixture for tunnel boring machine (TBM) excavation. By specifically investigating the effects of bentonite and sodium silicate on the mechanical properties of the grout, this study offers a targeted approach to improving the performance of grouting materials used in urban tunnelling projects. The research's innovative aspect also stems from its comprehensive testing methodology, which includes assessing parameters such as Gel-time, viscosity, water bleeding, uniaxial compressive strength, and direct shear strength. By conducting a series of tests to evaluate various aspects of the grout's behaviour, the study provides a detailed understanding of how different mixing designs impact the material's properties.

1. Gel-Time decreases with the presence of bentonite and sodium silicate in the grout mixture, and it changes with variations in the amount of these two materials.
2. Bentonite, as one of the grout structure components, increases the viscosity of the grout due to water absorption and reduces the water-to-cement ratio in the mixing design. Similarly, sodium silicate-containing grouts also have high viscosity.
3. Bentonite, due to its high-water absorption capacity, reduces the bleeding of the grout and contributes to stabilizing the first component of the grout. This demonstrates the critical role of bentonite in the herded grout.
4. Both bentonite and sodium silicate play an essential role in increasing the strength and resistance of the grout due to their inherent properties.
5. In addition to bentonite and sodium silicate, the age of the grout also has a significant impact on the increase in strength and resistance.
6. Increasing the amounts of bentonite and sodium silicate in the grout mixture leads to an increase in both the shear strength and compressive strength of the grout.
7. Increasing the sodium silicate in the grout mixture results in an increase in the values of cohesion and internal friction angle. Both cohesion and internal friction angle depend on the mixing design and will change with variations in the material quantities.

Finally, based on the results obtained from the conducted tests, the permissible ranges for the results of each test were examined according to the existing standards. Mixing designs with results outside the permissible range was eliminated. Mixing designs numbered 1 to 5 were within the permissible range, among which mixing design number 3 is introduced as the optimal design for the injection grout combination.

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## SAŽETAK

### Laboratorijsko ispitivanje utjecaja natrijeva silikata i bentonita na mehanička svojstva smjese za injektiranje pozadine tunelskih segmenta pri strojnome iskopu

Danas je u tunelogradnji u urbanim sredinama znatno porasla upotreba strojeva za bušenje tunela (TBM). Jedan od najučinkovitijih parametara iskapanja prilikom korištenja ovih vrsta strojeva jest upotreba smjese za injektiranje pozadine tunelskih segmenata kako bi se spriječilo slijeganje tla i prodiranje u tunel. Ispitivanje utjecaja dvokomponentne injektne smjese (bentonit i natrijev silikat) na njezina mehanička svojstva igra ključnu ulogu pri strojnome iskopu. Stoga je cilj ovoga članka istražiti utjecaj različitih parametara na svojstva dvokomponentne smjese koja se koristi za injektiranje pozadine tunelskih segmenata. U ovome istraživanju razmatrano je osam različitih načina miješanja. Tijekom istraživanja za svaki način miješanja provedeni su testovi vremena geliranja, testovi viskoznosti, određivanje izdvajanja vode, testovi jednoosne tlačne čvrstoće (UCS) i testovi izravnoga smicanja. Ispitivanja jednoosne tlačne čvrstoće provedena su za osam načina miješanja i pri četiri različita vremena starosti smjese (2 sata, 1 dan, 7 dana i 28 dana), dok je ispitivanje izravnoga smicanja provedeno za pet načina miješanja starosti 1 dan. Rezultati provedenih ispitivanja pokazali su da je povećanje udjela natrijeva silikata s 4 % na 9,4 % smanjilo vrijeme geliranja na 7 sekundi, a povećanje udjela bentonita s 2,3 % na 4,58 % povećalo vrijeme viskozimetra na 12 sekundi. Jednoosna tlačna čvrstoća smjese za injektiranje porasla je na 0,682 MPa u vremenu od 28 dana. Na kraju, provođenjem ispitivanja direktnoga smicanja na smjesi i dobivanjem parametara kohezije i kuta unutarnjega trenja utvrđeno je da ova dva parametra ovise o vrijednostima bentonita i natrijeva silikata, a mijenjaju se s povećanjem ili smanjenjem komponenata smjese.

**Ključne riječi:**
strojno iskopavanje, dvokomponentna injekcijska smjesa, bentonit, natrijev silikat, vrijeme geliranja, jednoosna čvrstoća

## Author’s contribution

**Erfan Khoshzaher (1)** (PhD candidate of Mining Engineering) performed experimental tests, processed their results and prepared the samples for UCS and direct shear tests. **Samaneh Khodaei (2)** (MSc graduated of Mining Engineering) performed experimental tests, processed their results and prepared the samples for tests. **Hamid Chakeri (3)** (PhD, Associate Professor) proposed the idea and guided the research.