The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Use of foam and polymer for conditioning rheological properties of weathered granite soils in EPB tunneling

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ABSTRACT

The earth pressure balance (EPB) shield tunnel boring machine (TBM) is a widely used tunneling method that ensures face stability by regulating muck discharge during excavation. To enhance the properties of the excavated soil (muck), additives are introduced through a process known as soil conditioning. This study investigates the rheological properties of weathered granite soils conditioned with foam and polymer additives, using slump tests and laboratory pressurized vane shear tests. The additives were applied at varying injection ratios and concentrations. Vane shear tests were conducted under a chamber pressure of 200 kPa, simulating an excavation depth of approximately 20 m. Key rheological properties such as workability, peak strength, and yield stress were evaluated.

1. INTRODUCTION

Earth pressure balance (EPB) shield tunnel boring machines (TBMs) maintain tunnel face stability by counterbalancing earth pressure with the pressure inside the excavation chamber. A critical factor in successful EPB tunneling is soil conditioning, where additives such as foam and polymers are used to modify the properties of the excavated soil. These additives reduce internal friction, enhance plastic flow, and improve face support. Foam facilitates lubrication and fluidization (Avunduk et al., 2021; Peila, 2014), while polymers increase cohesiveness and reduce permeability, both of which contribute to lower cutterhead torque and smoother excavation (Alberto-Hernandez et al., 2018). In this study, the rheological behavior of weathered granite soils

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conditioned with foam and polymer was assessed through slump tests and laboratory pressurized vane shear tests. The findings provide insights into the effectiveness of foam and polymer conditioning for weathered granite soils in EPB tunneling applications.

2. RHEOLOGICAL PROPERTIES

To investigate the rheological properties of conditioned soils, torque data obtained from vane shear testing were used to generate rheograms, which represent the relationship between shear stress and shear rate, as defined in Eqs. (1) and (2). From these rheograms, key parameters such as peak strength and yield stress were derived. In this study, shear stress distribution was assumed to follow the geometry of the vane, with uniform stress applied along the outer cylindrical surface. It was also assumed that the vane rotates freely without upper or lower constraints, consistent with previous studies (Meng et al., 2011).

$$\tau = \frac{2T_m}{\pi {D_v}^3 \left(\frac{H_v}{D_v} + \frac{1}{3}\right)} \tag{1}$$

$$\dot{\gamma} = \frac{4\pi {D_c}^2}{60({D_c}^2 - {D_v}^2)} \omega_{vane} \tag{2}$$

where τ is the shear stress (Pa), T_m is the measured torque $(N \cdot m)$, D_v is the vane diameter (m), H_v is the vane height (m), and $\dot{\gamma}$ is the shear rate (s^{-1}), D_c is the chamber inner diameter (m), and ω_{vane} is the vane rotation speed (rpm).

3. EVALUATING RHEOLOGICAL PROPERTIES OF CONDITIONED SOIL

3.1 Soil Condition

For the slump and laboratory pressurized vane shear tests, a weathered granite soil was prepared, which is classified as poorly graded sand (SP) according to the unified soil classification system (USCS). The dry unit weight of the soil specimens was assumed to be 1.9 t/m^3, with a specific gravity of 2.69. This type of soil is representative of ground conditions suitable for EPB shield TBMs, as suggested by Maidl (1995).

3.2 Slump Test

The workability of conditioned soil with varying additive injection levels was evaluated using slump tests for selected cases. The tests were conducted in accordance with ASTM C143 (2020), and the experimental cases and results are summarized in Table 1.

Table 1. Slump test cases and results

Case number	FIR (%)	PIR (%)	Slump value (mm)	Note
F1	20	-	26	Effect of foam
F2	30		133	
F3	40		190	
F4	50		220	

FP1	30	5	95	Effect of foam and polymer
FP2	30	10	70	
FP3	30	15	55	
FP4	30	20	41	

The slump value increased as the foam injection ratio (FIR) increased. Cases F2 and F3 fell within the optimal slump range for desirable workability. Among them, FIR 30% (Case F2) provided the most favorable workability and was therefore selected as the baseline condition for evaluating the effect of polymer conditioning. When polymer was additionally injected under this baseline condition, the slump value decreased as the polymer injection ratio (PIR) increased.

3.3 Laboratory pressurized vane shear test

The rheological properties of conditioned soils were investigated using a laboratory pressurized vane shear test apparatus developed by Lee (2021). The apparatus features a torque sensor for real-time measurement of rotational resistance and is equipped with dual pressure sensors to monitor internal chamber pressure. The vane, designed according to ASTM D4648 (2016), comprises four blades with a diameter-to-height ratio of 1:2 (50 mm in diameter and 100 mm in height). To simulate in-situ stress conditions at an excavation depth of 20 m, the vane shear tests were conducted under a chamber pressure of 200 kPa.

4. ANALYSIS OF RHEOLOGICAL PROPERTIES OF CONDITIONED SOIL

4.1 Effects of Foam Injection

The laboratory pressurized vane shear tests were performed for Cases F1 through F4 to investigate the influence of the FIR on the rheological behavior of conditioned soils. Fig. 1 presents the rheological properties of the conditioned soils across varying FIR levels. As the FIR increased, both peak strength and yield stress generally decreased. Notably, beyond the FIR 30%, the rate of reduction in these rheological properties diminished considerably.

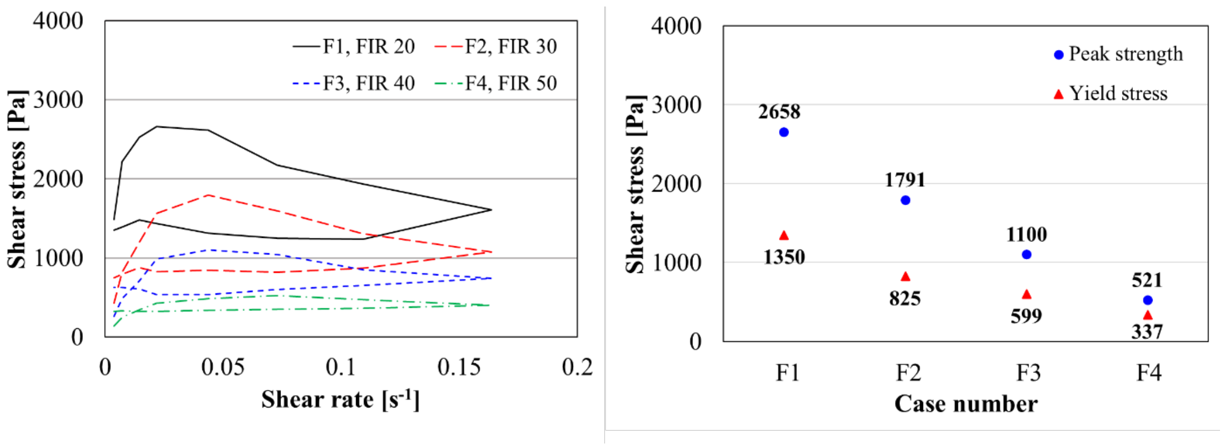

Fig. 1 Rheological properties according to FIR

4.2 Effects of Polymer Injection

Fig. 2 illustrates the rheological properties of conditioned soils across varying PIR levels. As the PIR increased, both peak strength and yield stress exhibited corresponding increases. In particular, the rate of increase in peak strength accelerated with higher polymer content, suggesting a nonlinear reinforcing effect associated with increasing PIR.

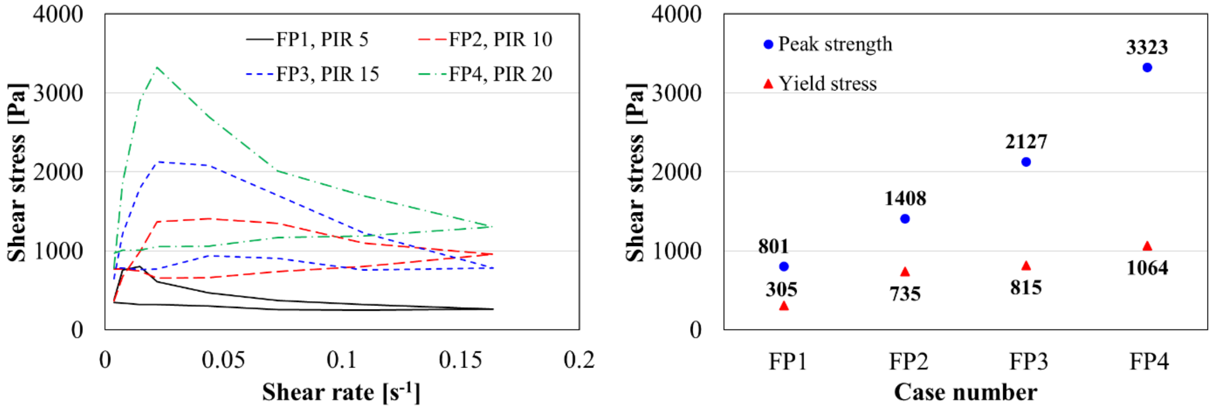

Fig. 2 Rheological properties according to PIR

5. CONCLUSIONS

This study investigates the rheological behavior of weathered granite soil conditioned with both foam and polymer additives using a laboratory pressurized vane shear test. Initial workability was assessed through slump tests. The results demonstrate that increasing the FIR enhances both the workability and rheological properties of the conditioned soil. However, beyond an FIR of 30%, the incremental improvements in rheological performance diminish, indicating a reduction in conditioning efficiency. The addition of polymer at FIR 30% generally led to increased peak strength and yield stress. Nevertheless, when the PIR was below 15%, the yield stress was lower than that observed in the FIR 30% condition without polymer. These findings suggest that while excessive polymer content may be counterproductive, an appropriate level of polymer supplementation can effectively improve the rheological performance of foam-conditioned soils, thereby contributing to more stable and efficient EPB shield tunneling operations.

ACKNOWLEDGEMENT

This study received financial support from the “National R&D Project for Consecutive Excavation Technological Development Project of Tunnel Boring Machine (RS-2022-00144188)” funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport and managed by Korea University.

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