

Research Article

Mohammed S. Mohammed*, Samir H. Hussein, and Mahmood D. Ahmed

Comparison between cement and chemically improved sandy soil by column models using low-pressure injection laboratory setup

<https://doi.org/10.1515/jmbm-2022-0258>

received March 19, 2022; accepted September 21, 2022

Abstract: The jet grouting method for soil improvement represents an innovative geotechnical alternative for problematic soils when the classic foundations' designs cannot be appropriate, sustainable solutions for these soils. This study's methodology was based on producing column models using a low-pressure injection laboratory setup designed and locally manufactured to approximate the field-equipment operation. The setup design was inspired by the works of previous researchers, where its functioning was validated by systematically performing unconfined compression tests (UCTs). Two soil improvement techniques were investigated, one by low-pressure injection of a mixture of water and ordinary Portland cement (OPC) with 0.8, 1, and 1.3 W/C ratios. The other type uses silica fume (SF) as a chemical additive with 10% of the cement weight added to the water and cement mix with 1, 1.3, and 1.6 W/C ratios. The study revealed that the UCT results of SF column model samples were higher than those of OPC with an equal W/C ratio. For each binder type, the UCT sample results increase with a decrease in the W/C ratio.

Keywords: sand improvement, jet grouting, silica fume, unconfined compression test

1 Introduction

Ground improvement or ground enhancement denotes the modification techniques for the soil engineering characteristics executed in a field where the soil in its natural conditions does not have suitable characteristics for the planned civil engineering projects [1]. Essential research works into developing and improving ground modification methods have been carried out in the last few years. Thus, new types of machinery, materials, and applications are regularly suggested on the market and offered to practitioners as an appropriate alternative [2].

The ground improvement involves any process executed to enhance the shear strength, reduce the compressibility and permeability, or modify the soil's geotechnical characteristics to be more suitable for expected engineering applications. Many techniques have been developed for ground modification from the ground surface down to depths of 20 m or more, depending on the field situation. The improvement may be made by (excavating the poor soil and replacing it with desired soil properties down to 3 m depth in the absence of the water table) compaction, drainage, grouting, preloading, reinforcement, electrical, chemical, or thermal methods. Among the various soil stabilization procedures, the most suitable one is selected depending on the type of soil available, time, cost, etc. [3].

This experimental study was performed by utilizing a low-pressure injection laboratory setup designed and locally manufactured with almost the same performance as the field equipment operation but with a reduced footprint and cost. The improved soil was loose fine sand with a 20% relative density from Karbala province. For comparison between cement and chemical improvement techniques, this laboratory setup injected two binders, one by using OPC with 0.8, 1, and 1.3 W/C ratios and the other by using SF with 10% of the cement weight as a chemical additive to the water and cement mixture with 1, 1.3, and 1.6 W/C ratios.

* **Corresponding author: Mohammed S. Mohammed**, Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq, e-mail: mohammed.bridge@gmail.com

Samir H. Hussein: Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq, e-mail: Samirsreh@gmail.com

Mahmood D. Ahmed: Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq, e-mail: dr.mahmood.d.a@coeng.uobaghdad.edu.iq

The design of the laboratory setup was inspired by and based upon the works of both Nikbakhtan [4] and Khalili *et al.* [5]. Its operation was verified by methodically performing UCTs program. In addition, the setup performance was validated regarding the homogeneity and reproducibility of the low-pressure injected model column samples (performing many laboratory-injection trials to determine the suitable ranges of the setup operational parameters like injection pressure (kPa), flow rate (l/min), diameter (mm), number of nozzles, lifting/penetrating speed (cm/min), and rotating speed (rpm) of the drilling and injection rod).

Grouted cement is an appropriate method to enhance the geotechnical characteristics of the soil. Unfortunately, field conditions do not usually provide a considerable study of the injected soil's behavior. Therefore, the soil injection technique has been reproduced in the laboratory. In many instances, the laboratory injection test's key objective is to evaluate grout injectability in a particular soil. Some applicable injectability procedures have therefore been suggested. Laboratory injection tests are intended to comprehend the physical or chemical mechanisms that occur while the injected binder permeates the soil. Another purpose of laboratory injection setup is to prepare consistent homogenous model of the injected samples for modeling geotechnical field cases to be improved by grouted columns technique [6].

2 Grouting techniques and material properties

2.1 Jet grouting

Jet grouting or high-pressure grouting can be utilized in just about all soil types, from gravels to clays (irrespective of the size of particles, pore size, or void ratio), to produce different forms (stiff, impermeable poles, sheets, or wings). Cement grouting uses a high-pressure jet (a minimum of 30 MPa jetted out of the nozzles at excessive-rotation speed) to destroy the subsoil structure to mix and partly substitute it with the grout [2]. The additive contains a mix of cement and water in different ratios. The water–cement mix achieves a significant amount of kinetic energy or velocity while passing through the nozzles on the cement grouting equipment, which creates a soilcrete body with strength properties independent of the initial soil texture [7].

Grouting has been widely used to achieve various purposes, including enhancing the bearing capacity of foundations, increasing the stability of slopes and sub-ground infrastructures, and mitigating the liquefaction phenomenon [8]. The essential benefit of grouting is that it is straightforward, profitable, simple equipment, and eco-friendly. Grouting is categorized generally as cement or jet grouting and chemical grouting. According to previous practical studies, jet grouting has achieved many practical advances concerning the size of jet grouting columns and their geotechnical properties [9].

Njock *et al.* studied the advanced jet grouting manufacturing approaches to remove the troubles that come with cement grouting, such as inconsistency of the grouted columns and spoil grouting encountered in cement grout applied on the sand. It was revealed that the compressive strength and the continuity properties could be enhanced. Using the cement grouting method, the geotechnical properties of underground layers are improved, resulting in an increase in the soil elasticity modulus and stiffness. Cement grout is multipurpose because it can be executed in vertical, tilted, or even horizontal directions [10].

Cement grouting columns are installed mainly to enhance bearing capacity and reduce settlement of footings on soft soils under static loading. However, cement grouted columns will similarly alternate soft soil deposits' responses to seismic excitation [11]. It must also be noted that cement-grouted columns can be utilized as a mitigation technique for soils that have the potential to liquefy under seismic loading [12]. Shen *et al.* established an empirical formulation to state the size of the obtained column by grouted cement practice as a function of grouted pressure, nozzle size, a withdrawal rate of grouting rod, type of subsoil, and soil undrained shear strength [13].

The maximum influencing factor affecting the success of grouting applications within the subsoil is the characteristics of grouted materials or binder materials. OPC is used as a grouted substance contracted by medium- to fine-grained soils because of its grain size (finesness) [14]. For the grouting performed in medium- to fine-grained soil types, fine-grained cement is most required. Grouting using fine-grained cement has advantages over OPC concerning the rheological characteristics. Grouting with fine-grained cement shows more stable properties [15].

The results of cement grouting applications on sand depend on the sand's relative density and particle size, the type of cement used, the (W/C) ratio of the grouted mix, and the preparation procedure of grouting [16]. The presence of relatively large gaps between the minimum

and maximum particle size of soil causes a substantial rise in penetrability. On the contrary, the soil with a homogeneous particle-sized distribution impedes the permeation of binder particles through soil pores, resulting in inaccessibility to the required spaces [17]. In a field study (Al-Kinani and Mahmood, 2020) in Iraq to improve clayey soil layers using the cement grouting technique, it was revealed that the cement grout produced a rise in UCS of the natural soil (which ranged from 30 to 40 kPa) to about 4 MPa after improving [18].

2.2 Chemical grouting

Chemical grouting is an active technique to enhance soil characteristics by mixing additives into the soil. Generally, the additives are lime, cement, fly ash, SF, and bituminous substances. These additives improve the soil characteristics. Typically, the two main reactions for chemical soil improvement are the cementation and cation exchange reactions. The typical chemical agents for cementation are lime, PC, bituminous emulsion, fly ash, and sodium silicate polyacrylamides [19]. Kazemian and Huat (2010) remarked that several grouted chemicals are formed from the mixture of sodium silicate and a reagent to produce a gel. The chosen reagent type and its ratio can regulate the gel time, the initial viscosity, and the strength order of grouted soil [20].

Grouted chemicals are injected into pores as a solution as opposed to cementitious grouting, which suspends the elements in a fluid medium. The dissimilarity between grouted chemicals and grouted cement is that grouted chemicals can seal the smaller pores of soil grains up to 10–15 nm. It has better infiltration capability than grouted cement [21]. Grouted chemicals can be categorized into single-step and two-step procedures. In the one-step procedure, all the constituents are premixed earlier to grouting, proportioning the constituents so that reaction occurs within the soil. In the two-step process, the initial chemical is grouted into soil particles, followed by the second chemical constituent for reaction with the first field injected material for soil stabilizing [22].

Grouted chemicals are used in the pre-treatment of relatively coarse soils for tunnel construction or sealing off water from seeping into deep excavations or tunnels. Applications of chemical grouting for expanding the serviceable life of construction activities are improving collapsible soils, reducing the soil's liquefaction potential, reducing secondary compression, and reducing soil

coefficient of conductivity by decreasing water seeping under footings. The benefits of grouting chemicals are the capability of stabilizing current main roads without transportation disruption, improving the soil with a low conductivity coefficient (about 10×10^{-5} cm/s) up to a practical depth of 30 m, and producing long-lasting constructed projects. Defects are extended periods for project design, constructing, observing periods, extended setting periods, somewhat above average budgets, some chemicals with high toxicity, and disintegration of grouted chemicals over time, thus decreasing their effectiveness [23].

2.3 SF

SF is defined by the American Concrete Institute as “very fine non-crystalline silica produced in electric arc furnaces as a by-product in the production of alloy silicon or elemental silicon” [24]. The gases produced through the furnace operation are a fine powder known as silica fume that is condensed in the bag house through the filtration system to be packed for commercial usage. SF consists of very fine spherical particles less than 1 μ m in diameter [25]. SF is a very reactive pozzolanic material in concrete for it contains a very high amount of amorphous silicon dioxide.

SF not only fills the pores between the particles but also improves the bonds between the soil and injection mixtures owing to its microscopic grain structure [26]. As the PC in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from the PC [27].

Wilson *et al.* stated that SF contained in concrete samples raises the stiffness and reduces the conductivity coefficient. According to scanned electron microscope image investigation, nanoscale SF is not just a filling substance but also improves consistent hydration distributions. In addition, they observed that SF is an energizer to improve the micro-patterned cement paste [28]. Zhang and Li (2013) stated that adding SF to concrete and fly ash mix has significantly enhanced its durability and workability (regarding carbonation resistance and freeze-thaw resistance, waterproofness, and dry shrinkage property). Also, it was revealed that the increase in the SF% resulted in a slight increase in the samples' relative dynamic elastic modulus, and a decrease in the length of water permeability and the carbonation depth [29].

3 Manufacturing low-pressure injection laboratory setup

The laboratory low-pressure injection setup (as shown in Figure 1), which was manufactured by the study researchers in the local industrial markets, consists of the following parts:

- A steel frame consists of hollow square steel tube sections welded together to hold the setup parts and supported by heavy-duty steel swivel caster wheels.
- A mixing tank with a 100 L capacity (Plate 1) is supplied with a mixing motor connected by a mixing rod ending with a blending blade. The mixing motor of 0.5 HP is controlled by three-phase frequency converters to control the mixing speed rotation of the mixing rod. A $\frac{3}{4}$ inch diameter galvanized pipe connects the bottom of the mixing tank to the injection pump that connects the circulating pipe.
- A drainage valve plug for washing, cleaning, and draining the injecting tank is supplied to the bottom of the mixing tank.
- The used injection pump is an open impeller type, usually used for thick fluid pumping (like the injection fluid) with 1 HP and 3,000 rpm connected to the mixing tank from one side and the soil-injecting system from the other.
- The pipe system connected with the injecting pump branched into three branches. The main branch connects the bottom of the mixing tank to the injecting pump (controlled by a gate valve kit and a diaphragm pressure gauge for controlling the fluid injection pressure that ranges from 15 to 25 kPa depending on soil injection depth and the required column models diameter). The second branch circulates the surplus grouting fluid to the mixing fluid tank. Moreover, the third part joins



Plate 1: Side view of the low-pressure injection laboratory setup.

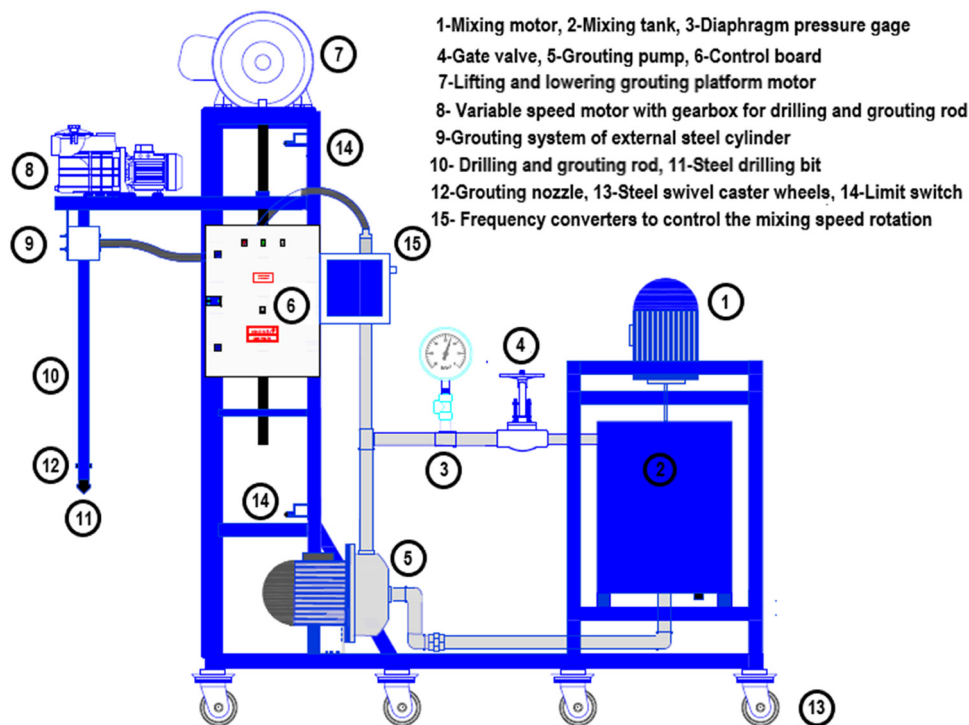


Figure 1: Schematic diagram of the low-pressure injection laboratory setup.

a reinforced plastic hose to transmit the injection fluid from the injection pipe (main branch) to the injection system.

- The injection system (Plates 2 and 3) consists of an external steel cylinder, an internal rotating drilling injection rod for fluid injection, a set of O-ring seals, oil seal kits for preventing grouting fluid leakage, and a set of ball bearings.
- The injection rod (Plate 3) is a 65 cm long steel pipe (16 mm external diameter and 6 mm internal diameter). It ended with a 20 mm steel drilling kit and two opposing nozzles with 3 mm openings (Plate 4).
- The lifting and lowering of the platform injection system consist of:



Plate 2: Front view of the low-pressure injection laboratory setup.



Plate 3: Rotating motor and grouting system.



Plate 4: Steel drill kit and the nozzles.

- A 3-phase electric motor is coupled to a gearbox (Figure 1). The gearbox is connected to a 30 mm diameter screw shaft with square threads supplied with a large nut. This nut is welded to an inner box that is slipped into an external box fixed to the frame setup. According to platform motor rotation speed and its gearbox reducing speed, the internal steel box (supporting the injection system) slipped (at 0.2 m/min) up and down into an external steel box within a vertically ranged distance limited and controlled by electric limit switches which were fixed to the setup frame.
- A three-phase variable speed geared motor with 1 HP will rotate the injection rod clockwise and counter-clockwise (Plate 3).
- The three-phase electric control board consists of accessories like electric contactors, overloads, selector switches, phase failure device, emergency switch, pushbuttons, and all other fittings to control and operate the motors and the grouting pump.

4 Preparing the soil testing box

The tested soil in this study is poorly graded sand passing through sieve #10 (2 mm opening) size, and its geotechnical characteristics are listed in Table 1. The preparation of the soil testing box requires the following steps:

- The sand in the soil box is spread in layers with 10 cm height for each layer using the raining (air pluviation) technique (shown in Plates 5 and 6). This technique is used to prepare uniform sand layers for testing large-

Table 1: Index geotechnical characteristics of sand mixtures

Characteristics of tested sand	Value	Standard or specifications
Soil relative density (D_r %)	20%	According to study requirements
Max. dry unit weight (γ_{dmax}), kN/m ³	18.5	ASTM D4253
Min. dry unit weight (γ_{dmin}), kN/m ³	16.8	ASTM D4254
Selected dry unit weight (γ_d), kN/m ³	17.1	Calculated from Equation (1)
Selected saturated unit weight (γ_{sat}), kN/m ³	20.2	Calculated from soil phase relationships
Specific gravity (G_s)	2.63	ASTM D854
Max. void ratio (e_{max})	0.565	Calculated from soil phase relationships
Min. void ratio (e_{min})	0.42	Calculated from soil phase relationships
Depended void ratio	0.54	Calculated from soil phase relationships
Uniformity coefficient (C_u)	2.36	A uniformity coefficient value of 2 or 3 is classified as poorly graded soil.
Coefficient of curvature (C_c)	0.95	The soil is well-graded if the value of C_c lies between 1 and 3.
Soil classification USCS	Poorly-graded sand (SP-few or no fines)	ASTM D422 and ASTM D2487
Dry friction angle, ϕ°	30	Direct shear test ASTM D3080/D3080M-11
Saturated friction angle, ϕ_{sat}°	24	Direct shear test/undrained condition

**Plate 5:** Soil raining of diffuser sieve.**Plate 6:** Soil raining by elevated funnel.

sized specimens based on laboratory maximum and minimum relative density values (or dry densities) by referring to Eq. (1).

$$D_r = \frac{\gamma_{dmax}}{\gamma_d} \times \frac{\gamma_d - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}} \times 100. \quad (1)$$

- In this study, a 20% relative density was chosen for the laboratory soil specimen preparation (liquefiable sand).
- The weighted dry sand is spread (rained) inside the soil box using a funnel (40 cm diameter and 35 cm height) suspended at 2.5–2.75 m height by a car's engine crane. This elevated funnel is connected with a 5 cm diameter plastic hose for homogenous sand samples spread within the marked lines drawn on the inner sides of the soil box

(made of steel and provided by a polycarbonate transparent front panel).

- After sand rain completion, each layer surface is leveled up (finished by small taping on the layer surface) to the required level marked by lines inside the soil box sides.
- After sand box preparation, it was directly applied 1 inch thick plastic sandwich panel drilled with the required diameter and number of circles for the column models to be grouted, as well as a thin plastic layer of polythene sheet under this panel to prevent the back-flow or the spoils (a mixture of grout, water, and sand) from infiltration down into the soil during the grouting operation. A small part of this polythene sheet layer

corresponding to the grouted columns is removed consecutively during the grouting process.

5 Low-pressure laboratory injecting process

- After mixing the injection materials (separately in a bucket) according to the required proportions, the injection fluid is poured into the mixing tank. Then, the mixing motor is operated according to the suitable rotation speed by the variable frequency drive inverter on the control board.
- The injection pump is operated by circulating the injection fluid from the bottom of the mixing tank through the pipe system and returning it to the top inlet of the mixing tank to ensure the injection pump operates appropriately.
- Then, the drilling-injection rod is rotated and lowered into the sand box.
- Before the injection process, a trial injection pumping (pumping a small amount of injection fluid over the soil surface) is carried out to ensure the proper operation of the nozzle. This initial injection process is vital to guarantee the non-plugging of nozzles (by sand grains intrusion) and injection continuity operation during the soil drilling and injecting process.
- The injecting process is performed on the soil box by directing the platform injecting system downward and rotating (at 50 rpm revolution speed) the drilling and injecting rod in a clockwise direction. The injection process is performed in two stages.
 - The first injecting stage is associated with the downward drilling process of the injecting hole with a suitable fluid injecting pressure to stabilize the hole wall-sides.
 - The second stage (primary injection process) starts upward after the injection rod reaches the hole bottom of the soil box. From the control board, the rod rotation is reversed in the counterclockwise direction, and the platform grouting system is directed upwardly at the previously prescribed speed with the required injection pressure of pumped fluid according to the diaphragm pressure gauge.
- During the injection process, some spoils flow from the injection hole surface to be removed from the soil box surface.
- The lifting process for the drilling and injecting system platform continues during the injecting process until the nozzles reach the soil box surface, which is the end of the soil injecting column model performance process that leads to a consistent and homogenous injected column model.
- During the soil injecting process, there is a lowering in the surface area of the injected column model (local densification for injection leading to shortening of the injected column model' length) to be substituted with the same soil properties mixed with the upward spoiled injected fluid.
- The injection process continued by moving to another location of the soil box until the required number of column model were injected (Plate 7).
- After the injection of column model, the curing process is started by immersing them in a suitable water basin for a 28 days curing period (Plate 8).



Plate 7: Grouted columns models.



Plate 8: Grouted columns models with diameters of 4–8 cm.

6 Unconfined compression test (UCT) results

Most testing programs stated in experimental research works use the unconfined compressive apparatus to investigate the influencing factors on the validity of improving the soil by grouted cement. The UCT is essential for the acquisition of expertise concerning soil cement injection assessment. It is also uncomplicated and quick, while being reliable and inexpensive. In this study, the unconfined compressive apparatus tested two sample groups of the low-pressure injected model columns (LPIMCs). The first sample group was cut from randomly chosen LPIMCs for OPC binder with 0.8, 1, and 1.3 W/C ratios. The other sample group was cut from randomly chosen LPIMCs for SF binder (10% by cement weight added to water and cement mix with 1, 1.3, and 1.6 W/C ratios). An automatic loading apparatus with a maximum capability of 50 kN equipped with a calibrated load cell and data logger for data acquisition was utilized for the tests.

According to ASTM D2166 [30], the samples were centrally loaded at a displacement rate of 1.2 mm/min up to the failure to obtain the maximum applied load. The tests were performed on identical samples for each binder group to minimize the variation in the testing conditions and materials. Because the data error was less than 5%, the obtained results were validated. The test results are listed in Table 2. By utilizing the CurveExpert Professional software version (2.7.3) for generating high-quality results using a cross-platform solution for curve fitting and data analysis, the trend of UCS and the W/C ratio relation for improving both the binders (Figures 2 and 3) revealed the same behavior as those shown in the previous studies [31]. The data for mathematical modeling showed a high coefficient of determination (R^2) for both relations.

Table 2: Average UCT results of grouted cement and chemical grouted columns samples

No.	Binder type	W/C	Average UCT (MPa) after 28 days of curing
1	OPC + 10% SF	1	22
2	OPC + 10% SF	1.3	18
3	OPC + 10% SF	1.6	12
4	OPC	0.8	14
5	OPC	1	12
6	OPC	1.3	10

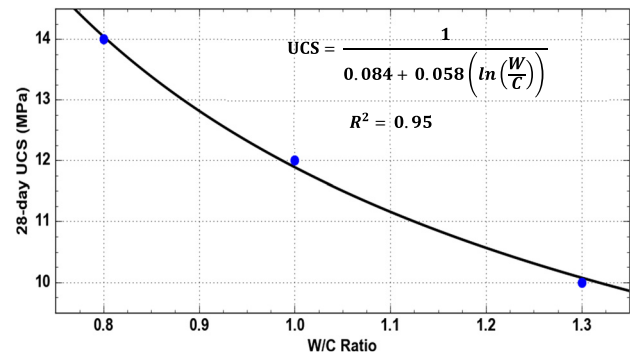


Figure 2: Unconfined compression strength (UCS) – W/C ratio for OPC binder.

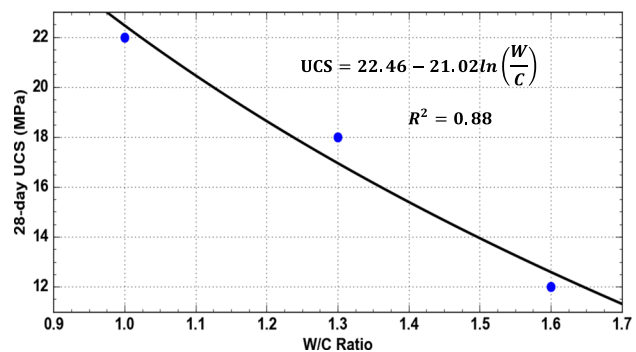


Figure 3: UCS – W/C ratio for SF binder.

7 Conclusion

- In specific cases, a preliminary trial for a cement injection operation must be performed on an alternative site where the soil properties should be identical to those of the construction site's soil. After this trial, the grouted columns are excavated for a field checkup and to perform the required test. In performing trials of the jet grouting method, finding a site similar to the job site is not always feasible. It can be expensive and time-consuming, and it may not even lead to desired results. Therefore, the utilization of a low-pressure injection setup to model the cement grouting improvement technique is essential in geotechnical designs.
- The main benefit of manufacturing a low-pressure injection setup is to determine the suitable ranges of the influencing injection operational factors (like grout pressure in kPa, flow rate in l/min., diameter and number of nozzles, lifting/penetrating rate in cm/min. and rotating speed in rev/min. of the drilling and injection shafts) affecting the injection process of an injected binder for improving a given soil in order to obtain consistent

or homogeneous low-pressure injected model column samples.

- The low-pressure injection laboratory setup is a suitable tool for model improvement for almost all soil types (most suitable for sandy soils) depending on injection operational factors, cement type (or its fineness) or binder type, and soil characteristics.
- Methodologically or systematically performing the UCTs on representative samples of the low-pressure injected column models has considerable importance in validating the binder injectability process in terms of the homogeneity and reproducibility of these samples.
- In this study, the objective for performing UCTs was to determine the effect of the W/C ratio factor on the strength of low-pressure injected model columns for improving both the methods. It was revealed that at the same W/C ratio for both soil binder types, the UCTs results for samples of the SF additive binder are higher than that (about double) for samples of the OPC binder only. So, the influences of SF on the characteristics of injected soil samples were recognized.
- The paper methodology emphasized the design and local manufacture of a low-pressure injection laboratory setup for modeling a column or a pile injection process. A comparison between two injected binder types was performed using this setup by carrying out UCTs on representative samples of low-pressure injected model columns, so the importance was on the W/C ratio as a primary variable for both the binder types and keeping the SF as a constant parameter for the other binder (so 1% of SF was used for this purpose).
- For both binder types, the UCS results of the low-pressure injected column model samples increase with a decrease in the W/C ratio.
- From a sustainable point of view, using SF as a chemical additive to the cement–water mixture for improving loose sand can lead to higher strength and less consumed cement but at a higher cost.

Funding information: The researchers affirm that no finance was received.

Author contributions: All researchers have been responsible for this document's whole enclosure and accepted its handing over.

Conflict of interest: The researchers express no contradictory interests.

References

- [1] Jehan B. Improvement of bearing capacity of sandy soil by grouting. *Sarhad Univ Int J Basic Appl Sci.* 2017;5(1):33–9.
- [2] Croce P, Flora A, Modoni G. Jet grouting technology, design and control. Boca Raton (FL), USA: CRC Press; 2014.
- [3] Kumar S. A study on the engineering behaviour of grouted loose sandy soils [dissertation]. Kochi: Cochin University of Science and Technology; 2010.
- [4] Nikbakhtan B. Development of thermal-insulating soilcrete using laboratory jet grouting setup [dissertation]. Edmonton, Canada: University of Alberta; 2015.
- [5] Khalili HD, Ghalandarzadeh A, Moradi M, Karimzadeh R. Effect of the distribution pattern of D.S.M. columns on the efficiency of liquefaction mitigation. *Sci Iran.* 2020;27(5):2198–208.
- [6] Dano C, Derache N. Grout injection in the laboratory. In: Ochiai H, Omine K, Otani J, Yasufuku N, editors. *Landmarks in Earth Reinforcement: Proceedings of the International Symposium on Earth Reinforcement*; 2001 Nov 14–16; Fukuoka, Japan. CRC Press, 2001. p. 21–27.
- [7] Akin M, Akin M, Çiftçi A, Bayram BB. The effect of jet-grouting on the cyclic stress ratio (C.S.R.) for the mitigation of liquefaction. *Elektronik Mesleki Gelişim ve Araştırma Dergisi.* 2015;1:9–20.
- [8] Li SC, Sha F, Liu RT, Zhang QS, Li ZF. Investigation of fundamental properties of microfine cement and cement-slag grouts. *Constr Build Mater.* 2017;153:965–74.
- [9] Kumar GS, Sumanth MK, Samuel M. A review paper on stabilization of sandy soil using cement grouting technique. *J Crit Rev.* 2020;7(14):902–8.
- [10] Njock PGA, Shen JS, Modoni G, Arulrajah A. Recent advances in horizontal jet grouting (H.J.G.). *An overview Arab J Sci Eng.* 2018;43(4):1543–60.
- [11] Sedighi P, Schweiger HF, Wehr WJ. Effect of jet-grout columns on the seismic response of layered soil deposits. *ASCE Int J Geomech.* 2017;17(3):04016085.
- [12] Guler E, Secilen GG. Jet grouting technique and strength properties of jet grout columns. *IOP J Phys Conf Ser.* 2021;1928(1):012006.
- [13] Shen SL, Wang ZF, Cheng WC. Estimation of lateral displacement induced by jet grouting in clayey soils. *Geotechnique.* 2017;67(7):621–30.
- [14] Dano C, Hicher PY, Tailliez S. Engineering properties of grouted sands. *J Geotech Geoenviron.* 2004;130(3):328–38.
- [15] Mollamahmutoglu M, Yilmaz Y, Kutlu I. Grouting performance of microfine cement and silica fume mix into sands. *J ASTM Int.* 2007;4(4):1–7.
- [16] Schwarz LG, Krizek RJ. Effect of preparation technique on permeability and strength of cement-grouted sand. *Geotech Test J.* 1994;17(4):434–43.
- [17] Olgun M, Kanat A, Senkaya A, Erkan IH. Investigate the properties of jet grouting columns with fine-grained cement and silica fume. *Constr Build Mater.* 2021;267:120637.
- [18] AL-Kinani AM, Mahmood DA. Field study of the effect of jet grouting parameters on strength-based on tensile and unconfined compressive strength. *IOP Conf Ser Mat Sci Eng.* 2020;737:012083.

- [19] Kazemian S, Huat BBK, Prasad A, Barghchi M. A review of stabilization of soft soils by injection of chemical grouting. *Aust J Basic Appl Sci.* 2010;4(12):5862–8.
- [20] Kazemian S, Huat BBK. Assessment of stabilization methods for soft soils by admixtures. *International Conference on Scientific & Social Science Research (CSSR 2010)*; 2010 Dec 5–7; Kuala Lumpur, Malaysia. IEEE, 2011. p. 118–21.
- [21] U.S. Army Corps of Engineers, Engineering Manual NO. EM 1110-1-3500, “Engineering and Design Chemical Grouting”, Department of the Army U.S. Army Corps of Engineers Washington, DC; 1995.
- [22] Shroff AV, Shah DL. Grouting technology in tunnelling and dam construction. 2nd ed. Amsterdam, Netherlands: A.A. Balkema; 1999.
- [23] U.S. Department of Transportation, Federal Highway Administration. Ground modification methods reference manual. Vol. II. Publication No. FHWA-NHI-16-028; 2017.
- [24] Aldred JM, Holland TC, Morgan DR, Roy DM, Bury MA, Hooton RD, et al. Guide for the Use of Silica Fume in Concrete. Farmington Hills (MI), USA: ACI Committee; 2006.
- [25] Raveendran KG, Rameshkumar V, Saravanan M, Kanmani P, Sudhakar S. Performance of silica fume on strength and durability of concrete. *Int J Innovative Res Sci Eng Technol.* 2015;4(10):10162–6.
- [26] Li H, Xiao HG, Yuan J, Ou JP. Microstructure of Cement Mortar with Nano-Particles. *Compos Part B Eng.* 2004;35(2):185–9.
- [27] Hasanzadeh A, Shooshpasha I. Effects of silica fume on cemented sand using ultrasonic pulse velocity. *J Adhes Sci Technol.* 2019;33:1184–200.
- [28] Wilson M, Kannangara K, Smith G, Simmons M, Raguse B. Nanotechnology basic science and emerging technologies. 1st ed. Boca Raton (FL), USA: CRC Press; 2002.
- [29] Zhang P, Li Q. Effect of silica fume on durability of concrete composites containing fly ash. *Sci Eng Compos Mater.* 2013;20(1):57–65.
- [30] ASTM D2166. Standard test method for unconfined compressive strength of cohesive soil. West Conshohocken (PA), USA: ASTM International; 2016.
- [31] Federal Highway Administration Design manual: Deep mixing for embankment and foundation support. Publication Number: FHWA-HRT-13-046; 2013.