# Experimental study on the mechanical properties of chemically grouted sandy soil

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## ABSTRACT

This paper presents an experimental study on the effect of chemical grouting on the mechanical properties of sandy soil. The soil sample was collected from a railway construction site in Iksan, South Korea and was classified as silty sand (SM). Newly developed acrylate grout composed of component A (acryl-prepolymer, and catalyst) and component B (hardener) with a mixing ratio of 2:1 was used. Laboratory experiments such as direct shear test, unconfined compression test with various curing durations (1, 4, 7, 14, and 28 days), and oedometer test were conducted for a reconstructed soil sample. Various void replacement ratios (VRR) of 0, 60, 80, and 100% by the acrylate grout was considered. Experimental results showed the increase of shear strength with increasing curing time and replacement ratio of voids. The secant modulus was also increased according to the void replacement ratio. Finally, it was found that the acrylate grout with 60% of void replacement ratio satisfies the standard criteria for subgrade of high-speed railway construction.

**Keywords:** acrylate grout, embankment, direct shear, unconfined compression, oedometer, sandy soil.

## 1 INTRODUCTION

Improvement of soft ground is important for the construction and management of high-speed railways (HSR) since the residual settlements can cause serious problems to the train operations. Generally, the subgrade soils for the construction of high-speed railways require higher durability compare to those of normal railways. The embankment for HSR consists of natural soil, subgrade layer, prepared subgrade layer, sub-ballast, and ballast layer. To ensure the strength of these sublayers of HSR, the elastic modulus on second loading by plate load test (Ev2) for the strengthening ballast layer below the rail (>0.3 m) and the sub-ballast layer (>0.5 m) should be higher than 300 and 120 MPa, respectively. For the prepared subgrade layer (>2 m) and the subgrade layer (>2 m), it should be higher than 80 and 60 MPa, respectively (Egeli, 2003). In Korea, the sandy soil is used to construct the prepared subgrade for HSR. Although sandy soils have adequate characteristics for compaction, durability, and compressibility, in general, but it can induce excessive settlement according to various influential factors (geological feature, groundwater drawdown, embankment height, the degree of compaction, and long-term dynamic of the train).

To secure the stability and durability of the HSR, Sluz et al. (2014) used the cement grout (1:1 W/C ratio) by pumping at a pressure between 1 to 2 MPa through the embankment and Lee et al. (2013) also used the pressurized rapid-hardening cement grout method to restore the concrete track settlement. However, chemical grouting can be used for the ground improvement of sandy soil to ensure the stability and durability of the embankment by enhancing engineering properties of the ground and groundwater control. The main advantages of chemical grout are that it has controllable gel time, low viscosity, high durability, and high strength, whereas its disadvantage lies on its toxicity and harmfulness for the environment. The most common chemical grouts are sodium silicate, acrylate, lignin, urethane, and resin grouts. The acrylate grout has been used in many ground improvement sites since it has low viscosities as low as 1 cp, controlled gel time (range from 3-4 seconds to 12 hours), and high strength as high as 1.5 MPa (US Army Corps of Engineers, 1995; Karol, 2003).

In this study, newly developed acrylate grout was used to investigate the effect of the acrylate grout on the mechanical properties of soil (shear strength parameters, secant modulus, and unconfined compressive strength). Various void replacement ratios (VRR), i.e. 60, 80, and 100% of the acrylate grout with the rapid gel time were considered to conduct the experiment.

## 2 MATERIALS AND METHODS

### 2.1 Material used

The testing material was collected from a railway construction site in Iksan city, South Korea. Results of the basic properties and the grain size distribution of the soil are shown in Table 1 and Fig. 1, respectively. According to the Unified Soil Classified System (USCS), the soil sample was classified as silty sand (SM).

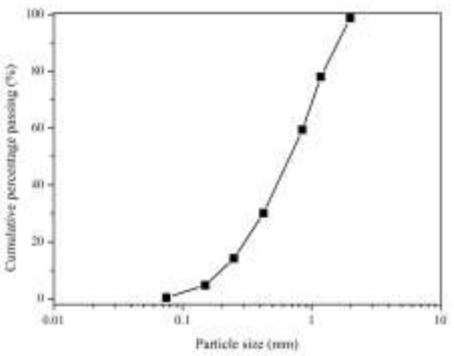


Fig. 1. Grain size distribution of silty sand.

Table 1. Basic properties of silty sand

| Basic properties | Value |
|---|---|
| *Specific gravity* | 2.65 |
| *Grain size distribution* | |
| Gravel (≥ 4.75 mm, %) | 1.4 |
| Sand (≤ 4.75 mm, %) | 86.0 |
| Fine (< 75 μm, %) | 12.6 |
| *Unified soil classification system* | SM |
| *Permeability test* | |
| Coefficient of permeability (cm/s) | 0.0003 |
| *Direct shear test* | |
| Cohesion (kN/m$^2$) | 3.82 |
| Friction angle (°) | 31.17 |
| *Standard compaction test* | |
| Maximum dry unit weight (kN/m$^3$) | 18.31 |
| Optimum water content (%) | 13.65 |

Fig. 2 shows a newly developed acrylate grout composed of a base material (acryl-prepolymer), activator (catalyst), and initiator (hardener) with a proportional ratio of 18.46:1:9.73 by weight, respectively. With the predetermined mixing ratio, the gel time was measured as 2 minutes at a temperature of 20 °C ± 2.


Fig. 2. The composition of the acrylate-cement grout.

## 2.2 Sample preparation

In the present work, a series of experiment was conducted to study the effect of acrylate grouting on the mechanical properties of the sandy soil. Laboratory experiments such as direct shear test, oedometer test, and unconfined compression test were conducted with the reconstructed soil samples.

Table 2. Mixing ratio of acrylate grout with different VRR.

| | | Test condition | | | |
|---|---|---|---|---|---|
| Designation | | AG-0 | AG-60 | AG-80 | AG-100 |
| Void replacement ratio (%) | | 0 | 60 | 80 | 100 |
| Chemical composition | Acryl-prepolymer | - | 37.94 | 50.59 | 63.24 |
| | Catalyst | - | 2.06 | 2.74 | 3.43 |
| | Hardener | - | 20.00 | 26.64 | 33.33 |

With the optimum water contents by the result of compaction test as in Table 1, the soil sample was reconstituted by mixing the dry sandy soil with the chemical composition as the VRR (0, 60, 80, and 100%). After mixing the grout with dry sandy soil, the grouted soil was poured into the mold and compacted in three layers to achieve a consistent initial condition and homogeneity. Next, the specimens were stored and cured in a humid room for 24 hours. And then, the specimens were extracted from the mold before the experiment.

## 2.3 Laboratory tests

### 2.3.1. Direct shear test

To conduct the direct shear test (ASTM D6528-00. 2000), the amount of dry sandy soil was mixed with a predetermined chemical composition as shown in Table. 2. The soil samples with the dimension of 20 mm in height and 60 mm in diameter were prepared and placed into the shear box. Three normal stresses (70, 140, and 210 kN/m$^2$) were applied in each test condition.

### 2.3.2. Unconfined compression test

Under the maximum dry unit weight ($\gamma_{d(max)}$), 15 specimens (35 mm in height and 70 mm in diameter) were reconstructed by mixing the dry sandy soil with the chemical composition in different VRR by the acrylate grout. The unconfined compression test for specimens with different curing times (1, 4, 7, 14, and 28 days) was conducted according to ASTM C4219-02, 2016. The grouted specimens were compressed with a strain rate of 1 mm/min using a loading frame (LoadTrac-III).

### 2.3.3. Oedometer test

To perform the oedometer test (ASTM D2435/D2435M-11. 2014), the soil samples (20 mm in height and 60 mm in diameter) were prepared and placed into the consolidation cell and incremental loading was applied at an interval of 24 h (12.5, 25, 50, 100, 200, 400 and 800 kN/m$^2$). In addition, the secant modulus of silty sand was determined by Eq. 1 suggested by Philipponnat and Hubert (1997).

$$E_{oed} = -\frac{\Delta\sigma}{\Delta e}(1+e_1) \qquad (1)$$

## 3 RESULTS AND DISCUSSION

### 3.1. Shear strength

Fig. 3 presents the relationship between the shear stress and horizontal displacement with a different void replacement ratio. In Fig. 3, the shear stress augmented by increasing the VRR of acrylate grouted silty sand. Furthermore, the variation of shear stress and normal stress was shown in Fig. 4. From these results, it can be clearly seen that the shear stress linearly rises with increasing the normal stress on both the ungrouted and grouted samples. As the VRR increased from 0 to 100%, the friction angle slightly decreased from 31.17° to 30.04° while the cohesion increased about 5.14, 9.78, and 16.23 times for 60, 80, and 100% of VRR, respectively. In general, the internal friction angle depends on the particle size distribution and the shape of grains. As increasing the VRR, particle contact, bonding stress, and cohesion are also increased by chemical grout. Thus, the cohesion of sandy soil increases with increasing the VRR. The finding is consistent with previous researches by Delavar and Noorzad (2017) and Porcino et al. (2012).

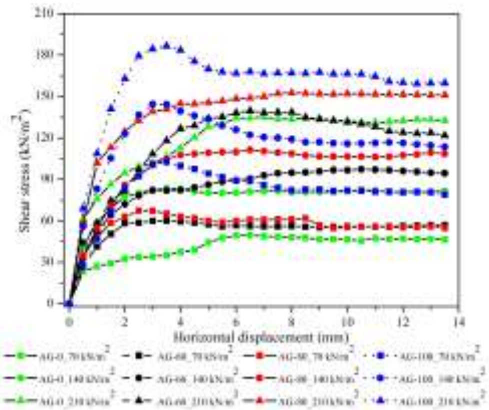


Fig. 3. Shear stress-horizontal displacement diagram of the ungrouted and grouted soil sample.

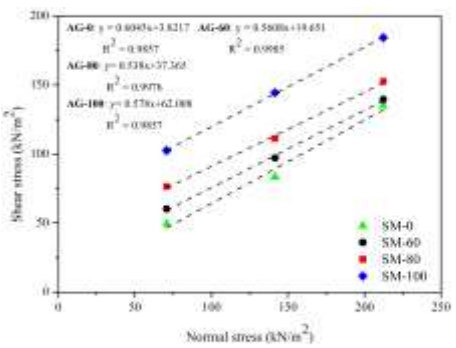


Fig. 4. Variation of shear stress and normal stress of the ungrouted and grouted soil sample.

### 3.2. Unconfined compressive strength

Fig. 5 shows the relationship of the vertical stress-strain of the grouted soil specimen with a different curing time. As shown in this figure, the acrylate grout influenced both the strength and stiffness. It can be noticed that the peak of vertical stress increases with the increasing of VRR as well as curing times. Based on the graphs in Fig. 6, the unconfined compressive strength (UCS) of grouted soil increased with increasing VRR and curing time. According to the test results, the strength of acrylate grouted soil at 28 days with 60 to 100% of VRR were 449.34, 768.76, and 864.71 kPa, respectively. The increase of the strength is caused by cohesion of the grout and high bonding stress between the acrylate grout and particles. These experimental results are consistent with the previous study (Ozgurel and Vipulanandan, 2005).

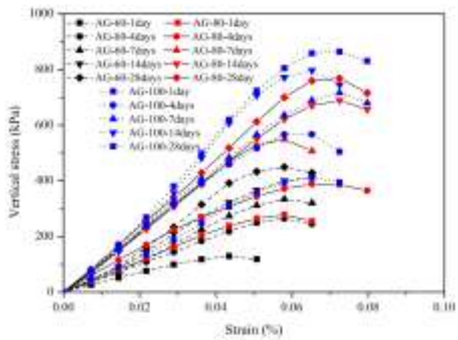


Fig. 5. UCS of the grouted silty sand specimens.

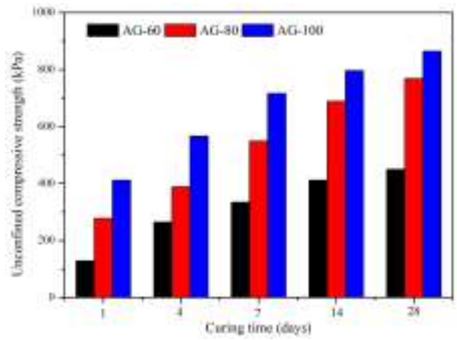


Fig. 6. UCS of the acrylate grouted silty sand in relation to curing time.

### 3.3. Compressive behavior and secant modulus

Fig. 7 shows the vertical effective stress-void ratio relationship of silty sand with various VRR by oedometer test. At the initial loading stage, the initial point of these four cases slightly differ from each other due to the volume expansion of acrylate grout during solidification. The acrylate grout affected the $e_f$, $C_s$, $C_c$, $\sigma'_c$, and $E_{oed}$. Based on the experimental result as illustrated in Table. 2, the $C_s$ and $C_c$ decreased with the increment of void ratio filled by chemical grouting, i.e. 0 to 100%. In addition, the $e_f$ and $\sigma'_c$ significantly increased proportionally with the amount of chemical grout. Similarly, the $E_{oed}$ for treated soil dramatically increased about 2.06, 2.56, and 2.63 times compared to the untreated soil. The comparison of secant modulus with a different VRR by acrylate grout was presented in Fig. 8. The most noticeable observation is that the secant modulus of acrylate grouted soil exceeds standard criteria for the subgrade of high-speed railway construction (80MPa) even for 60% of VRR.

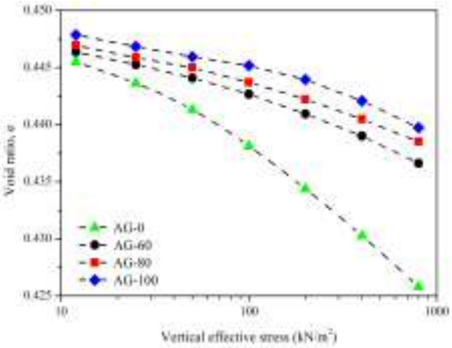


Fig. 7. Variation of void ratio with the vertical effective stress.

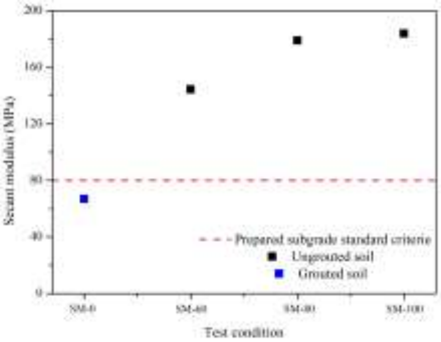


Fig. 8. Variation of secant modulus with a replacement ratio.

Table 2. Test results on the ungrouted and grouted soil sample.

| Test cond. | $e_0$ | $e_f$ | $C_s$ | $C_c$ | $\sigma'_c$ (kPa) | $E_{oed}$ (MPa) |
|---|---|---|---|---|---|---|
| AG-0 | 0.448 | 0.429 | 0.0059 | 0.0149 | 64.37 | 69.95 |
| AG-60 | | 0.437 | 0.0035 | 0.0079 | 96.39 | 144.35 |
| AG-80 | | 0.439 | 0.0032 | 0.0065 | 109.93 | 178.99 |
| AG-100 | | 0.440 | 0.0033 | 0.0078 | 169.07 | 183.81 |

## 4. CONCLUSION

This study investigated the effect of acrylate grout on the mechanical properties of silty sand. A series of the experimental work was performed. Based on the results obtained, several conclusions have been drawn:

- Acrylate grout has significant effects on the mechanical properties. With increasing VRR by acrylate grout, UCS, secant modulus, and cohesion of sandy soil increased.
- As VRR increased from 0 to 100%, the friction angle slightly decreased to 30° while the cohesion increased greatly up to 60.01 kPa.
- With 60 to 100% of VRR by acrylate grout, the UCS of the grouted silty sand at 28 days reached 449.34, 768.76, and 864.71 kPa.
- Compared with the untreated soil, the secant modulus of treated soil increased by 2.06, 2.56, and 2.63 times for VRR of 60, 80, and 100%, respectively.
- It was found that even 60% of VRR can provide the higher secant modulus than the design standard for the subgrade of high-speed railway.

## ACKNOWLEDGEMENTS

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## REFERENCES

ASTM D2435/D2435M-11. (2014). Standard test method for one-dimensional consolidation properties of soil using incremental loading. West Conshohocken, PA, USA: ASTM International.

ASTM D6528-00. (2000). Standard test method for consolidation undrained direct simple shear testing of cohesive soil. West Conshohocken, PA, USA: ASTM International.

ASTM D4219-02. (2005). Standard test method for unconfined compressive strength index of chemical grouted soils. West Conshohocken, PA, USA: ASTM International.

Delavar I. N., and Noorzad R. (2017). Drained shear strength parameters of silty sand grouted by colloidal silica. International Journal of Geotechnical Engineering, Published online, 1-8.

Egeli I. (2003), Design and Construction Aspects of High-Speed Train Railway Embankments-An Overview. Engineering Consultancy Report, Taiwan High-Speed Railway Construction Project, Taiwan.

Karol R. H. (2003). Chemical Grouting and Soil Stabilization. 3rd edn., Rutgers University, New Brunswick, NJ: Marcel Dekker.

Lee I.W., Lee S.J. Lee S.H., and Shin H. Y. (2013). Innovation restoration method for concrete track settlement. Science in Cold and Arid Regions, 5(4), 0461-0467.

Ozgurel H. G., and Vipulanandan C. (2005). Effect of grain size and distribution behavior of acrylamide grouted sand, Journal of Geotechnical and Geoenvironmental Engineering, 131(12), 1457-1465.

Philipponnat G., and Hubert B. (1997). Foundations et overage en terre. Paris: Eyroolles.

Porcino D., Ghionna V. N., and Granata R. (2012). Static and dynamic properties of a lightly cemented silicate-grouted sand, Canadian Geotechnical Journal, 49(10), 1117-1133.

Sluz A., Sussman T. R., and Samavedam G. (2003). ASCE, Geotechnical Special Publication 120. Grouting and Ground Treatment, 2, 803-812.

US Army Corps of Engineers (USACE) (1995), Chemical grouting. Washington, DC: Manual No. 1110-1.