Direct Shear Test on The Mechanical Behavior of Aqueous Foam-Treated Sandy Soil

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Abstract: Aqueous foam has demonstrated excellent performance in improving soil properties. To study the evolution of the mechanical behavior of foam-treated soil under varying foam contents, a series of direct shear tests were conducted. Experimental results reveal that foam markedly alter the mechanical characteristics of the soil by reducing interparticle friction and modifying its stress–strain response. But the improvement in soil behavior is strongly dependent on the foam content. A critical foam content threshold was identified, beyond which the foam effectively lubricates particle contacts and enhances plastic deformation, whereas below this threshold, the conditioning effect remains minimal. Thus, achieving the optimal foam content is essential to ensure both soil stability and flowability during tunneling operations.

Keywords: ***Aqueous foam, Foam content, Direct shear test, Stress strain behavior.***

Introduction

Aqueous foam is defined as a stable dispersion of gas bubbles within a continuous liquid phase, stabilized by surfactants or foaming agents that reduce the surface tension at the gas-liquid interface. The stabilization mechanism prevents bubble coalescence, drainage and collapse, maintaining foam integrity over time.

In Earth Pressure Balanced shield (EPB) tunnelling, aqueous foam is one of the most used soil conditioning agents. Foam is generated by injecting compressed air into a surfactant solution at a foam expansion ratio (FER). The foam is introduced into the excavation chamber via multiple injection ports and mixed with the excavated soil through the mechanical action of the cutterhead and mixing paddles. By injecting a certain amount of foam and ensuring uniform mixing, the soil transitions from a dense, frictional material to a plastic, cohesive and flowable composite (Galli and Thewes, 2019). This transformation enhances its rheological behavior, flowability and pressure transmission, allowing for effective face pressure control and muck transport through the screw conveyor.

When introduced into granular soil such as sand, foam bubbles occupy pore spaces, forming thin liquid films around soil grains that reduce internal friction and interparticle contact. At moderate foam contents, the foam provides lubrication and uniformity, reducing torque and energy consumption. However, at excessive foam contents, the foam films coalesce, disrupting stress transmission chains between particles and producing an overly soft, unstable material. Therefore, foam content plays a decisive role in governing the mechanical and deformation characteristics.

Due to the time-dependent instability of aqueous foam, including bubble coalescence, liquid drainage and collapse, rapid testing is required to accurately evaluate its mechanical behavior before significant foam degradation occurs (Pourmand et al., 2018). Compared with commonly used slump test, which primarily provides a qualitative assessment of the workability and flowability of conditioned soil, the direct shear test offers a comprehensive evaluation of the mechanical behavior under stress and deformation conditions. Conducting direct shear tests under different stresses and foam injection ratios allows for a realistic assessment of how foam conditioning modifies the soil's strength, stiffness and deformation response.

Accordingly, this study focuses on two principal variables: normal stress and foam content. A series of monotonic direct shear tests were performed on aqueous foam-treated sand to investigate how these factors jointly influence mechanical behavior. The primary objectives were to (1) characterize the stress–strain response of foam-treated soils at varying foam injection ratios and (2) identify transitions in mechanical behavior associated with increasing foam content.

Material and Testing Process

The base material used in this study was standard No. 6 silica sand, which served as the host soil for foam treatment. The particle-size distribution curve of the sand is presented in Figure 1. The sand exhibits a median particle size d_{50}, 0.22 mm, classifying it as medium-to-fine sand. The aqueous foam employed in this study was produced from a 5% surfactant solution using a manual foaming device designed to ensure uniform bubble dispersion. The foam expansion ratio (FER) defined as the ratio of total foam volume to liquid volume—was measured to be 13.2. The relative density of the pure sand specimen was set at 80%, with the aim of studying the stress response of dense soil.

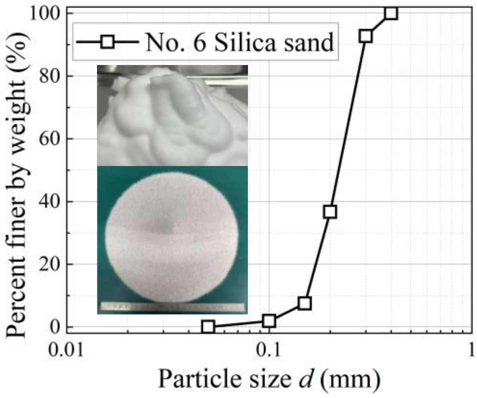

Figure 1, Particle size distribution of silica sand.

To evaluate the effect of foam content on soil behavior, four target foam contents were selected: 0%, 20%, 30% and 40%, corresponding to the volumetric fraction of foam relative to the total specimen volume in the direct shear box. During specimen preparation, the prescribed mass of dry sand and foam were gently but thoroughly mixed in a container to ensure uniform distribution. The resulting foam-treated soil was then placed into the direct shear box in three layers. After placement, the specimen was consolidated under the designated normal stress until the axial deformation stabilized. The monotonic direct shear test was then performed at a constant rate of 0.5 mm/min.

Results and Discussion

Direct shear tests were conducted with 4 different foam contents under the stress of 100 kPa. The corresponding shear stress and volumetric deformation responses are presented in Figures 2 and 3. The pure sand specimen exhibited a pronounced peak stress and followed by softening. As foam content increased, the overall shear strength decreased. Notably, the reduction in peak stress became particularly significant between 30% and 40% foam content, indicating a threshold beyond which the soil matrix transitions toward a foam-dominated structure with higher compressibility and reduced friction (Huang et al., 2019). No substantial difference was observed in the stress–strain response between the 20% and 30% foam-treated specimens, suggesting that moderate foam inclusion is insufficient to modify the structure and contact mechanics between particles.

A similar trend was evident in the volumetric deformation, as derived from the monitored vertical displacement during shearing. The unconditioned sand exhibited clear dilatancy, consistent with its dense packing state. With increasing foam content, the volumetric response shifted toward contraction, culminating in a fully contractive response at 40% foam content. The abrupt increase in volumetric deformation between 30% and 40% foam content further supports the notion of a structural transition—from a frictional granular skeleton to a viscoplastic, foam-saturated composite with higher pore compressibility and reduced effective stress transmission.

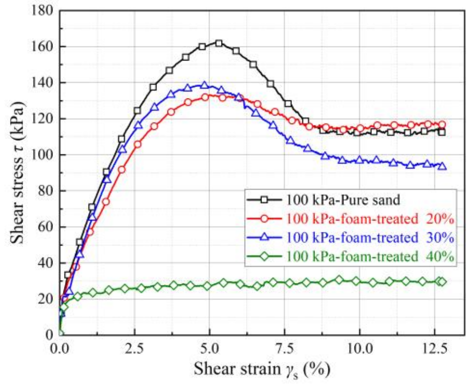

Figure 2, Shear stress with different foam contents.

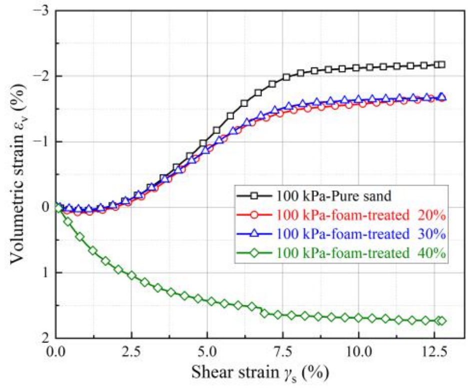

Figure 3, Volumetric strain with different foam contents.

Conclusion

Direct shear tests on foam-treated soil identified foam content as the key factor affecting its mechanical behavior. The results show that:

- Foam addition markedly alters soil behavior, with effectiveness strongly dependent on foam content.
- A critical foam content threshold of 30–40% (by volume) marks the transition from a particle-dominated to a foam-dominated structure.

References

Galli, M., and Thewes, M. (2019). Rheological characterization of foam-conditioned sands in EPB tunneling. International Journal of Civil Engineering, 17 (1), 145–160. https://doi.org/10.1007/s40999-018-0316-x

Pourmand, S., Chakeri, H., Sharghi, M., Bonab, M. H., and Ozcelik, Y. (2020). Laboratory studies on soil conditioning of sand in mechanized tunneling. Journal of Testing and Evaluation, 48 (5), 3658–3672. https://doi.org/10.1520/JTE20170395

Huang, Z., Wang, C., Dong, J., Zhou, J., Yang, J., and Li, Y. (2019). Conditioning experiment on sand and cobble soil for shield tunneling. Tunnelling and Underground Space Technology, 87, 187–194. https://doi.org/10.1016/j.tust.2019.02.011