Characteristics of Pile Models Injected by Low-Pressure-Injection Laboratory Setup for Chemical Improving Loose Sandy Soil

Mohammed S. M.[1, a*] and M. D. Ahmed[1, b]

[1]Department of Civil Engineering, University of Baghdad, Baghdad, raq

[a]mohammed.bridge@gmail.com and [b]dr.mahmood.d.a@coeng.uobaghdad.edu.iq

*Correspondent author

Abstract. The jet grouting method for soil improvement is a novel geotechnical alternative for enhancing problematic soils where traditional foundation designs cannot provide sustainable solutions. The paper methodology was based on improving loose fine sandy soil using silica fume as a chemical additive added (with 10 percent of the cement weight) to the water and Portland cement mixes with different W/C ratios to produce pile models injected by a low-pressure injection laboratory setup that was designed and locally manufactured for this purpose. The setup design was inspired by previous research works, where its performance was validated by systematically performing unconfined compression tests (UCTs) on samples of the laboratory-injected pile models. Based on the UCTs results, high determination coefficient (R^2) mathematical models were developed that related the W/C ratios of the injected mixtures to the basic parameters (cohesion, friction angle, and elasticity modulus) of the grouted pile models, validating the laboratory setup injection efficiency.

Keywords: Sand improvement; jet grouting; silica fume; unconfined compression test.

1. INTRODUCTION

The term "ground improvement" refers to enhancing the performance of a site's foundation soils or a project's earth structures under design and/or operational loading conditions. When soil replacement is impractical due to environmental concerns, technical difficulties, or high cost, geotechnical construction methods and technologies can be used to fulfill ground improvement goals [1]. Cement injection is a fairly new discovery utilized mostly for soil enhancement and presents efficient solutions to numerous geoenvironmental and geotechnical challenges. Cement injection displaces and instantly combines subsoil with binder injected to create hard, impermeable wings, columns, or panels. In this process, the soil is immediately mixed in place with a binder (often a combination of cement and water), which is pumped at a very high pressure (at least 30 MPa) [2]. The cement injection technique improves the geotechnical properties of the subsoil, resulting in a rise in bearing capacity and elasticity modulus. Cement-injected columns can also be utilized to produce impervious walls. Jet grouting is particularly adaptable since it may be used vertically, obliquely, or horizontally. In general, cement-injected columns are used to increase bearing capacity and decrease foundation settlements in soft soils under static loading, but they will also alter the behavior of soft soil strata exposed to seismic loading [3-6].

Jet grouting is an effective procedure for improving problematic soil's physical or chemical properties. Unfortunately, the in-situ conditions do not frequently allow a thorough examination of the injected soil's behavior. As a result, the soil injection procedure is replicated in the laboratory for this purpose. In many cases, the primary goal of laboratory injection tests is to assess the injectability of grout with a specific binder for a particular type of soil and to understand the physical or chemical mechanisms that occur as the injected binder impregnates the soil. As a result, some injectability procedures have been proposed [7]. This experimental study assessed the efficiency of improving loose sandy soil with injected cement by utilizing a low-pressure injection laboratory setup designed and locally fabricated with nearly the same performance as the in-situ equipment operation but with a smaller footprint and lower expense. The studied soil was loose fine sand with a 20 percent relative density brought from Karbala Province, improved by low-pressure injection binder (using S F added with 10 percent of cement weight as a chemical additive to the water and Portland cement mixtures with different W/C ratios) [8].

Since most experimental programs reported in the literature have used UCTs, which are easy, quick, reliable, and cheap to evaluate soil grouting effectiveness with cement, the UCTs program was used in this study to validate injected soil homogeneity and determine the impact of operational factors on the low-pressure injection laboratory setup's performance. Based on the UCTs results, high determination coefficient (R^2) mathematical models were established that related the W/C ratios of the injected mixtures to the basic parameters (cohesion, friction angle, and elasticity modulus) of the grouted pile models, validating the performance of the laboratory setup for sustainable soil improvement.

2. GROUTING TECHNIQUES AND MATERIAL PROPERTIES

2.1 Cement Grouting

The cement grouting technique utilizes high-velocity hydraulic energy to reconstitute the soil as the initial phase of the procedure. The eroded soil grains are then taken out of the borehole and filled with reinforcing binders, including grout and cement, to make a hardened field feature recognized as a grouted column. The injected binder or water is pressurized through a tiny nozzle by injection pressure to provide high-velocity energy to remold and weaken the soil's strength [5]. In general, jet grouting can be performed using one of three basic systems depending on the number of fluids utilized in the operation. These are classified as single, double, and triple fluid systems. The most sophisticated way is the triple fluid system, which employs three tubes to transport water, grout, and air individually. More soils are extracted in the triple fluid system, and it is feasible to completely substitute the soil with a binder [9].

The triple fluid system is the most efficient soil-improving technique for cohesive soils. It is also easier to control and safer for sensitive constructions than a single fluid system. After selecting the cement injection system, the cement injection operating factors are designed based on previous practices. It is unknown how these factors and soil qualities impact soilcrete properties [10]. These uncertainties may raise the project's overall risk and cost. They may limit the usage of cement injection in various circumstances. Many investigators and cement injection professionals have sought to assess the effects of various factors on the grouted columns properties. They also computed several soilcrete mechanical, structural, and/or physical characteristics. These approaches, however, are limited and have significant drawbacks [11].

Field trial cement injection is commonly used to assess grouted columns properties. The trial jet grouting is carried out in a temporary area with identical geotechnical parameters as the major project. It entails grouting multiple columns (typically fewer than 10) with various grouting operational parameters. After curing, the trial columns are excavated. Their required properties are measured in accordance with the project requirements. Finally, based on the results of the field trial tests, the real operating parameters for achieving the desired soilcrete qualities on the main job site are determined [12].

2.2 Chemical Grouting

The term "chemical grout" refers to a broad category of grouting materials in which no particles are suspended in solution. Chemical improvement is an efficient way of enhancing soil properties by incorporating chemicals. Cementation and cation exchange reactions are two of the main chemical stabilization reactions. Lime, Portland cement, silica fume, sodium silicate, bituminous emulsion, and fly ash are common chemical materials used in cementing [13]. Numerous chemical binders are formed by the reaction of sodium silicate with a reagent to generate a gel. Calcium chloride is used as a reagent in the chemical grouting procedure in coarse granular soils: bicarbonates, sodium aluminates, organic esters, and other reagents. The gel duration, initial viscosity, and grouted soil strength order can be adjusted by altering the reagent and ratio [14,15].

Chemical injections, as opposed to cementitious injections, are grouted into pores as a solution. The distinction between chemical injection and cementitious injection is that chemical grout can be used to fill finer spaces among soil grains up to 10 to 15 ηm in diameter. In other words, it is more permeable than cementitious grout [16]. Chemical grout can be categorized as either a one-step or a two-step process. In a one-step process, all parts are pre-blended before injection, and the system is designed to make the reaction in situ. In the two-step process, the initial chemical is injected into the soil mass, followed by the second chemical material, which reacts with the first chemical in situ and stabilizes the mass [17].

2.3 Silica Fume

Silica fume is a byproduct substance produced in large quantities around the world as a byproduct of the production of silicon or ferrosilicon alloys. First, the raw substances (coal and quartz) are smelted at high temperatures in an electric arc furnace to produce silica fume. The smoke produced by the furnace is a fine powder called silica fume. Finally, the silica fume is captured in the baghouse's filtration system and packaged commercially. In general, silica fume particles are spherical and less than one μm diameter with an average of 0.1 μm. As a result, the particles of silica fume are about 100 times smaller than the average particle of cement [18]. Furthermore, due to its extreme fineness and high amorphous silicon dioxide content, silica fume is a highly reactive pozzolanic material. As a result, it is widely regarded as one of the best pozzolans for concrete. Many studies have been conducted to determine the effect of silica fume on concrete behavior. Previous research has shown that using silica fume as an admixture in cement-based materials has many advantages, including improved resistance to abrasion and chemical attack and increased compressive, tensile, and flexural strengths [19].

The advantages of silica fume are due to changes in the microstructure of the concrete. These alterations are the outcome of two distinct but equally essential processes. The first is the physical contribution of silica fume, while the second is its chemical contribution. The physical contribution of adding silica fume is that it brings millions and millions of microscopic particles to a concrete mixture. Like fine aggregate fills in the spaces between coarse aggregate particles, silica fume fills in the spaces between cement grains. This phenomenon is frequently referred to as "particle packing" or "micro-filling" [20]. At the same time, the chemical contribution of silica fume is that it is a very reactive pozzolanic material in concrete because of its very high amorphous silicon dioxide content. As the Portland cement in concrete reacts chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form an additional binder material called calcium silicate hydrate, similar to the calcium silicate hydrate formed from Portland cement. Essentially, this extra binder gives silica-fume concrete its improved hardening properties [21-23].

3. IMPORTANCE OF UNCONFINED COMPRESSIVE STRENGTH IN ASSESSING STRENGTH OF GROUTED SOIL

The measurement of the unconfined compressive strength (UCS) of the grouted specimen retrieved by coring or sampling from a grouted ground is commonly used to identify and judge the quality of the reinforcement or improvement after the injection of grout. This is because the grouting method has many uncertainties regarding controlling the shape and position of the grout suspension in the field. However, coring or sampling is time-consuming and costly, and it can even disrupt the grouted ground to prepare the specimen for an unconfined compression test. As a result, prior studies have proposed various empirical correlations to estimate the UCS of grouted sand for quality control of grouted sand. Furthermore, the development of empirical UCS calculating formulas is desirable because evaluating the strength of grouted sand before injecting the grout into the sand deposit enhances the cost-effective design of soil improvement [24].

The strength of grouted ground is determined by the properties of the binder materials (the water-to-cement ratio and specific surface of cement) and the characteristics of ground to be improved (relative density or porosity, particle size, mineralogy, fines content, specific surface of soil), as well as the types and details of grouting, curing period, and loading condition. Table 1 lists some factors that influence the strength of the treated ground. Figure 1 depicts the trend of rising UCS with decreasing W/C ratio from different sources for cement binders combined with inorganic soils in laboratories. Although there is some variation in the data, the general trend shows that the 28-day UCS of the mixes decreases as the total W/C ratio of the mixture increases. This follows the tendency of decreasing strength as W/C ratio increases in concrete. However, typical total W/C ratio values for jet grouting are significantly higher than average W/C ratio values for concrete [25].

Table 1: Factors affecting the strength of grouted soil (After Bruce et al., 2013 [25]).

Category	Factors
Characteristics of binder	• Type of binder(s) • Quality • Mixing water and additives
Characteristics and conditions of soil (especially important for clays)	• Physical, chemical, and mineralogical • properties of soil • Organic content • pH of pore water • Water content
Mixing conditions	• Amount of binder • Mixing efficiency • Timing of mixing/remixing
Curing conditions	• Temperature • Curing time • Humidity • Wetting and drying, freezing and thawing, etc.
Loading conditions	• Loading rate • Confining pressure • Stress path (e.g., compression, tension, and simple shear)

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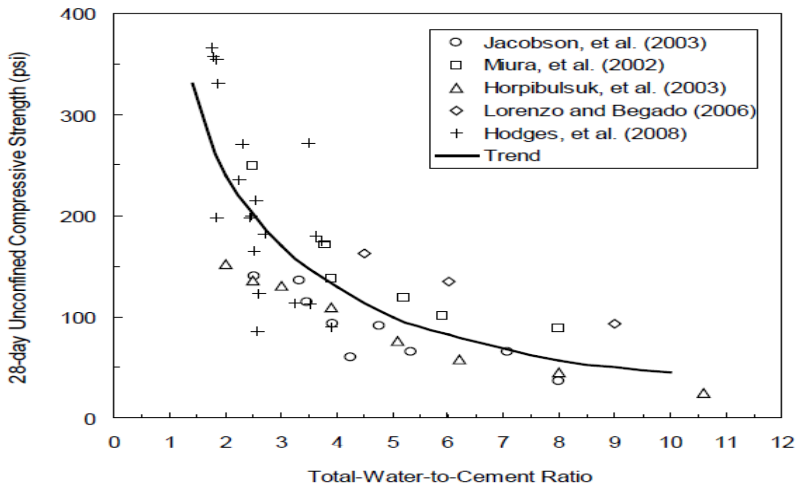

Figure 1: UCS versus W/C ratio for laboratory-mixed and tested specimens (After Bruce et al., 2013 [25]).

4. PREPARING OF THE SOIL TESTING BOX

The studied soil was poorly graded sand passing through sieve size #10 (Figure 2 illustrates the soil grain size distribution curve), and its geotechnical properties are listed in Table 2.

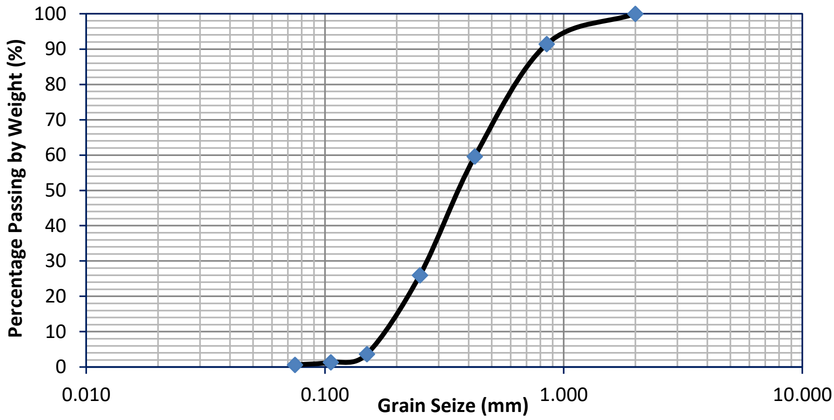

Figure 2: Soil grain size distribution curve.

The preparation of the soil testing box requires the following steps:

- Using the sand raining (air pluviation) technique [26] (shown in Figures 3 and 4), the sand in the soil box is spread in uniform layers with 10 cm height for each layer according to the required relative density. This technique is used to prepare uniform sand layers for testing large-sized specimens based on maximum and minimum laboratory dry unit weights by referring to Equation (1) [27].

$$D_r = \frac{\gamma_{d\,max}}{\gamma_d} \times \frac{\gamma_d - \gamma_{d\,min}}{\gamma_{d\,max} - \gamma_{d\,min}} \times 100$$
(1)

Where Dr, γ_d, $\gamma_{d\,max}$, and $\gamma_{d\,min}$ are the selected soil relative density, the selected dry unit weight, the soil dry unit weight in the densest state, and the soil dry unit weight in loosest conditions, respectively.

- For this investigation, where a 20% relative density was chosen for liquefiable sand specimen preparation, and from Equation (1), the corresponding dry unit weight for the soil is calculated.
- From each layer's calculated dry unit weight and volume, the required dry sand weight is (rained) inside the soil box using a hopper funnel with a 40 cm diameter and 35 cm height suspended at 2.5–2.75 m height by a car's engine crane. This raised funnel is linked to a flexible plastic hose with a 5 cm diameter so that uniform samples can be spread along the parallel lines drawn on the inside of the

soil box, which is made of steel and has a clear polycarbonate front panel.

- Following the completion of the sand rain, each layer surface is leveled up (completed by gentle taping on each layer surface) to the required level marked by lines inside the soil box sides.
- After preparing the sand box, a one-inch-thick plastic sandwich panel was drilled with the required diameter and number of circles for the column models to be grouted, and a thin plastic layer of polythene sheet was placed beneath this panel to prevent backflow or spoils from infiltrating down into the soil box during the grouting operation. During the grouting process, a small piece of this polythene sheet layer is removed successively each time a column model is grouted with cement.

Table 2: Geotechnical characteristics of investigated soil.

Characteristics of tested sand	Value	Standard or specifications
Selected soil relative density (D_r %)	20	According to study requirements
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 soil phase relationships
Max. dry unit weight ($\gamma_{d\ max}$), kN/m^3	18.5	ASTM D4253
Min. dry unit weight ($\gamma_{d\ min}$), kN/m^3	16.8	ASTM D4254
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
Selected void ratio	0.54	Calculated from soil phase relationships
Uniformity Coefficient (C_U)	2.36	poorly graded soil (CU < 6)
Coefficient of Curvature (C_C)	0.98	poorly graded soil (CC does not lay between and 3)
Fines, %	0.6	ASTM D6913
Plasticity index	N.P.	ASTM D4318
Soil classification according to USCS	SP	ASTM D422 and ASTM D2487
Dry friction angle, $\emptyset^{\circ}$	30	Direct shear test ASTM D3080/ D3080M-11
Saturated friction angle, $\emptyset^{\circ}_{sat}$	24	Direct shear test/undrained condition

Figure 3: Sand box preparation by raining.

Figure 4: Sand box preparation by raining from the elevated hopper funnel through the diffuser screen.

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5. Low-Pressure Injecting Laboratory Process

After performing many laboratory injection trials to get consistent column models by determining the best operational injection factors (the drilling and injection rod rotation speed in rev/min, the drilling and injection rod penetrating and withdrawal speed in cm/min, the pumping pressure and flow rate of the binder fluid, and the number and opening diameter of the injection holes), the following steps are needed to perform homogenous laboratory injected column models.

- After mixing (with a portable electric handheld mixer) the injection materials in a separate bucket according to the required proportions, the injection fluid is poured into the mixing tank of the low-pressure injection setup (Figures 5, 6, and 7). Then, the mixing motor is operated to the suitable rotation speed from the variable-frequency drive inverter on the control board.
- To ensure the injection pump works correctly, the injection fluid is circulated from the bottom of the mixing tank via the setup pipe system and back to the top of the mixing tank from the top inlet.
- The drilling and injection rod is then rotated clockwise and lowered into the sand box at a speed of 20 cm/min.
- Before starting the low-pressure injection process, a trial injection (pumping a small amount of injection fluid over the soil surface) is carried out to ensure the proper operation of the nozzles. This trial injection is very important to ensure that nozzles don't get clogged by sand grains intrusion and that the injection keeps going while the soil is drilled and injected.
- The low-pressure injecting process is made in the soil box by directing the platform injection system downward and rotating (at 50 rpm revolution speed) the drilling and injection rod in a clockwise direction, where the low-pressure injection process is performed in two stages:

1. The first stage is associated with the downward drilling process of the injection hole with a suitable fluid grout pressure to stabilize the hole walls.
2. The second stage (primary process) starts upward after the injected rod reaches the hole bottom in the soil box. From the control board, the rod rotation is reversed in the counterclockwise direction, and the platform injection system is directed upward at the previously prescribed speed with the required injection fluid injection pressure according to the diaphragm pressure gauge.

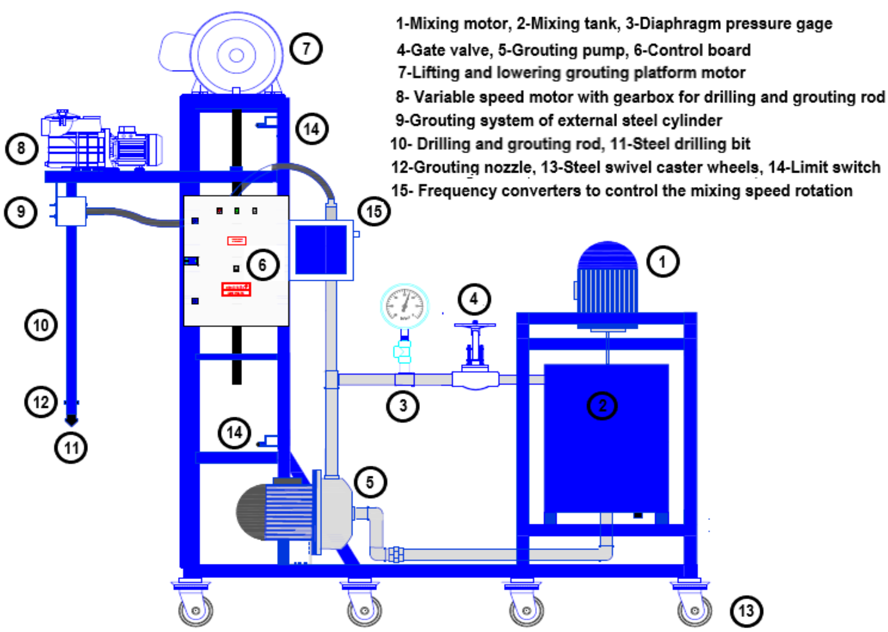

Figure 5: Schematic diagram of the low-pressure injection laboratory setup.

- During the low-pressure injection process, some spoils flow from the injection hole surface to be removed from the soil box surface.
- The drilling and injection system platform moves upward until the nozzles reach the soil box surface in the low-pressure injection process. This is the end of the low-pressure soil injection process, which

makes injected column models that are homogenous and consistent.

- During the low-pressure injection process, there is a little depression in the surface area of the column models (local densification for the laboratory injection process leads to a shortening of the columns' model length) to be substituted with the same soil properties mixed with the upward-spoiled binder.
- The laboratory injection process continued by moving the setup to another location in the soil box until the required number of column models was injected.

After the column model laboratory injection is completed (Figures 8 and 9), the curing process begins by immersing them in a suitable water basin for a 28-day curing period.

Figure 6: Laboratory setup (front view).

Figure 7: Laboratory setup (side view).

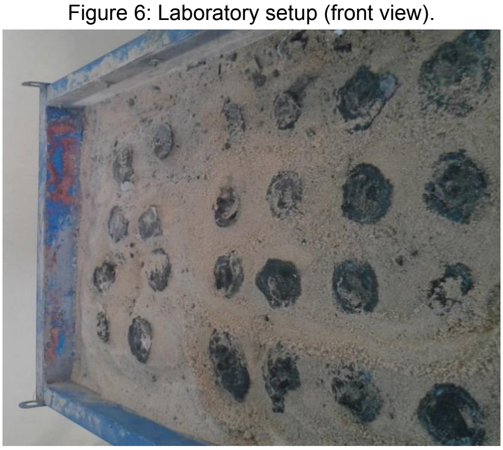

Figure 8: Grouted column models.

Figure 9: Extracted grouted columns.

6. STUDY RESULTS AND DISCUSSION

Cement grouting can be used effectively to raise the compressive strength of sand by filling voids and imparting cohesion and adhesion factors. When grouted with cement, the shear strength parameters (c) and (Ø) indicate a notable increase. The W/C ratio of the grout is a crucial control factor for the strength gain of sandy soils, with increased cementation in granular soil increasing cohesion, tensile strength, and friction angle at low confining pressures [28]. As a constitutive model, the Mohr-Coulomb failure criterion is extensively utilized to estimate the strength of geomaterials such as soils and rocks. The shear strength is assumed to vary linearly with the applied normal stress through two shear strength factors generally known as the angle of internal friction (Ø) and the cohesion (c). The correct design parameters are required for carrying out the designs and modeling soil or rock-related problems. Cohesion (c) and friction angle (Ø) in soils are determined using laboratory experiments such as triaxial or direct shear testing or indirectly through in situ tests [29]. Even though the Mohr-Coulomb criterion is often used to figure out the shear strength of soils, it can be used for lightly cementitious stabilizing soil or aggregate bases. Many researchers have used triaxial tests to study cement-treated soils and aggregates. Yet, the triaxial test requires highly expensive equipment and takes too long to prepare and test samples, making it unsuitable for everyday laboratory or field experimentation. Christensen and Bonaquist (2002) developed an alternate approach to determining c-Ø properties for asphalt concrete base course material using indirect diametrical tensile tests and UCTs [30].

Unconfined compression testing is one of the most popular and straightforward experiments that may be performed with the basic minimum of laboratory equipment to determine the UCS values of stabilized materials and cohesive soils. The indirect diametrical tensile test, occasionally referred to as the Brazilian test, was invented by two Brazilian investigators, Barcellos and Carneiro, in 1952 to determine the tensile strength of brittle materials by applying a compressive load along two opposing sides of a cylindrical sample [31]. Typically, the Mohr-Coulomb criterion is depicted graphically by plotting a sequence of Mohr circles indicating stress states at incipient failure under increasing amounts of confining stress and then drawing a tangent to these circles, representing the Mohr-Coulomb failure envelope. The failure envelope is then used to determine c and Ø. The IDT and UC tests can be used to determine the c and Ø of cementitious stabilized granular materials. The stress status of the samples at failure during IDT and UC testing is depicted by Mohr circles, as shown in Figure 10. Failure occurs theoretically when the shear and normal stress are plotted above the Mohr-Coulomb envelope. Based on these geometrical relationships, Ø and c can be expressed as follows:

$$\emptyset = \mathbf{sin}^{-1}\left(\frac{\mathbf{UCS} - \mathbf{T}}{\mathbf{UCS} + \mathbf{T}}\right) \tag{2}$$

$$\mathbf{a} = \frac{(\mathbf{T})^2}{\mathbf{UCS} - \mathbf{T}} \tag{3}$$

$$\mathbf{c} = (\mathbf{a} + \mathbf{T})\mathbf{tan}(\emptyset) \tag{4}$$

Where Ø and c are the friction angle and cohesion of the Mohr-Coulomb envelope of stress circles, and UCS and T are the unconfined compression strength and splitting tensile strength of soilcrete. Concrete members' compressive strength and splitting tensile strength are two crucial properties used in the design. The direct tension test, the modulus of rupture test, and the split cylinder test are the three methods that can be used to evaluate the tensile strength of concrete. The split cylinder test is well-known for its ease of execution and the trustworthy information it provides when subjected to uniform stress [32].

However, performing the splitting tensile test is not always straightforward from an experimental standpoint. Researchers have sought to predict the splitting tensile strength using theoretical and empirical methodologies based on compressive strength as a substitute for the costly and time-consuming direct measurements of the splitting tensile strength. The square root function was presumably chosen to easily predict tensile strength from compressive strength. However, current investigators have found that the square root correlation between splitting tensile strength and compressive strength is not the best fit for maturing concrete, and the power of compressive strength ranges from 0.6 to 0.8 [33].

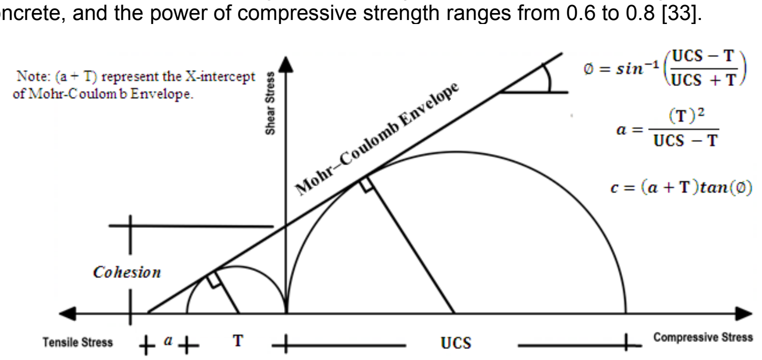

Figure 10: Mohr-Coulomb Envelope for Mohr circles stress of T and UCS of the injected soil (after Kramadibrata et al.-2008 [34], and AL-Kinani and Ahmed-2020 [35]).

The study experimental program includes performing unconfined compression tests on samples of low-pressure injected column models for improving loose fine sandy soil using silica fume (S.F) as a chemical additive added (with 10 percent of the cement weight) to the water and Portland cement mixes with different W/C ratio groups to determine their (cohesion, friction angle, and elasticity modulus) parameters. The identically chosen samples were cut with height-to-diameter ratios between 2.0 and 2.5 from each W/C ratio of the group samples. According to ASTM D2166 [36], the samples were centrally loaded by an automatic loading apparatus (at a displacement rate of 1.2 mm/min up to the failure to obtain the maximum applied load) equipped with a calibrated electronic load cell and a data logger for data acquisition was utilized for these tests. The tests were performed on identical samples for each W/C ratio group to minimize the variation in the testing conditions and materials. Because the data error was less than 5%, the obtained results were validated. Table 3 lists the improved soil unconfined compression strengths and their correlated calculated splitting tensile strengths using several relationships based on unconfined compression strengths.

The Curve Expert Professional software version (2.7.3) was utilized for generating high-quality mathematical models using a cross-platform solution for the study's curve fitting and data analysis. Figure 11 shows that the average unconfined compression strength values of the improved soil go down as the W/C ratio increases, showing the same behavior as those found in the literature on soil improvement. This relationship has a good correlation and a high determination coefficient (R^2=0.96). (Figures 12, 13, and 14), relating the variations in average elasticity modulus values, average friction angle values, and average cohesion values of laboratory low-pressure injected pile models with decreasing W/C ratios at high determination coefficients R^2.

Table 3: Calculated splitting tensile strength values of improved soil (Using several relationships based on unconfined compression strengths).

W/C Ratio	Average UCS values q_u (MPa)	Split tensile strength values (MPa) (T)							Average tensile strength (MPa) ($T_{average}$)
		ACI 363R-1992 [37]	ACI 318-1999 [38]	Ahmad and Shah, 1985 [39]	Gardner et al., 1988 [40]	Gardner, 1990 [41]	Arıoglu et al., 2006 [42]	Lavanya and Jegan 1915 [32]	
		$T_1=0.59(q_u)^{0.5}$	$T_1=0.56(q_u)^{0.5}$	$T_1=0.462(q_u)^{0.55}$	$T_1=0.47(q_u)^{0.59}$	$T_1=0.34(q_u)^{0.66}$	$T_1=0.387(q_u)^{0.63}$	$T_1=0.249(q_u)^{0.772}$	
1.6	12.00	2.04	1.94	1.81	2.04	1.75	1.85	1.70	1.88
1.5	13.20	2.14	2.04	1.91	2.15	1.87	1.97	1.83	1.99
1.4	16.33	2.38	2.26	2.15	2.44	2.14	2.25	2.15	2.25
1.3	18.00	2.50	2.38	2.27	2.59	2.29	2.39	2.32	2.39
1.2	19.20	2.59	2.45	2.35	2.69	2.39	2.49	2.44	2.49
1.1	20.10	2.65	2.51	2.41	2.76	2.46	2.56	2.53	2.55
1.0	22.76	2.82	2.67	2.58	2.97	2.67	2.77	2.78	2.75

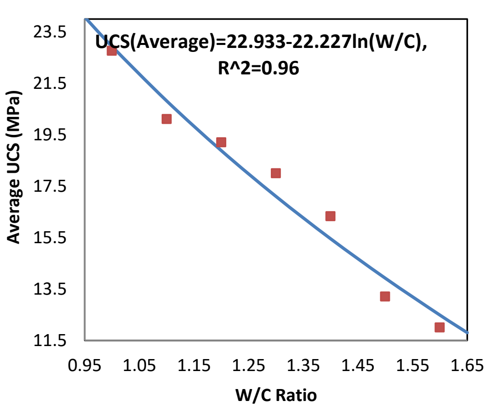

Figure 11: $UCS_{average}$ variation with W/C ratios.

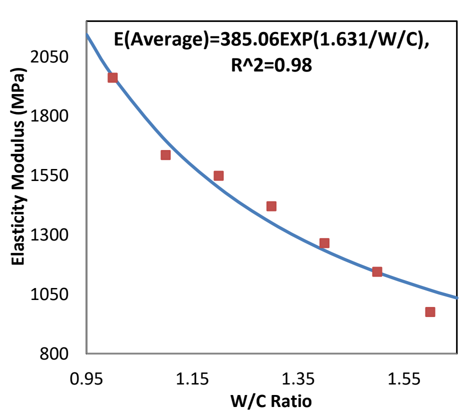

Figure 12: $E_{average}$ variation with W/C ratios.

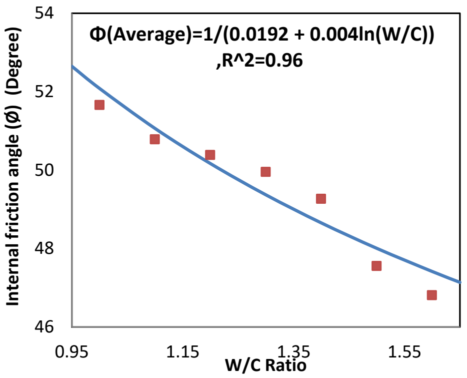

Figure 13: Figure 13: $Ø_{average}$ variation with W/C ratios.

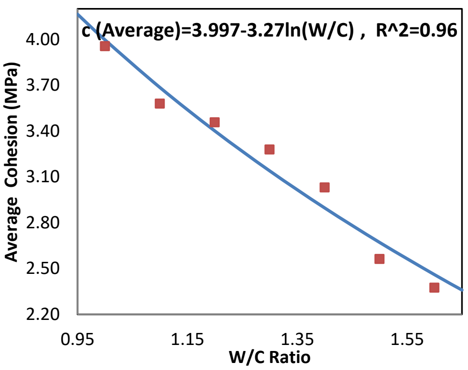

Figure 14: $c_{average}$ variation with W/C ratios.

7. CONCLUSIONS

- This manufactured low-pressure injection laboratory setup, which is used to study the injection efficiency of soil under specific conditions, is an essential and efficient tool and reference for geotechnical engineers to execute soil improvement sustainable projects instead of using field grouting equipment and large-scale grouted columns to save money and time.
- The unconfined compression tests were performed systematically to validate the low-pressure injection laboratory setup performance and the efficiency of the low-pressure injection process for soil in terms of homogeneity and reproducibility of grouted pile models.
- The laboratory-consistent grouted pile models were obtained after a large number of low-pressure injection laboratory trials to determine the appropriate ranges of the influencing operational laboratory injection factors (the rotation of the drilling and injection rod in revolutions per minute, penetrating and withdrawal rates of the drilling and injection rod in cm/min, the injection pressure and flow rate of the binder, and the number and diameter of the injection nozzles) of an injected binder for improving a given soil.
- The Mohr-Coulomb failure criterion is a simple linear elastic-perfectly plastic constitutive model that is widely used for design applications in geotechnical engineering to simulate geo-materials such as soils and rocks response under monotonic loading. There are two distinct parameters for shear strength based on the Mohr-Coulomb failure criterion: the internal friction angle (Ø) and cohesion value (c). In soil mechanics, the shear strength factors friction angle (Ø) and cohesion (c) are determined from laboratory tests like direct shear tests, triaxial tests, or indirectly from field tests. Performing triaxial tests on samples to determine the shear strength parameters is an arduous and hard task.
- However, the triaxial test is not practical for everyday laboratory or field experimentation since it requires expensive equipment and a long period of time to prepare and evaluate samples. Unconfined compression tests and indirect diametrical tensile tests were proposed as an alternate method of determining c-Ø characteristics for geo-materials.
- Performing split tensile strength tests is not always easy from an experimental point of view. Theoretical and empirical correlation methods based on compressive strength can be used to predict splitting tensile strength, avoiding the need for time-consuming direct measurements. Therefore, the strength parameters of the injected soil can be determined based on the UCS tests to assess the effectiveness of soil improvement.
- Using silica fume makes cement-grout mixtures stronger than cement mixtures without a pozzolanic additive. This is because silica fume has very small grains, which not only fill the microspaces between particles but are also highly reactive pozzolanic material. Like the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form an additional binder material called calcium silicate hydrate, similar to the calcium silicate hydrate formed from Portland cement.
- The effect of decreasing the W/C ratio resulted in increasing the parameters (average unconfined compressive strength, average elasticity modulus, average friction angle, and average cohesion) of the laboratory-injected soil samples while increasing the amount of water or decreasing the cement quantity in the mixture led to a decrease in the density (higher porosity) and inferior quality of the hardened soilcrete.

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