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Experimental study on Injectivity of Backfill Grouts for Shield TBM

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ABSTRACT

Grouting is considered an important process in the shield TBM tunneling for ensuring tunnel stability (ex. controlling water ingress and reducing ground settlement). To address this, two-component grouts incorporating gelling agents, such as sodium silicate, have become standard practice. However, current tunnel specifications lack clear criteria for mix proportions and key performance indicators such as injectivity. Especially, the ratio of sodium silicate is critical for gel formation, yet previous studies have mainly focused on water-cement ratios, with limited attention to sodium silicate content and injectability. In this study, fresh-state tests and injectivity tests were conducted to investigate the effect of sodium silicate content on the injection performance of silicate-based backfill grout. Based on the experimental results, optimal mix proportions were proposed for practical field applications.

1. INTRODUCTION

The shield tunneling method is increasingly being adopted for urban tunnel excavation due to its advantages over conventional drill-and-blast methods, such as the NATM (New Austrian Tunneling Method). In urban environments, soft ground conditions—such as reclaimed layers and soil-cobble layers—are frequently encountered, requiring ground reinforcement or improvement. Grouting is widely

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employed to stabilize tunnel excavations in such soft soils (Yoon et al., 2018). In particular, during the installation of concrete segment linings, backfill grout is injected to fill the annular gap between the segment and the excavated surface to ensure structural stability and prevent void-induced settlement (Fig. 1). In shield TBM tunneling, backfill grouting is a critical procedure for maintaining tunnel integrity by minimizing ground subsidence and groundwater inflow into the tunnel.

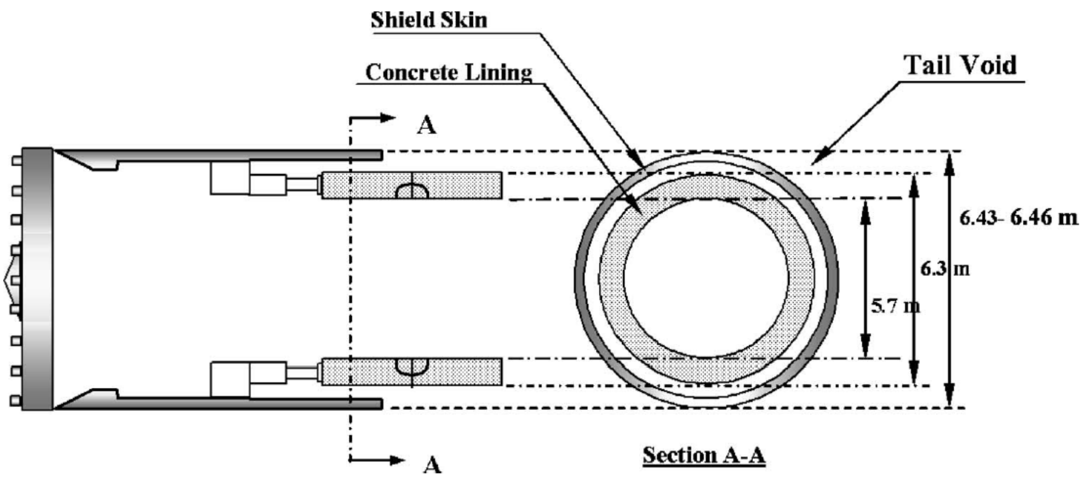

Fig. 1 Tail void between the concrete lining and the excavated surface (Suwansawat & Einstein, 2007)

In tunnel construction, two-component backfill grout is predominantly used for backfilling. This system consists of Component A, a suspension composed of cement, water, bentonite, and stabilizers, and Component B, primarily made of sodium silicate. When Components A and B are mixed and injected, the gelation process is influenced by several factors, including the water-to-cement ratio, stabilizer content, and most significantly, the concentration of sodium silicate in Component B (Zhu et al., 2021). The gelation characteristics directly affect the injectivity of the backfill grout. However, there is a lack of quantitative construction guidelines related to backfill grout application in both domestic and international standards. According to the Korean tunnel specifications, there are no detailed references or examples regarding the material properties or mixing ratios of two-component backfill grout. Furthermore, key factors such as filling capability—crucial for shield TBM operations—are not adequately addressed. As a result, the absence of proper guidelines has led to inconsistent on-site practices, often relying on empirical methods. This has led to a range of issues, including water leakage into the tunnel interior, as reported in various case studies.

There are numerous studies that analyzed mix proportions of backfill focusing on properties such as compressive strength, density, and permeability coefficient. However, most of the previous research has concentrated on the influence of the water-to-cement (W/C) ratio, particularly in relation to the durability of two-component grouts, while studies on the filling capability associated with the sodium silicate (B-component) content remain limited. For instance, Lee et al. (2022) conducted experiments on inorganic thixotropic backfill grouts, analyzing the compressive strength and gelation time with varying W/C ratios. In addition, other researchers have examined trends in properties such as density, compressibility, and permeability with respect to the W/C ratio (Zhu et al., 2021; Han et al., 2007; Yu et al., 2018). Since the gelation is primarily influenced by sodium silicate content, an evaluation of the backfill grout with varying sodium silicate ratios is essential. In particular, the injectivity of backfill grout is strongly influenced by the content of sodium silicate. Key parameters related to injectivity include gelation time, thixotropy maintenance time, and flowability. It is important that a grout cannot be considered optimal based on a single favorable parameter. Rather, a balanced combination of all relevant parameters is essential for achieving a mix design with effective injectivity.

In this study, laboratory tests including gelation time, thixotropy maintenance time, and flow table tests were conducted on two-component backfill grout commonly used in the field. Based on the results, the optimal mixing ratio of Sodium silicate for achieving desirable injectivity was identified. To validate the selected ratio, an injection test was carried out using an reduced-scale experimental model to assess its injectivity.

2. Injectivity Characteristics of Fresh-State Grouts

Gelation time, thixotropy retention time, and flowability were selected as key indicators relevant to grout injectability. Laboratory tests were performed using two-component backfill grouts commonly applied in field. Three different A-component formulations were prepared: the standard field material (B), a modified material with an increased bentonite content compared to the standard (B-1), and a material in which the cement in the standard formulation was replaced with ordinary Portland cement (OPC) (B-2). For each A-component, five different sodium silicate (B-component) ratios were tested, resulting in a total of 15 test cases. The physical properties of each case were evaluated through experiments (Table 1).

Table 1. Mix proportions of materials used in this study

Material	Case	Component A					Component B	W/C [%]	H/W [%]
		Cement [kg]		Bentonite [kg]	Retarder [kg]	Water [kg]	sodium silicate [kg]		
		TC	OPC						
B	B-1	330	-	24	3	810	100	245	10.71
	B-2						75		8.06
	B-3						50		5.39
	B-4						125		13.33
	B-5						150		15.94
B-1	B-1-1	330	-	60	3	900	100	272	9.65
	B-1-2						75		7.26
	B-1-3						50		4.86
	B-1-4						125		12.02
	B-1-5						150		14.38
B-2	B-2-1	-	330	24	3	810	100	245	10.71
	B-2-2						75		8.06

	B-2-3						50		5.39
	B-2-4						125		13.33
	B-2-5						150		15.94

*TC: Thixotropy Cement, OPC: Ordinary Portland Cement, W/C: Water to Cement Ratio, H/W: Harder (Sodium Silicate) to Water Ratio

2.1 Gelation time

Gelation time is a key parameter of the workability of grouting materials. The addition of sodium silicate significantly accelerates the hydration of cement. The main component, $Na_2O·nSiO_2$, reacts with $Ca(OH)_2$ to rapidly form C–S–H gel. This reaction also promotes the hydration of C_3S by consuming $Ca(OH)_2$, further increasing gel formation and leading to a sharp rise in viscosity (Wang et al., 2019).

The gelation time was obtained using the inverted cup method, in which Component A and Component B are alternately poured and mixed by tilting between two beakers (Fig. 2). This method is widely adopted in construction sites due to its practicality. According to ASTM standards, the gelation time is defined as the time required for the mixture to reach a viscosity of 100 mPa·s (ASTM D4016-14). However, this method is difficult to apply directly in field conditions. Therefore, in this study, the inverted cup method was chosen as a more practical approach that better reflects field conditions. Fig. 3 shows that an increase in the sodium silicate (B-component) content resulted in a longer gelation time in all materials. Notably, when thixotropy cement was used, the gelation time remained within approximately 10 seconds, which is about half that of the mix using ordinary Portland cement (OPC). This indicates that thixotropy cement is more suitable for ground conditions requiring rapid gelation, such as soft ground or highly permeable ground with a high risk of dilution by groundwater. Additionally, despite an increase in bentonite content, the change in gelation time was minimal, suggesting that bentonite has little influence on the gelation process in this study.

Fig. 2 Inverted cup method

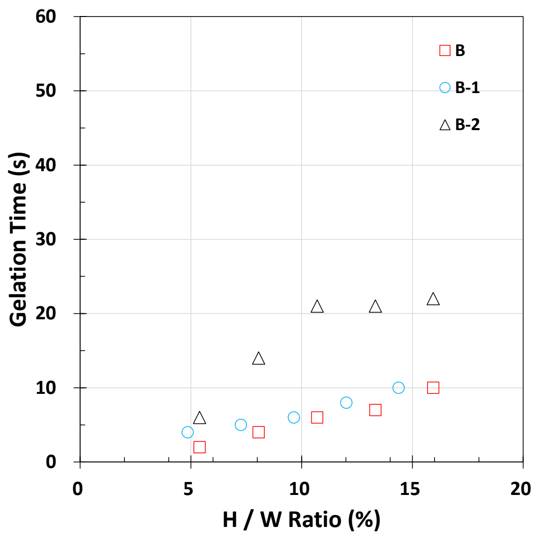

Fig. 3 Gelation time of materials according to H/W ratio

2.2 Thixotropy maintenance time

The thixotropy maintenance time test was conducted in accordance with an on-site quality control procedure, where manual pressure was applied to grout in a plastic bag at 5-minute intervals to identify the point of material breakage (Fig. 4). Fig. 5 showed that thixotropy maintenance time decreased as the sodium silicate content increased. The materials containing thixotropy cement exhibited superior thixotropy maintenance time compared to those using ordinary Portland cement (OPC) or increased bentonite content. Furthermore, when the harder-to-water (H/W) ratio exceeded 12%, thixotropy maintenance time dropped sharply—by approximately 80%—and converged to 5 minutes across all materials. This indicates that excessive use of sodium-silicate in the field may significantly reduce the workable time, increasing the risk of hose clogging. Therefore, maintaining the sodium silicate content within an acceptable range is recommended for field implementation.

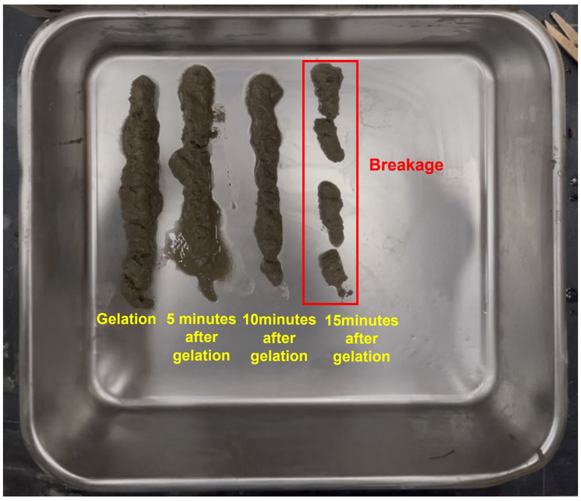

Fig. 4 Thixotropy maintenance test

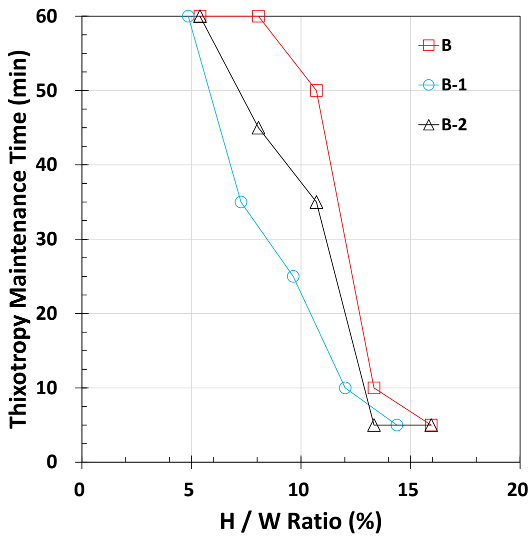

Fig. 5 Thixotropy maintenance time of materials according to H/W ratio

2.3 Flowability

Flowability of the materials was measured through a flow table test conducted in accordance with the ASTM standard (ASTM C 1437). Flowability was defined as the ratio of the base diameter (D_i) measured immediately after gelation to the average base diameter (D_{avg}) measured after 25 drops at a rate of one drop per second (Fig. 6 and Eq. (1)). The average base diameter was determined by taking four measurements and calculating their average.

$$Flowability\ (\%) = \frac{D_{avg}}{D_i} \tag{1}$$

As the sodium silicate content increased, the flowability decreased (Fig. 7). The material containing thixotropy cement exhibited the highest flowability. Consistent with the thixotropy maintenance time results, it was observed that when the harder-to-water (H/W) ratio exceeded 12%, flowability was significantly reduced or lost across all material.

Fig. 6 Flow table test

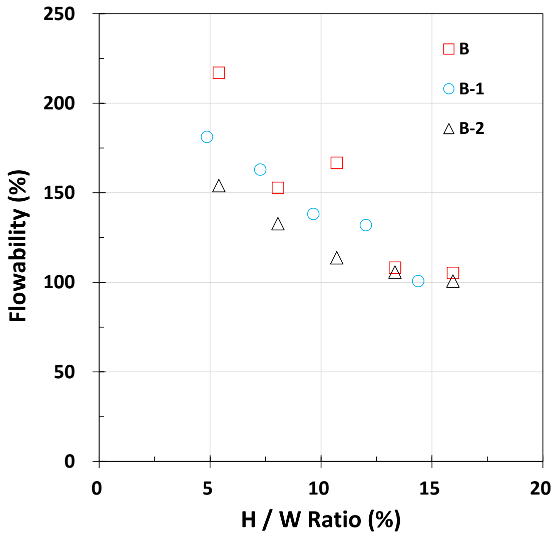

Fig. 7 Flowability of materials according to H/W ratio

3. Selection of the Optimal Sodium Silicate Content Based on Injectivity Indicators

The optimal dosage of sodium silicate was derived based on a comprehensive assessment of three critical parameters governing injectivity performance: gelation time, thixotropy maintenance time, and flowability. According to commonly adopted field criteria, the appropriate gelation time ranges from 5 to 20 seconds, the minimum required thixotropy maintenance time is 15 minutes, and the minimum flow rate value should exceed 112.5%, as defined by ASTM standards. Considering these criteria, the optimal hardener-to-water ratio satisfying all criteria was found to be 10.2 ± 0.5 % (Fig. 8). This analysis was conducted using the materials containing thixotropy cement, which consistently showed superior performance across all fresh-state tests.

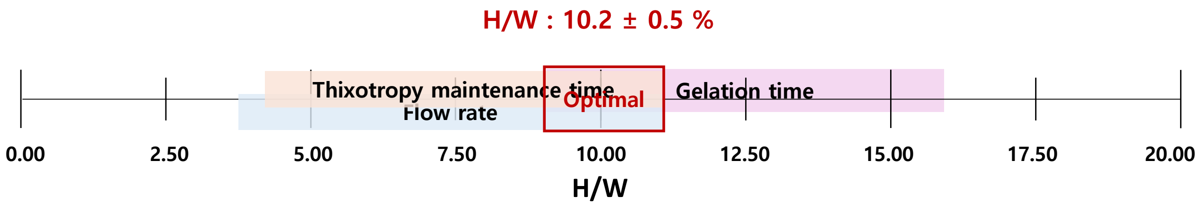

Fig. 8 Selection of the optimal sodium silicate content based on injectivity indicators

4. Validation of the Optimal Sodium Silicate Content Through Injection Test

To evaluate the injectivity of the selected sodium silicate ratio, an injection test system was constructed. As shown in Fig. 9, Components A and B were delivered through separate tubing lines using peristaltic pumps and injected into the experimental model simultaneously. A T-shaped injection pipe was used to ensure simultaneous flow of both components, simulating the actual field injection process. The tail void model used in the experiment represents a 1/8 scale replica of the actual power tunnel geometry.

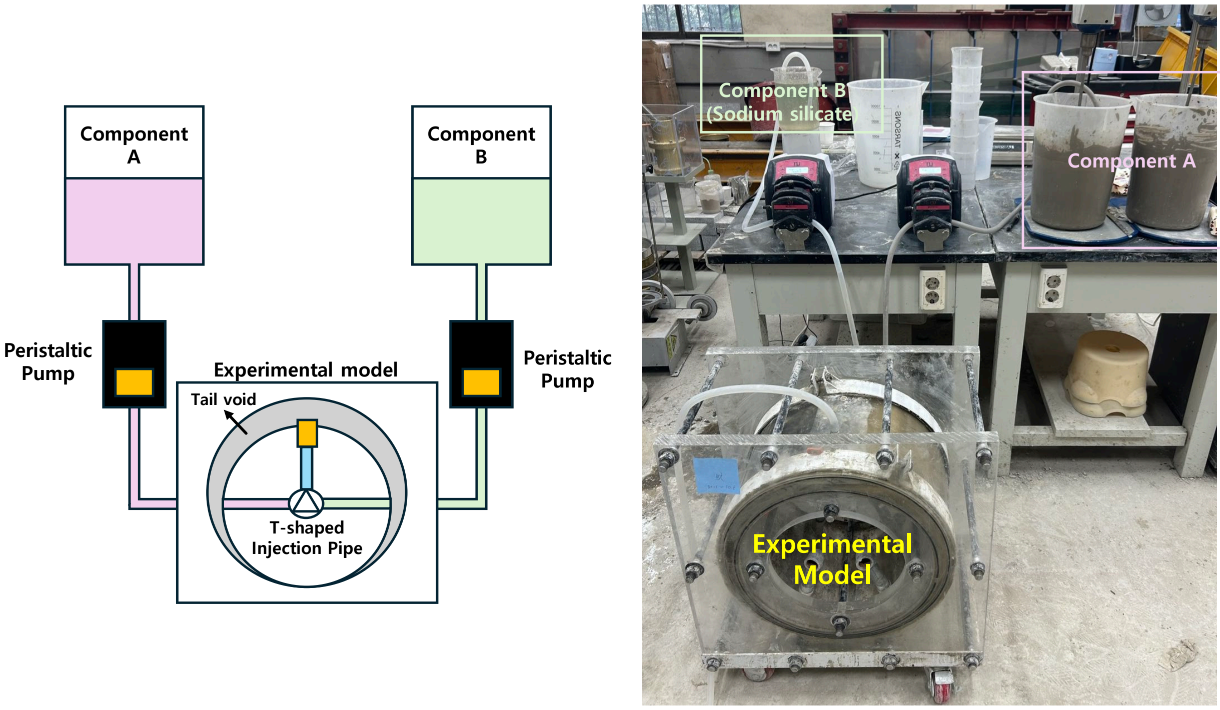

Fig. 9 Schematic diagram (left) and experimental set up (right) of the injection test system

In this study, the injectivity of backfill grout was analyzed under three different conditions (Fig. 10). Case 1 used the optimal sodium silicate ratio, while Cases 2 and 3 involved under-dosing and over-dosing of the sodium silicate, respectively. Under identical injection pressure conditions, both non-optimal cases resulted in approximately 1.2 kg less grout being injected compared to Case 1. This corresponds to roughly 20% of the actual tail void volume, indicating a 20% reduction in backfilling. In the under-dosed case, the gelation time was as short as 2 seconds, causing the grout to set before adequate injection could occur. In contrast, in the over-dosed case, the thixotropy maintenance time was limited to only 5 minutes, providing insufficient workable time for complete filling. On the other hand, the optimal mix ratio satisfied all performance criteria, enabling stable and complete grout injection. These findings underscore the importance of establishing an appropriate sodium silicate dosage to ensure effective and reliable backfilling in shield TBM operations.

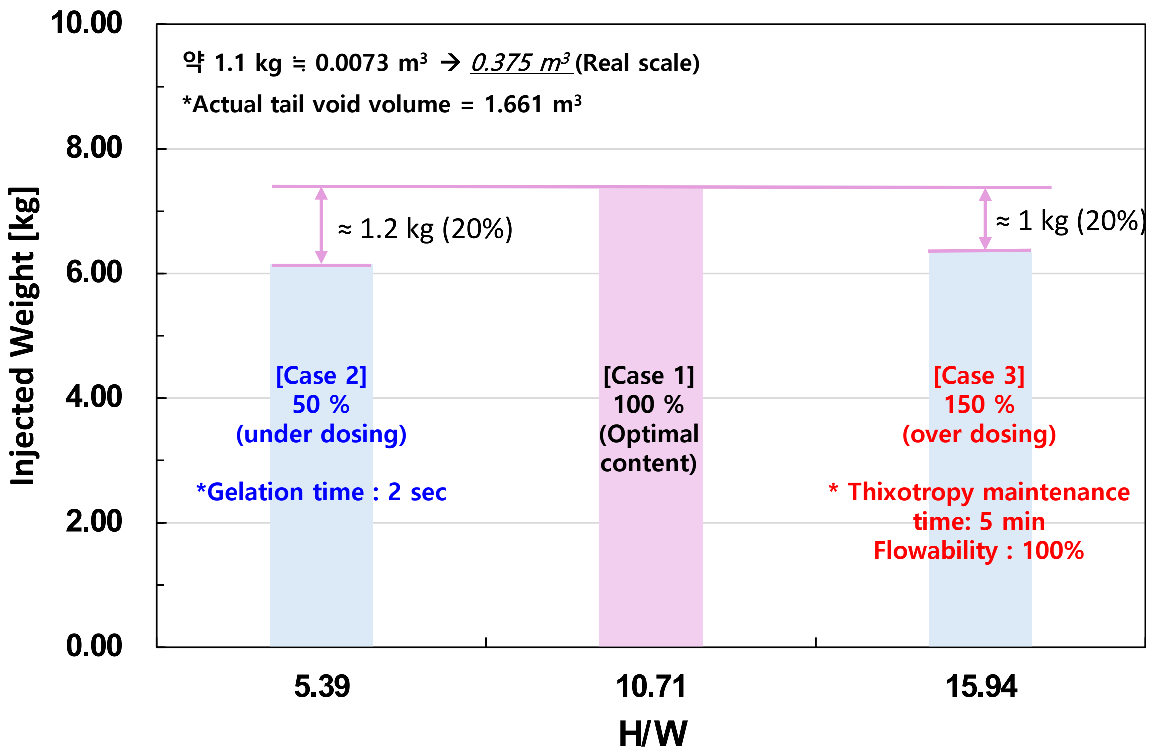

Fig. 10 Injectivity performance by dosage condition (optimal, under, over)

5. Conclusion

In this study, a series of fresh-state tests—gelation time, thixotropy maintenance time, and flow table tests—were conducted to evaluate the injectivity of two-component backfill grouts with varying sodium silicate content. The results are as follows:

- A gelation time within 5 to 20 seconds is desirable to ensure timely setting, particularly in soft ground conditions prone to groundwater dilution.
- Thixotropy maintenance time should exceed 15 minutes to allow for sufficient workability during field application.
- A flow rate of 112.5% or higher, as defined by ASTM standards, is recommended for ensuring optimal grout fluidity.

Thixotropic cement provides superior performance in terms of both workability and flowability. In particular, when the water-to-hardener (H/W) ratio is maintained at 10.2 ± 0.5 (range: 9.65–10.71), all three criteria is satisfied. Furthermore, Injection tests confirmed that using a non-optimal sodium silicate dosage can result in a 20% reduction in injectivity, highlighting the critical importance of proper sodium silicate dosage for achieving effective and reliable backfilling in shield TBM operations.

This study provides a practical guideline for optimizing sodium silicate dosage to ensure stable and effective backfilling in shield TBM applications. Future research should focus on validating the proposed mix under site-specific conditions—including groundwater and soft ground environments—and evaluating the long-term mechanical performance of the backfill material.

6. Acknowledgement

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