Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-522

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Mechanical properties of a gravel soil injected with a polyurethane binder

Propriétés mécaniques des sols graveleux injectés avec un liant polyuréthane

G. Tintelnot
Gtcs Chemical Solutions GmbH, Hamburg, Germany

G. Spagnoli*
Sweco, Essen, Germany

**giovanni.spagnoli@sweco-gmbh.de*

ABSTRACT: Chemical grouts refer to the use of polyurethane foams and gels, acrylates and epoxies. The usage of polyurethane (PU) is expanding for joint sealing in concrete construction work as well as for controlling seepage in cracked rock and concrete. As part of an experimental investigation, tests were carried out in soils with a constant granulometry (with grain diameter 1-4mm) grouted with a polyurethane binder. A hydraulic permeability of $k = 5.10^{-3}$m/s was specified as the target variable for the soils to be examined. Grouting tests were performed at a maximum pressure of 150kPa. After the grouting of the soils samples, three unconfined compressive strength and triaxial tests were performed in soils with relative densities of 1. Different binder quantities were injected into the soil. Results show that unconfined compressive strength values was about 6MPa. Triaxial tests performed on seven samples at relative densities between 0.89 and 0.94 showed peak deviatoric stress between 5.2 and 6.9MPa. PU binder is therefore suitable for permeation grouting in high permeable soils.

RÉSUMÉ: Les coulis chimiques font référence à l'utilisation de mousses et de gels de polyuréthane, d'acrylates et d'époxy. L'utilisation du polyuréthane (PU) se développe pour l'étanchéité des joints dans les travaux de construction en béton ainsi que pour contrôler les infiltrations dans la roche et le béton fissurés. Dans le cadre d'une investigation expérimentale, des essais ont été réalisés dans des sols à granulométrie constante (diamètre des grains 1-4 mm) injectés avec un liant polyuréthane. Une perméabilité hydraulique de $k = 5.10^{-3}$ m/s a été spécifiée comme variable cible pour les sols à examiner. Les tests d'injection ont été effectués à une pression maximale de 150 kPa. Après l'injection des échantillons de sols, trois essais de résistance à la compression libre et triaxiaux ont été réalisés dans des sols de densité relative 1. Différentes quantités de liant ont été injectées dans le sol. Les résultats montrent que les valeurs de résistance à la compression non confinée étaient d'environ 6 MPa. Les tests triaxiaux effectués sur sept échantillons à des densités relatives comprises entre 0.89 et 0.94 ont montré une contrainte déviatorique maximale comprise entre 5.2 et 6.9 MPa. Le liant PU convient donc aux injections de perméation dans des sols très perméables.

Keywords: Grouting; polyurethane; gravel; mechanical properties.

1 INTRODUCTION

The injection of a grout into a highly porous, granular soil to saturate and bind the particles together is known as permeation grouting. In general, the procedure is utilized to build a structural, load-bearing structure, a stabilized soil zone for tunnelling, and water cut-off barriers.

Chemical grouting is a technique where materials are fully dissolved in a fluid, i.e. called also solutions (Nicholson, 2015).

Chemical grouting is a technique used in geotechnical engineering to stabilize and strengthen soil or rock formations. It involves injecting chemical grout into the ground to fill voids, consolidate loose soil, or create impermeable barriers. Chemical grouts typically consist of a liquid or gel-like material that solidifies after injection.

Chemical grouting has various applications, including foundation repair, soil stabilization, tunnelling, and groundwater control. It is commonly used to address issues such as sinkholes, water infiltration, and unstable slopes. The process is relatively quick and can be performed in various soil and rock conditions (Karol, 2003). Among the different binder types used in chemical grouting (e.g. Fraccica et al., 2022), grouting with polyurethane (PU) resins is an efficient means of improving the mechanical and sealing qualities of soils and rocks (Bodi et al., 2012).

PU grouting materials are classified into three major classes based on their chemistry (Bodi et al., 2012):

- two-component (PU) organic resins;
- one-component organic resins;
- two-component organic-mineral resins (OMR).

In this paper a two-component PU binder was injected in a gravel sand (1-4mm grain) under low pressure (max. 150kPa injection pressure). Unconfined compressive strength and triaxial test values are presented. Similar tests were done in sand and presented by Spagnoli et al. (2023).

2 MATERIAL AND METHODS

The investigations were carried out with the injection of a two-component, fast-reacting, slightly flexible, silicate-based injection foam equipped with flame retardants.

2.1 Binder

The A component is based on a water glass solution (silicic acid) which has a density of 1.3 g/cm^3 and a dynamic viscosity of 30 mPas at a temperature of 23°C. The B component is based on an isocyanate mixture, which is characterized by a density of 1.21 g/cm^3 and a dynamic viscosity of 120 mPas at a temperature of 23°C.

The two components are mixed together for the reaction in a volume ratio of 1:1. At room temperature, there is a reaction between the two components about 30 seconds after mixing. A slowly hardening foam is formed. The foam volume is significantly larger than that of the two individual components (formation of air bubbles).

2.2 Soil

A hydraulic permeability of k = 5.10^{-3}m/s was specified as the target value for the soils to be examined. Table 1 shows the properties of the soil used in the experiment.

Table 1. Properties of the soil used in the test

Property	Value
Grain dimension	1-4mm
High dry density	1.877g/cm^3
Low dry density	1.608g/cm^3
Grain specific gravity	2.76
Low k-value	6.03·10^{-3}m/s
High k-value	1.81·10^{-2}m/s
D_{60}	2.8mm
D_{30}	2.0mm
D_{10}	1.7mm

2.3 Grouting set up

The test stand consists of a 50cm long commercial PVC pipe (DN 110), which is sealed airtight with an associated socket plug on the bottom (see Figure 1). To fix it, the pipe was screwed to a wooden structure using pipe clamps.

Small holes were drilled through the wall at the bottom of the tube to avoid uplift as a result of the injection. The air displaced by the foam could escape through these holes. In addition, a grid was fixed over the built-in soil on the pipe to produce test specimens with a constant volume. This prevented heaves due to volume expansion of the foam.

A cartridge gun operated with compressed air was used for the injection. The two individual components of the injection material were mixed and homogenized using commercially available static mixers.

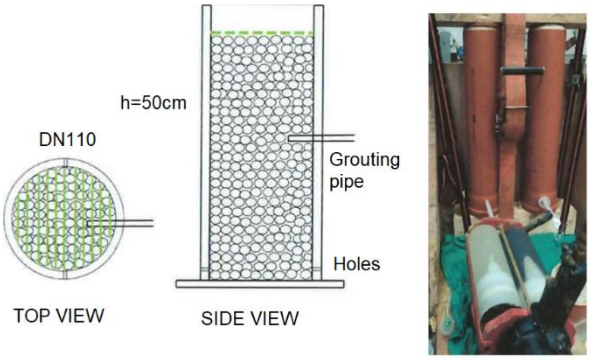

Figure 1. Set up for the grouting tests.

To investigate the vertical expansion behaviour of PU, 300ml, 400ml and 600ml of the mixed injection material were injected into soils, which had previously been installed in dense storage in the pipe, with an injection pressure of approx. 1.5 bar. The installation densities of the soils used were determined before the injection and ranged between 1.85 and 1.88 g/cm^3.

3 RESULTS AND DISCUSSION

Figure 2 shows the results for the grouted material injected into the 1-4mm gravel soil for 300, 400 and 600ml. The red arrow indicated the point of injection.

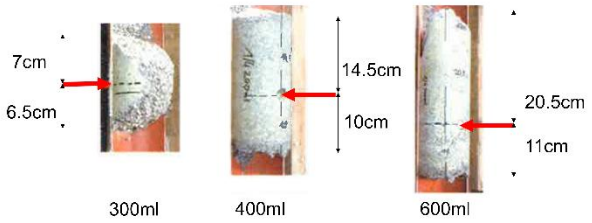

Figure 2. Results from the grouting test for 300ml, 400ml and 600ml injection material (from left to right).

Approximately 30 seconds after the start of the injection, the injected material hardens and foams at the lower end of the injection front. It forms the basis of the injected soil body.

Mechanical tests on the grouted samples were performed on 7 days curing age.

Three uniaxial compression tests according to DIN EN ISO 17892-7 (DIN, 2018a) were carried out on specimens (height-to-diameter ratio of 2) made from soil-foam mixtures. The installed soil dry density was 1.88 g/cm^3 (relative density Dr = 1.0).

The specimens were subjected to uniaxial loading and shearing at a constant rate of 0.2% of the initial height of the specimens per minute in accordance with DIN EN ISO 17892-7.

The determined stress-strain relationships of the three uniaxial compression tests on the soil-foam mixtures carried out under the same boundary conditions are shown in Figure 3. In addition, the test results are listed in Table 2.

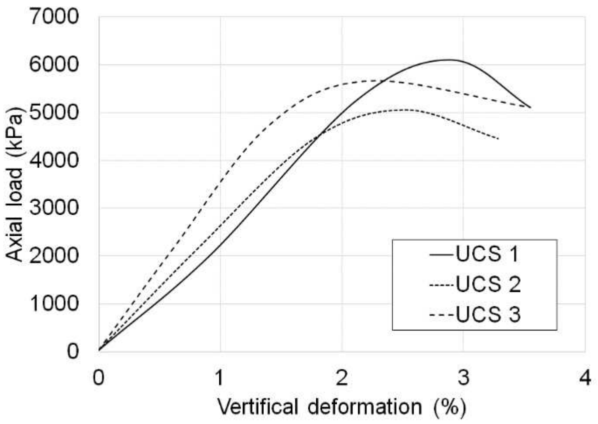

Figure 3. Results of UCS tests.

The modulus of elasticity secant E50 was determined in the stress range between 0kPa and 50% of σ_1 (i.e. the axial load).

Table 2. Data of UCS tests

Test	UCS (kPa)	E50 (MPa)
UCS 1	5100	269
UCS 2	5700	372
UCS 3	6100	239

The mean UCS and E50 values are respectively 5.6MPa and 293MPa.

Furthermore, triaxial tests were carried out on dry test specimens according to DIN EN ISO 17892-9 (DIN, 2018b). The specimens prepared with dry density between 1.84 and 1.86 g/cm^3. The cylinder samples (height 20cm, diameter 10cm) were sheared at a constant rate of 0.2% of the specimen height per minute (approx. 0.4mm/min).

A total of seven specimens were tested under triaxial conditions and sheared at different lateral pressures σ_3. The test boundary conditions are listed in Table 3.

Table 3. Data of triaxial tests

Test	Dr soil	σ_3 (kPa)	E50 (MPa)	Dr
TX 1	0.94	100	206	0.94
TX 2	0.94	200	293	0.94
TX 3	0.93	300	255	0.93
TX 4	0.93	500	282	0.93
TX 5	0.89	200	213	0.89
TX 6	0.89	300	216	0.89
TX 7	0.89	500	288	0.89

The triaxial tests show values of σ_1 - σ_3 between 5.2MPa and 6.9MPa, which occur at axial strains ε between 2.6% and 3.8% (see Figure 4). The stiffness E50 of the specimen varies between 200 MPa and 300 MPa. A clear increase in the strength and stiffness of the soil-foam mixtures with the lateral pressure σ_3 is not recognizable. The foam density is around 0.4 g/cm^3. A dependence of the results on the foam density cannot be determined given the small differences in foam density here.

To roughly determine the shear parameters of the soil-foam mixture, the results of the three uniaxial compression tests and the seven triaxial tests were transferred together into an t-s diagram (see Figure 5). For each individual test, the maximum value of the deviator stress ($t = \sigma_{1,max} - \sigma_3 /2$) and the associated mean principal stress ($s = \sigma_{1,max} + \sigma_3 /2$) are plotted in the t-s diagram. In the uniaxial compression test, $\sigma_3 = 0$. The black dots are the UCS tests, whereas the white dots the triaxial tests.

A regression line was then drawn through the points. Using the parameters α (angular coefficient) and b (intercept) according to Figure 5, the cohesion c and the angle of friction φ can be calculated as:

$$c = \frac{b}{cos\varphi} \qquad (1)$$

$$sin\varphi = tan\alpha \qquad (2)$$

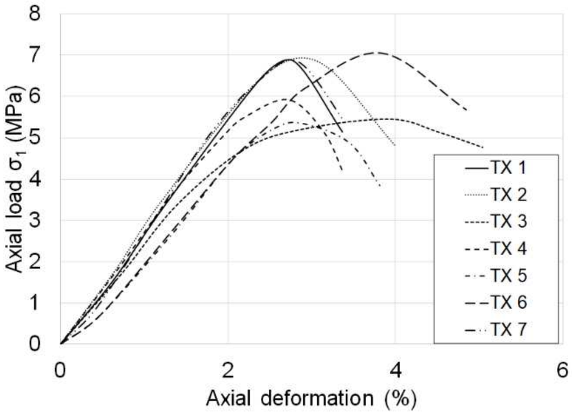

Figure 4. Results of the triaxial tests.

From the results of Figure 5, the cohesion is 887.5kPa and the friction angle φ is 48.7°, considering a value α of 36.9° and a value b of 585.5kPa.

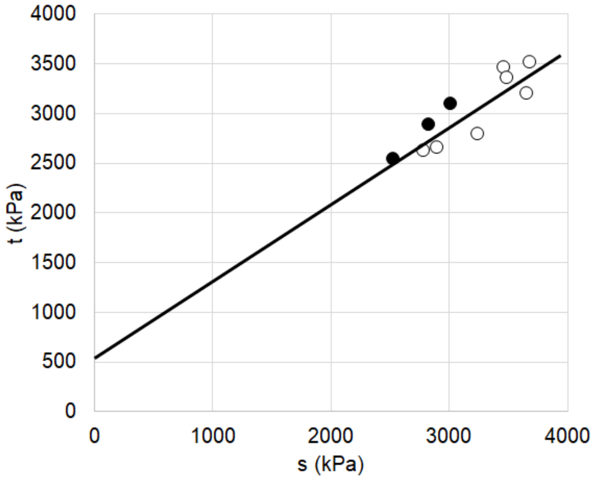

Figure 5. Results of the triaxial and UCS tests into the t-s diagram. Black dots are the UCS tests, white dots the triaxial tests.

4 CONCLUSIONS

The note showed some mechanical tests performed on a gravel soil with 1-4mm grains at a k value of $5 \cdot 10^{-3}$m/s. Axial load values for UCS tests range between 4 and 6MPa. Triaxial tests performed under different lateral pressure and relative density values demonstrate no discernible improvement in the strength and stiffness of the soil-foam combinations with lateral pressure σ_3. Given the modest changes in foam density here, a dependency of the results on foam density cannot be detected.

REFERENCES

Bodi, J., Bodi, Z., Scucka, J. and Martinec, P. (2012). Polyurethane Grouting Technologies. In *Polyurethane*, F. Zafar, and Sharmin, E. (eds.), pp. 307-336. London: IntechOpen. http://dx.doi.org/10.5772/35791.

DIN (2018a). *Geotechnische Erkundung und Untersuchung - Laborversuche an Bodenproben - Teil 7: Einaxialer Druckversuch (ISO 17892-7:2017).* Berlin: Beuth Verlag GmbH.

DIN (2018b). *Geotechnische Erkundung und Untersuchung - Laborversuche an Bodenproben - Teil 9: Konsolidierte triaxiale Kompressionsversuche an wassergesättigten Böden* (ISO 17892-9:2018). Berlin: Beuth Verlag GmbH.

Fraccica, A., Spagnoli, G., Romero, E., Arroyo, M. and Gomez, R. (2022). Permeation grouting of silt-sand mixtures. *Transportation Geotechnics*, 35, 100800. https://doi.org/10.1016/j.trgeo.2022.100800

Karol, R. H. (2003). *Chemical Grouting and Soil Stabilization*. CRC Press.

Nicholson, P. G. (2015). *Soil Improvement and Ground Modification Methods.* Elsevier.

Spagnoli, G., Collico, S. and Tintelnot, G. (2023). Mechanical behavior of grouted sands with acrylates and polyurethane resins. *Proceedings of the Institution of Civil Engineers - Ground Improvement*. https://doi.org/10.1680/jgrim.23.00005.

The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.