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Physical-mechanical assessment of full-scale soil-cement column constructed in clayey soil

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ABSTRACT

Jet grouting has recently become a soil improvement method used to solve most soil problems. In this study, seven full-scale soil–cement (SC) columns were constructed in clayey soil with different pressure injections (300, 325, 350, 375, 400 bar), jet grout rotations (25, 35, 45 rpm) and a w/c ratio of 1. These parameters were used to examine the geomechanical properties of the SC, such as strength characteristics (UCS and UPV), and SC–soil surface friction. The physical properties were observed by evaluating the water absorption rate, density, and porosity. The diameter variation was analysed to determine the effect of both parameters on SC diameter. The geomechanical properties of the grout columns generally varied with pressure and rotation. The average strength variation for pressure and rotation was 38% and 9%, respectively. The average water absorption percentage was 13% and 22%; the average density was 8% and 11%; the average porosity was 6% and 10%, respectively. The maximum surface friction angles were 19° and 18° for SC350–35 and SC400–45, respectively. This study theoretically predicts the diameter of the grout column for construction in clayey soil.

1. Introduction

Soil enhancement can be categorized into two principle processes. First, improving the strength characteristic of soil according to utilizing additives material to more stabilizers, which is detected as addition to the modification. Second, using moisture sensitivity and texture change methods as a soil modification, which leads to vary the plasticity of soils [1,2]. According to the previous literatures, the cement has been considered as the public materials that used as stabilizer element in improving the performance properties of clayey soils. In addition, regarding with stabilizing soil with cement, increasing amount of cement in clayey soil leads to increasing the compressive strength and reducing the plasticity index [3–6].

Several soil development techniques have been improved in engineering trainings to solve most of various geotechnical problems. Therefore, the high pressure grouting or jet grouting methods is detected as a common application for both its cost-effectiveness and efficiency. The principle understanding of jet grout is controlling the quantities injection (cement grout) through a very small hole diameter, which is called nozzle, and rotating the drill rod with high pressure which is varied from 300-to-600 bar. Through the injecting the water-cement (w-c) grout into the soil, cemented geometries has been created so-called soilcrete column (soil-cement) or

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jet grout column (cement based grout) which leads to improve the mechanic-physical properties of grout. Generally, it has been presented that the variation range of jet grouting diameter may change between 40-to-140 cm according to the implementing operational parameters and soil type [7]. In addition, the composition of the foundation soil and effectiveness of replacing soil with cement have been considered as main variables which effected on the mechanical and physical properties of the high modulus columns [8]. Besides that, w-c ration has been also detected as a main factor of controlling the mechano-physical properties of grout column. Generally, the w-c ratio of one is considered as common ratio that used in SC column's construction. In the substantial groundwater (highly water ground level), it's preferred to use low water/cement ration to get soilcrete (soil-cement) column with elasticity modulus [7–10].

In civil engineering application, most problem has been occurred when the expensive clay visible in the sub-structural area. Because, the low strength is the main critical properties that available in clayey soil and its leads to poor construction of building over those soils, the propensity to increase their volume when they come in exposure with moisture and to shrink if moisture is eradicated from them. These soils that contains more particles of clay have swelling properties through increasing the moisture content [11]. the properties of volume change in swelling type soils, available or non-available of moisture are the main problems in structural applications such as building, bridges roads etc, which are going to constructed on those soils [12]. Thomas et al. [13] also concluded that the clayey soil contain with high compressibility, low strength, and it's very sensitive, in the sense that their strength is reduced by mechanical disturbance. In the building construction and road application, it has to be a void failure through stabilizing the clayey soil's properties that presence in those zone. The idea of soil replacement with good engineering properties by filling and cutting is time consuming and extremely expensive [13].

The mechanisms of SC with its strength in different types of soils had been studied from Güllü et al. [14] and Ho et al. [15]. As a result, they found that the additional materials were used to improve the strength characteristics. The influences of curing time, soil density, cement type, and chemical reactions on the soil strength were primarily determined in laboratory conditions using strength tests such as unconfined compression tests. The literatures also indicated that the strength characteristics of full-scale samples is much lower compared with laboratory samples. Besides that, real construction situation and prevalent unknowns are not presented in the laboratory, and also it's a public way to investigate the microstructural parameters influencing the strength of grout column specimens, an inspection of these deliberations of the previous studies is not the concern of this study. Thus, to investigate the accurate study, and to quality control of the geometry of grout column, it has to be focusing on the full-scale dimensions of SC to scientifically analysis the microstructures of SC conditions [16–18].

Canakci et al. [19] concluded that the optimum percentage of glass fiber was 3% to investigate the better performance of strength after curing the specimens for 28 days for all clay contents. For 7 and 14 days curing times, the performance of strength generally increased with increasing glass powder, besides that, the strength had been improved with increasing the percentage of sand in clay content.

Through the studying interface friction angle, Canakci et al. [20] and Uesugi and Kishida [21] presented that there are many influencing issues that effects on the value of the interface friction angle, such as mineralogical composition, grain size, density, and gradation, even the deformation (roughness) surface of the materials considered as one of the most parameters that effect on the variation of friction angle. In addition, a deep understanding was investigated to measure the friction angle between soil (organic soil) and different construction materials such as concrete, smooth and rough steel, and wood. As a results, the maximum value of friction angle was detected between the concrete and organic soil compared with all other construction materials (smooth and rough steel, wood) regardless of the soil particle's shape. Additionally, the quantity and type of binder had a significant effect on the density. Through the comparing between two soil mixes, it presented that the mix density with a higher amount of kaolinite was lower than the rest density [22,23].

During to study the diameter and length parameters of SC, previous studies concluded that the length and diameter of SC were indicated as a main significant factors in the grout column's geometry that related to the prediction approaches [24–27]. Controlling the length of the grout column is not difficult, since it can be justified using drilling rods. Thus, controlling and measuring the diameter of SC was considered as a main part in jet grouting methods, therefore, Croce & Flora [28] presented the measuring and estimating of grout column's diameter and clarifying the parameters which effects on the size of diameter. Recently, deterministic form methods have been used to solve the quantitative problems in engineering divisions, On the other hand, the surface friction angle between the jet grout slab and wall had been studied during to finite element software [29].

This study aims a deeper understanding of geomechanical and surface friction properties of full-scale soil-cement (SC) column during injecting in the clayey soil that has been constructed in location Şahitkamil-Gaziantep -Turkey at 37°08′47.76″ N and 37°22′24.96″ E coordination. Additionally, this work investigated the effect of pressure injection on the uniaxial strength, shear strength, and diameter changes of the SC, revealing a lack of knowledge in this area. Besides that, the jet grout's rotations have been recorded a significant effect on the geomechanical properties of grout column samples. so the novelty of this paper around constructing grout column in clayey soil to enhancing the geotechnical engineering properties and investigating the strength development, surface friction, and vibration of diameter under different environments of grouting column regarding pressure injection and jet grout's rotation that considered as important parameters to show the significant effect of SC (Grouting) column during the grouting in the clayey soil. According to the direction (C, R, L, U, D), this study presented a significant effect on the physio-mechanical properties of SC column. At the end, this study reports large-scale efforts of SC, therefore, any conclusion has been observed in this paper can be deemed helpful for experiments.

2. Experimental work

The methodology of the case study has been presented in this section, which included to materials, jet grout technology, and sample preparations with test methods according to ASTM requirements.

2.1. Materials

2.1.1. Soil

The soil that has been used in this research is a clayey soil that is located in location Şahitkamil in the province of Gaziantep, Turkey, at coordinates 37°08′47.76′ N and 37°22′24.96′ E, as seen in Fig. 1. In addition, soil properties obtained according to ASTM standard requirements. Soil samples took from site work were saved in plastic bags to prevent moisture change. Based on unified soil classification system (USCS), the soil classified as clayey soil (CL) with low plasticity. According to soil tests, liquid limit and plastic limit was found to be 28.4% and 19.9% respectively, and all soil properties has been detailed in Table 1.

2.1.2. Water /cement

The full-scale jet grout column has been constructed in the site with water/cement ratio of one to analyzing the geomechanical, surface friction properties, and variation of diameter of SC in clayey soil. Benhamou [30] reported that this range of w/c ratio was utilized to observing the geotechnical applications such as permeation grouting, jet-gout, and cement grout for rock or soil injection. In addition, the Portland cement that used in this study is Portland cement (PC) type CEM I-42.5R according to ASTM C150 [31], which is the particle size distribution presented in Fig. 2 and chemical and physical properties of PC have been detailed in Table 2. Furthermore, the water-to-cement ratio was one to prepare the cement past (grout) mix, and the rheological properties of cement past (grout) has been obtained from grout mixture at various shear rates by using Coaxial rotating cylinder rheometer (ProRheo R180 Instrument, Germany), which is available in Gaziantep university – Geotechnic laboratory, as shown in Fig. 3a and b.

Fig. 1. Google map's location of the case study.

Table 1
Properties of clayey soil.

Property	Values
Specific gravity (ASTM D854-10) [59]	2.65
Water content (%)	20
Soil classification	CL
Liquid limit (%) (ASTM D4318-10) [60]	28.4
Plastic limit (%)	19.9
Plastic Index (%)	8.5
Maximum dry density (g/cm^3)	1.86
Optimum moisture content (%)	13.2

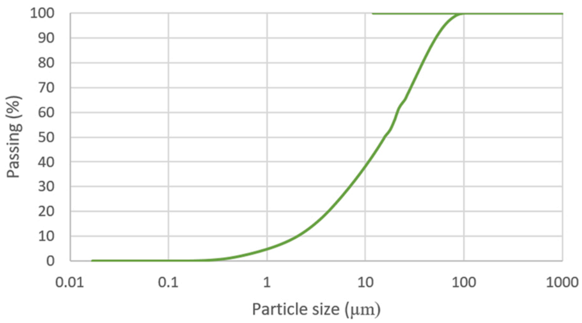


Fig. 2. Particle size distribution of OPC.

Table 2
Chemical and physical properties of ordinary Portland cement.

Properties	Composition	Average value
Chemical	CaO	67.46
	SiO_2	13.48
	Al_2O_3	3.69
	Fe_2O_3	7.78
	MgO	1.29
	Na_2O	0.36
	K_2O	0.98
	SO_3	4.82
Physical	Specific weight (g/cm^3)	3.18
	Specific surface area (Blaine) (cm^2/g)	3352
	Loss on Ignition (%)	1.98

2.2. Jet grout technology

The technology of jet grouting is an injection under high pressure of various chemical reagents – binders (strengtheners) which serve to improve the properties of the soil. In this study, grout column has been constructed in location Şahitkamil - Gaziantep -Turkey at 37°08′47.76″ N and 37°22′24.96″ E coordination as shown in Fig. 4a. In addition, after the drilling step, the injection process has been started to construct the SC by using the Comacchio MC 15 machine which presented in Fig. 4b, and the properties of jet grout machine was reported in Table 3. Then, in the grout mixer, make a cement paste by using Portland cement (PC) type CEM I-42.5R with a water-to-cement ratio of one. Then, grout paste has been injected with different pressure injection such as 300, 325, 350, 375, and 400 bar in the clayey soil and different jet grout's rotations which are 25, 35, 45 rpm to construct the 7 full-scale dimension of SC columns. Besides that, the method of jet grouting of case study was selected as a double fluid method. In this method uses two different nozzles which placed opposite each other in same rod, and from each one injected grout past and air with high pressure to erode the soil and replaced with grout past then formed the grout column after hardening. Fig. 5 presents the schematic diagram of SC column formation procedures.

2.3. Sample preparation and testing methods

This section covers the preparation of the test specimen after casting a full-scale soil-cement (SC) column in clayey soil. Next, the grouting column has been cured in the clayey soil for 28 days, then, the area around the column was excavated to extracted full-scale

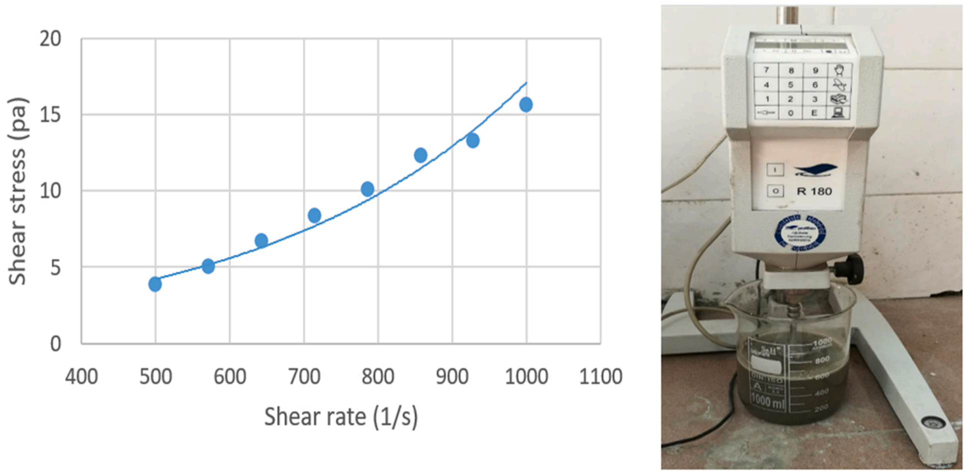


Fig. 3. Rheological properties of jet gout column: (a) Shear stress versus shear rate relationship; (b) Coaxial rotating cylinder Rheometer.

(a) (b)

Fig. 4. (a) Location of construction SC column;(b) Grout machine.

Table 3
Jet grouting column information.

Materials	Properties
Machine name	Comacchio MC 15
Rotation (rpm)	25, 35, 45
Pullout speed (cm/min)	85 cm/min.
Pressure (bar)	300, 325, 350, 375, 400 bar
Cement type	Cem I, 42.5R
W/C	1:1
Viscosity (sec/liter)	33 s/1000 ml
Fluidity of concrete	70%

dimensions and transporting to the geotechnical laboratory belong to Gaziantep university – Turkey, and taking a core sample then covered with plastic sheets to protect the moisture of sample, as shown in Fig. 6a-c. After preparing the test specimens, all specimens have been applied to the mechanical tests to study the mechanical (UCS, UPV) and physical (water absorption, density, and porosity) properties of full-scale SC column. The test samples are labeled according to different pressure injection such as 300, 325, 350, 375, and 400 bar with three different jet grout's rotations of 25, 35, and 45 rpm, therefore, the test sample has been labeled as SC300–35, it means that the (SC) is grout specimen, pressure injection is 300 bar, and jet grout's rotation is 35 rpm as detailed in Table 4. According to the directions, 5 samples have been selected for each parameter at the same surface layer which moved from center (C) to right(R) - left(L) and up (U) – down (D), for example: SC300-35-C, SC300-35-R, SC300-35-L, SC300-35-U, and SC300-35-D.

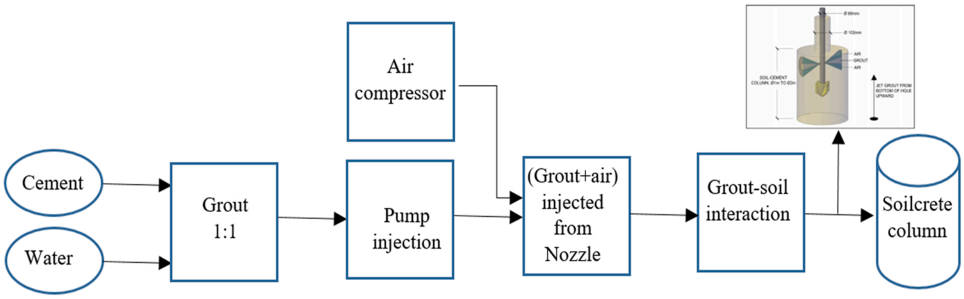


Fig. 5. Schematic diagram of SC column procedure formation.

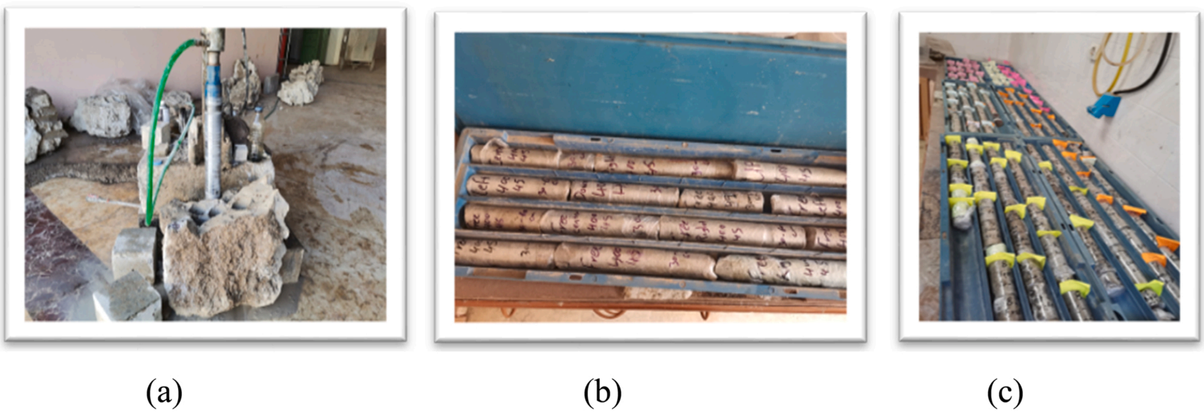


Fig. 6. SC sample preparations, (a) Coring samples, (b) covering with plastic sheet, (c) Labeling the samples.

Table 4
Material sampling of SC column.

Sample code	w/c	Pressure injection (bar)	Jet grout's Rotation (rpm)	Water content (%)
SC300-35	1:1	300	35	28
SC325-35	1:1	325	35	29
SC350-35	1:1	350	35	28
SC375-35	1:1	375	35	28
SC400-35	1:1	400	35	29
SC400-25	1:1	400	25	32
SC400-35	1:1	400	35	29
SC400-45	1:1	400	45	22

2.3.1. Unconfined compressive strength (UCS)

An unconfined compressive strength test was examined on the SC samples to measure the strength value of grout column according to different pressure injection and jet grout's rotations parameters. Next step, covering the up and down surface of specimens to observed smooth surface and more accurate results, as shown in Fig. 7a and b. The procedure test followed the ASTM D2166 [32] requirements. Therefore, it placed the samples in the center of the device and adjust the loading machine carefully till tach the surface of the sample then records zero. Afterward, applying the load with axial strain at a rate of 0.5–2.0% per minute according to ASTM requirement. Note, the rate of strain should be chosen so that the time to failure does not exceed about 15 min, therefore, 1% has been used in this study.

2.3.2. Ultrasonic plus velocity (UPV)

UPV test indicated as the one of most useful in non-distractive tests to assess the material homogeneity [33] and categorized the classification of UPV according to longitudinal wave's intervals which detailed in Table 5. In this study, the UPV test conducted for grout column specimens after curing process for 28 days in clayey soil according to ASTM C597-16 [34] requirement. PROCEQ model is one of the UPV test's marakka that the hertz interval ranged between 24 and 500 kHz as shown in Fig. 8. According to following procedure of ASTM requirement, the longitudinal pulse wave velocity of the cylindrical specimens is determined by the longitudinal vibration pulses applied in contact with the specimen surface, during the passing of longitudinal waves in specimens, the pulses are

(a) (b)

Fig. 7. Test specimens of SC, (a) covering the samples, (b) Unconfined compression machine.

Table 5
Classification of UPV (Anon, 1979).

Class	UPV (m/s)	Definition
1	< 2500	Very low velocity
2	2500–3500	Low velocity
3	3500–4000	Middle velocity
4	4000–5000	High velocity
5	> 5000	Very high velocity

Fig. 8. Ultrasonic plus velocity test machine.

received in measurements of the pulse velocity electronically.

2.3.3. Surface friction characteristics of SC column

A direct shear test was performed utilizing a conventional direct shear apparatus (ELE International), as shown in Fig. 9b. Single-stage direct shear tests were conducted under consolidated drained conditions to detect the interface shear properties under different normal stresses according to the ASTM D3080 [35] requirement. In this study, a shear test was conducted for soil-soil samples and soil-grout columns for comparison. Accordingly, the lower shear box was filled with grout sample for the first case and filled with soil for the second case with dimensions of 60 * 60 * 20 mm as presented in Fig. 9a; however, the upper shear box for all cases was filled with clayey soil to measure the interface shear behavior of the soil-soil and soil-grout column. During the test, three different normal loads (13.9, 27.8, and 55.6 kPa) were used, as shown in Fig. 9b, and 1.0 mm/min was considered the rate of shear box displacement for all tests.

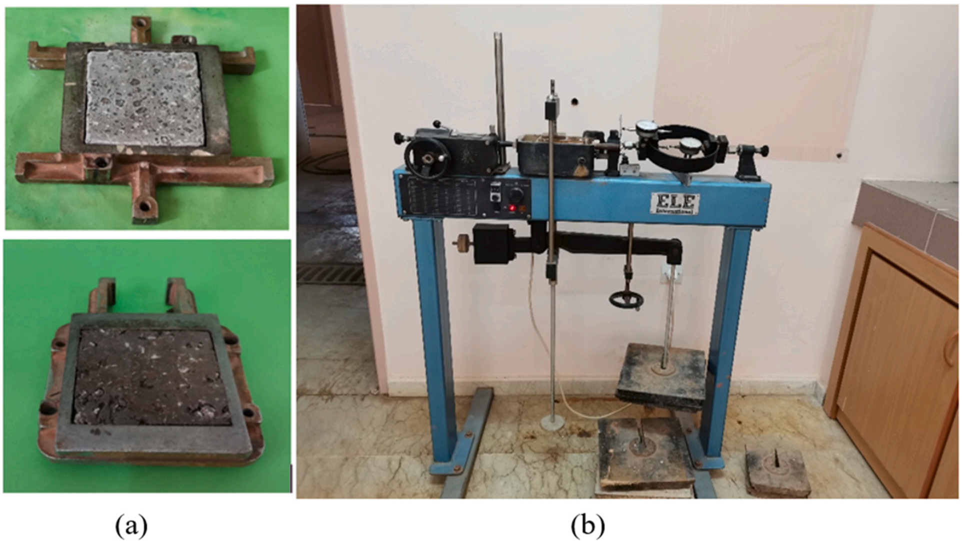


Fig. 9. Surface friction between clayey soil and SC, (a) clayey soil- SC molding, (b) direct shear test machine.

2.4. Physical properties of SC column (water absorption, density, porosity)

Generally, water absorption plays an important role in grout column manufacture and is utilized to determine the amount of water absorbed under specified conditions according to ASTM D6473-15 [36]. In addition, the porosity test calculated the volume of the void fraction in the specimens according to ASTM C20-00 [37].

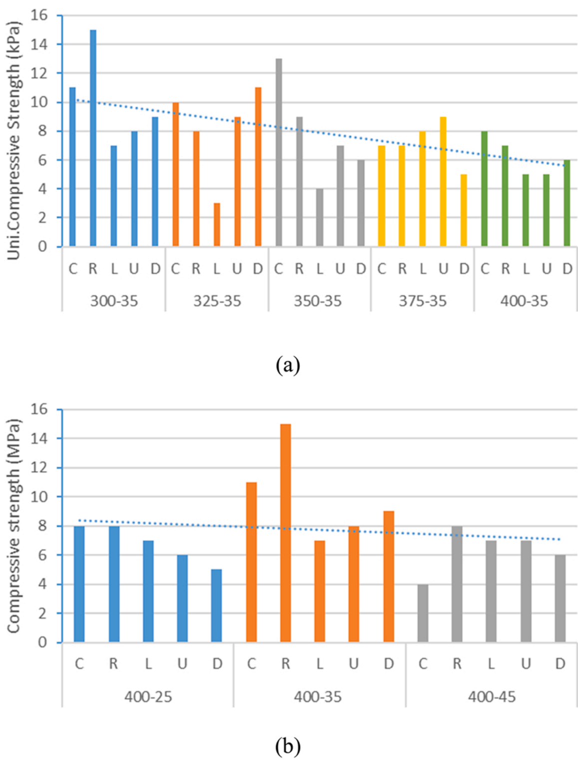


Fig. 10. Compressive strength variation of SC according to, (a) pressure injection, (b) jet grout's rotations.

3. Result and discussion

3.1. Mechanical properties of SC column

The mechanical properties results of SC have been presented in this section according to different parameters such as pressure injection of 300, 325, 350, 375, and 400 bar and jet grout's rotation (25, 35, 45) rpm regards with different location for each parameters, which is moved from the center of SC column to right-left and up-down directions.

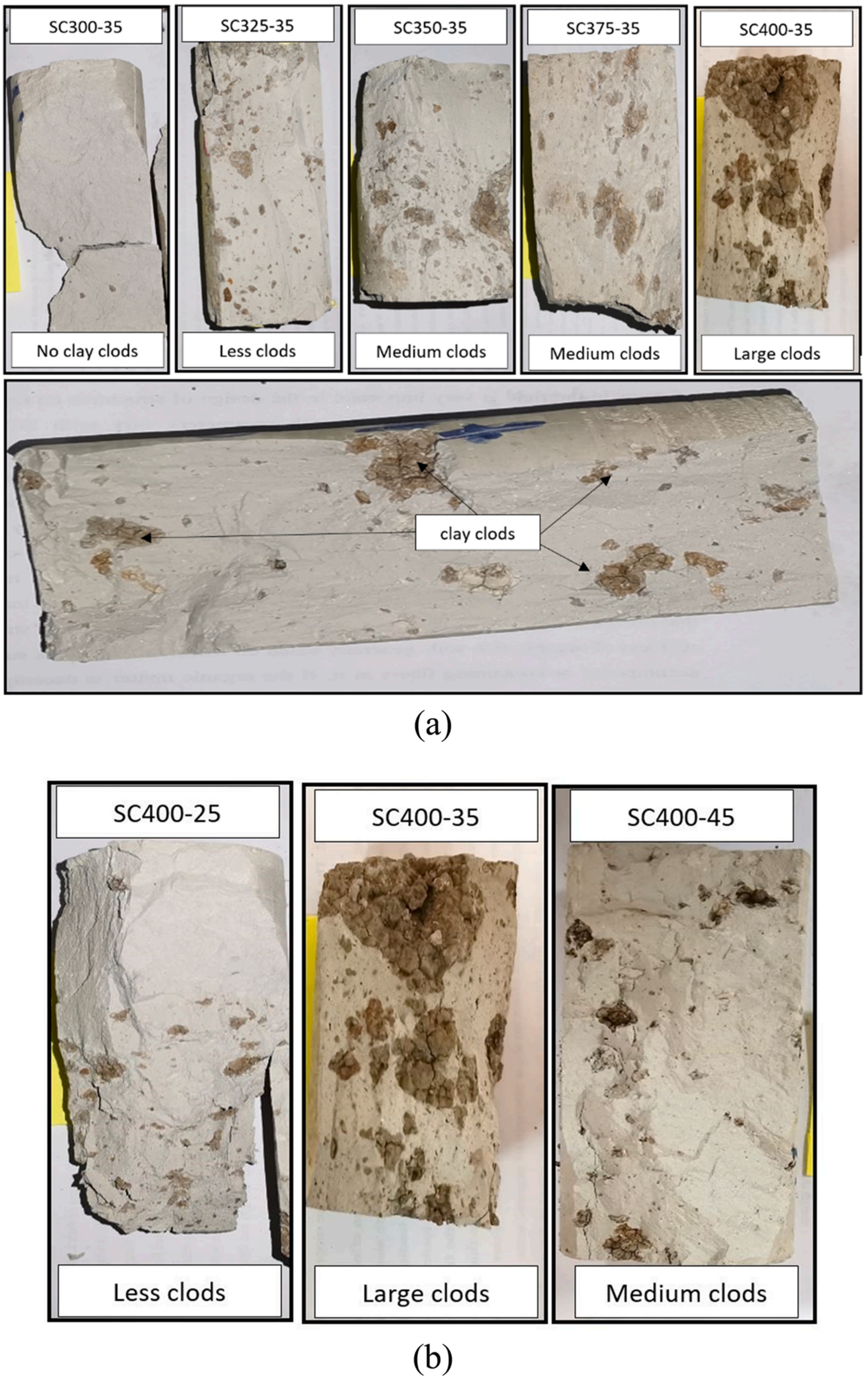


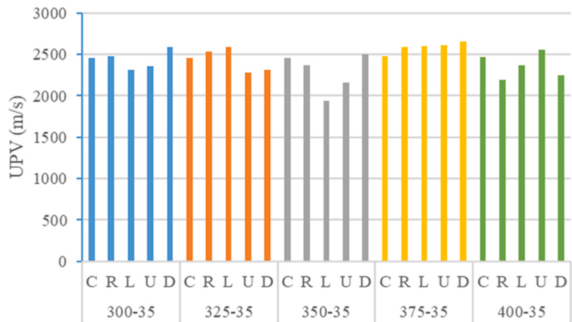
Fig. 11. Dispersion of clayey clods in soil-cement samples regards with, (a) pressure injection, (b) jet grouting rotations.

3.1.1. Unconfined compression strength (UCS) test

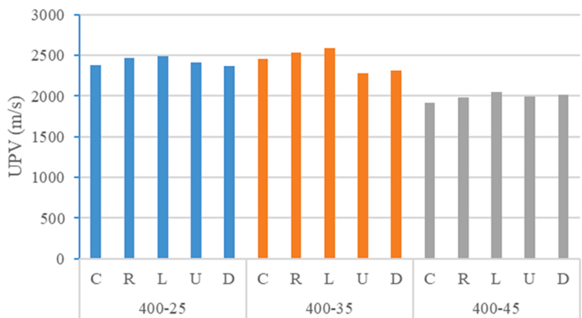
The UCS test indicated the strength of the SC column injected in clayey soil for 28 d of curing, with different pressure injection and rotation parameters, as shown in Fig. 10a and b. Generally, the results of SC samples prepared for this study are ranged from 6.2 to 10.0 MPa, which is very close with UCS results that obtained from literature studies [38–40], and it can be considered that used as clay soil stabilization. Fig. 10a presents the influence of injection pressure on the strength of grout specimens according to different directions which is from center to right-to-left and up-to-down, as realized from this study, the average strength is decreased with increasing the pressure (300, 325, 350, 375, and 400) bar, therefore, the specimen with 300 bar pressure (SC300–35) gained the highest value which is 10.0 MPa, compared with all other pressure injection's parameter, which are 8.2, 7.8, 7.2, and 6.2 MPa respectively as shown in Fig. 10a. This variation is acceptable compared with literatures which is the injection pressure effects of uniaxial strength with a lifting step, and it's reduced with increasing the pressure at short lifting step [41]. As a comparative with literatures, Aksoy [42] concluded that the compressive strength increased with decreasing the pressure injection for clay, dry sandy, and wet sandy soil at 28 days, were varied from 4.4-to-9.9 MPa, 20.3-to-24.3 MPa, and 21.5-to-24.6 MPa, respectively. According to direction, this study presented a significant variation of strength that the maximum and minimum strength recorded at 300-35-R and 325-35-L, which is 15.0 and 3.0 MPa respectively. Moreover, this study has been also investigated that the strength of SC samples randomly increased and decreased from the center to right-left and up-down because of variation of soil distribution. 15.0 MPa recorded as the maximum value at 300-35-R compared with other directions such as SC300-35-C, SC300-35-L, SC300-35-U, and SC300-35-D which are 11.0, 7.0, 8.0, and 9.0 MPa, respectively. For the rest pressure injection, test results recorded the same variation according to the directions.

The rotations of jet grout also have been used as a main parameter to investigate the strength variation of SC columns as presented in Fig. 10b. As seen, the average strength of SC samples are investigated a significant variation according to rotations (25, 35, and 45 r/min.), in addition, the maximum value measured at SC400-25 which is 6.8 MPa compared with the SC400-35 and SC400-45, which is 6.2 and 6.4 MPa, respectively. Besides that, the direction (from center to right-lift, and up-down) has been considered as a main parameter to present the variation of compressive strength regards with jet grouting rotation's parameter. According to the result, the strength randomly increased and decreased from the center to right- left, and up-down because of soil distributions. 8.0 MPa has been recorded as maximum value at SC400-25-C and 400-25-R compared with the SC400-25-L, SC400-25-U, and SC400-25-D, which is 7.0, 6.0, and 5.0 MPa, respectively. Other rotations have been recorded the same variation according to the directions.

Fig. 11a and b presents the variation of clay clod's availability according to pressure injection and jet grouting rotations, and it's roughly categorized to no clay clods, less, medium, large clay clods according to the rate of clay clod's availability. Fig. 11a details the crushed cores of SC columns that constructed at multi pressure injection such as 300, 325, 350, 375, and 400 bar, respectively. This study reported that the percentage of grout and soil-cement mixing decreased with increasing the pressure, thus, the pure grout gained



(a)



(b)

Fig. 12. UPV performance of SC column vs. pressure injection.

at the high pressure which is 300 bar at 35 rpm and the columns become lower clay clods and uniformity of samples increased compared with other specimens that labelled SC325-35, SC350-35, SC375-35, and SC400-35. The decreasing of clayey clods leads to increasing the strength and homogeneity of samples because of decreasing of failure path. In addition, sample SC300-35 shows no indication of clay clods and considered as most uniform sample and gained the maximum value of compressive strength for this study. Thus, the decreasing of clay clods numbers causes to increasing the strength and more homogeneity distribution of samples. Fig. 11b presents the effect of jet grouting rotations (25, 35, 45) rpm on the rate of clay clod's availability, and the percentage of clay clods increased and decreased with increasing the rotations. As seen, the specimen SC400-25 has been indicated as a less clay clods compared with SC400-35 and SC400-45, which leads to its be more homogenies and increasing the strength properties.

3.1.2. Ultrasonic plus velocity test (UPV)

Ultra sonic test has been conducted in this study to present the variation of velocity versus pressure injection and rotation of jet grout as shown in Fig. 12a and b. In this study, the average velocity of SC columns varied from 1994 to 2588 m/s that categorized as a low and very low velocity which reported in previous work as detailed in Table 5[33]. In addition, the variation of velocity depended on the density and homogeneity of specimens that leads to transport the wave faster [43]. According to the case study, the results reported that the ultra plus velocity (UPV) was different somewhat from the compressive strength especially concerning the clay contents, and it is considered that the sample SC375-35 provide the best performance in average result of UPV which is 2588 m/s compared with SC300-35, SC325-35, SC350-35, and SC400-35, which are 2441, 2436, 2287, and 2376 m/s, respectively, it can be attributed that it is most-dense compared with all other samples. Other researchers concluded that the silica fume caused to improve the solid structures of samples and the microstructural of specimens becomes denser which leads to transport the ultrasonic wave faster [44,45]. Besides that, this study has been also investigated that the velocity of SC samples randomly increased and decreased from the center to right-left and up-down because of variation of clay clods distribution that cause to failure path which shown in Fig. 12a. The sample SC300-35-D measured as the maximum result which is 2593 m/s compared with specimens SC300-35-C, SC300-35-R, SC300-35-L, and SC300-35-U, which are 2463, 2475, 2313, and 2361 m/s, respectively.

Generally, the rotations of jet grout significantly affected on the performance of velocity, and the results indicated that the UPV categorized as a very low velocity as presented in Fig. 12b. Moreover, the sample SC400-35 presented as a better performance in the average value of UPV which is 2436 m/s compared with SC400-25 and SC400-45, which are 2426 and 1994, respectively. According to directions, the velocity has been randomly varied because of random distribution of clay clods in SC spacimens, which lead to increasing failure path. From Fig. 7, 2488 m/s recorded as a maximum value of velocity at sample SC400-25-L, compared with SC400-25-C, SC400-25-R, SC400-25-U, and SC400-25-L, which are 2386, 2471, 2413, and 2373 m/s, respectively. The same approach finds out from the results that the maximum values of SC400-35-L and SC400-45-L, which are 2595 and 2054, respectively, compared with other locations. Canakci et al. [19] reported that the deep mixing inclusion with 4% clay content had been achieved better

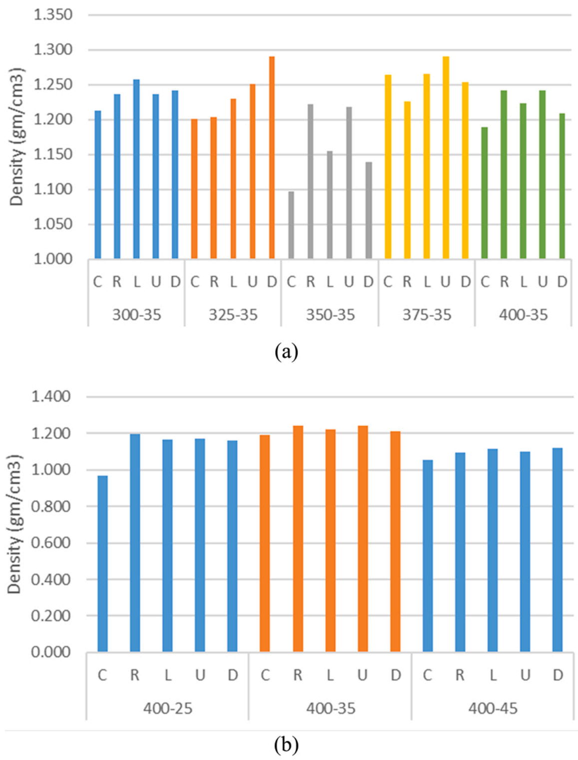


Fig. 13. Density variation of SC according to, (a) pressure injections, (b) jet groot's rotations.

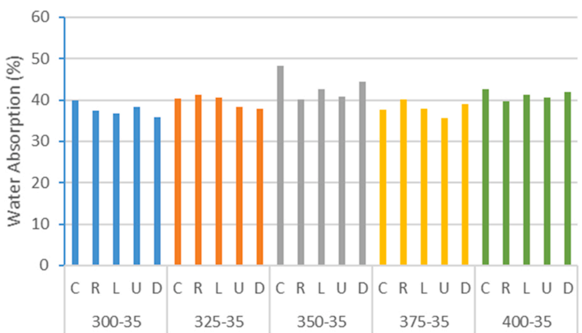
performance in UPV and oppositely with the UCS results which gained the same approach in this case study. This difference between UPV and UCS may be because of the homogeneity of samples. Relevant to this, it's concluded that samples with less clay content cause to producing less porosity and results to higher velocity [46].

3.2. Physical properties

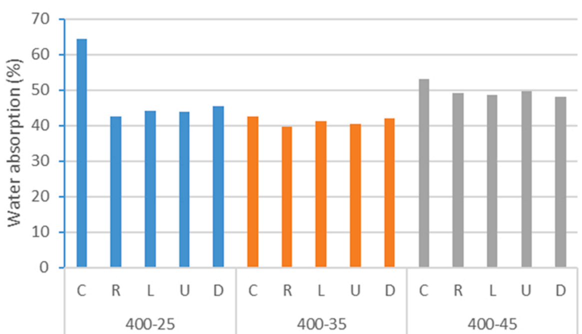
3.2.1. Density

This test calculated the density of SC column according to [37]. In this study, the results presented a significant variation in density according to pressure injection and jet grout rotations with different directions such as from center to right-left and up-down. Differences in density regard with locations of the sample and pressure injections (300, 325, 350, 375, and 400 bar) parameters which ranged from 1.097 to 1.291 g/cm^3 at specimens SC350-35-C and SC325-35-D,respectively, as shown in Fig. 13a. As seen, the results indicated that the average density at the sample SC300-35 has been achieved the highest result (1.237 g/cm^3), which is mean that the percentage of water absorption gained the minimum level at the same parameter, because of the relationship between water absorption and porosity are inverse relationship and statistical analysis showed that there were significant correlations at the 95% confidence level between density and water absorption [47]. Thus, the result of this study totally acceptable compared with previous studies. The present study reported that the density roughly increased from the center to the edges at the same surface of SC column because of increasing the percent of clay content. Totally, density in all the states decreases when increasing the soil quantity [48]. According to directions for each pressure injection, 1.258 g/cm^3 has been recorded as the highest result at sample SC300-35-L compared with SC300-35-C, SC300-35-R, SC300-35-U, and SC300-35-D, which are 1.213, 1.237, 1.236, and 1.242 g/cm^3, respectively. The result for other parameters according to directions achieved the same approach in variations that detailed in Fig. 13a.

Rotations of jet grout is also considered as an important parameter to show the variation of density regards with locations, which is 25, 35, and 45 r/min for 400 bar pressure injection, as detailed in Fig. 13b. Results predicted that the average density roughly varied with increasing the rotation. Thus, the maximum average density has been achieved at SC column sample SC400-35 (1.221 g/cm^3) compared with SC400-25 and SC400-45, which are 1.133 and 1.089 g/cm^3, respectively. According to directions for each pressure injection, the center of SC column has been measured the lowest values for all rotations. 0.969 g/cm^3 has been recorded as the minimum result at sample 300-35-C compared with 300-35-R, 300-35-L, 300-35-U, and 300-35-D, which are 1.198, 1.167, 1.169, and 1.161 g/cm^3, respectively. The result for other parameters according to directions achieved the same approach in increasing and decreasing that presented in Fig. 13b. When compared to the Croce et al. [16] research findings, somewhat lower values were reported for both parameters. Although, Muge [49] reported that the density of soilcrete column in silty and sandy soil was 1.617 and



(a)



(b)

Fig. 14. Water absorption's variation of SC according to, (a) pressure injections, (b) jet grout's rotations.

1.728 g/cm^3, respectively.

3.2.2. Water absorption

Generally, the water absorption plays an important role concrete's manufacture, which is utilized to determine the amount of water absorbed under specified conditions according to ASTM D6473–15. In the present study, it can be significantly seen that the results of water penetration for all test specimen randomly changes according to pressure injection and rotations regards with direction, which is from the center to right-left, and up-down. Variations of water absorption regard with locations of the sample and pressure injection which ranged between 36% and 48% at specimens SC325-35-D and SC350-35-C that presented in Fig. 14a. As seen, the maximum and minimum average results of water absorption recorded at the sample SC350-35 and SC300-35, which are 43% and 38%, respectively. Accordingly, the percentage of porosity gained the maximum level at the same parameter of SC column because the general relationship between water absorption and porosity are linear [50]. According to directions for each pressure injection, 40% has been measured as a highest result of average water absorption at sample SC300-35-C compared with SC300-35-R, SC300-35-L, SC300-35-U, and SC300-35-D, which are 38%, 37%, 38%, and 36%, respectively. The result for other parameters according to directions varied with the same approach in variation which reported in Fig. 14a.

Rotations of jet grout is also considered as an important parameter to show the variation of density regards with locations, which is 25, 35, and 45 r/min for 400 bar pressure injection, as detailed in Fig. 14b. Results have been reported that the average of water absorption roughly varied with increasing the rotation. Thus, the maximum average density has been achieved at SC column sample SC400-45 (50%) compared with SC400-25 and SC400-35, which are 48% and 41%, respectively. According to directions for each pressure injection, the center of SC column has been measured the highest values for all rotations. 64% water absorption has been recorded as the maximum result at sample SC400-25-C compared with SC400-25-R, SC400-255-L, SC400-25-U, and SC400-25-D, which are 43%, 44%, 44%, and 45%, respectively. The result for other parameters according to directions achieved the same approach in increasing and decreasing, as shown in Fig. 14b.

3.2.3. Porosity

The porosity test calculated the volume of voids fraction in the specimens according to [37]. Therefore, this study reported the obvious change in the percentage of the porosity according to pressure injection and rotations regards with direction, which is from the center to right-left, and up-down. Porosity variations of grout column regard with locations of the sample and pressure injection which ranged between 46% and 53% at specimens SC325-35-D and SC350-35-C as detailed in Fig. 15a. Generally, the pressure injections did

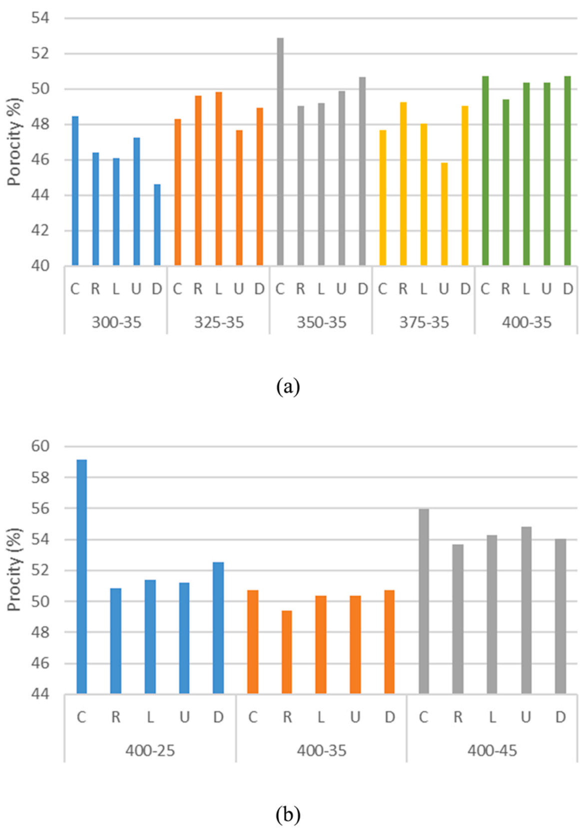


Fig. 15. Porosity variation of SC according to, (a) pressure injections, (b) jet grout's rotations.

not have effective role on the average porosity's variation which varied from 47% to 50% which have been observed at specimens SC375-35 and SC350-35 with SC400-35, respectively. Besides that, the rate of porosity at the center of SC column has been achieved the highest result, which is mean that the availability ratio of pure cement-paste was less and the dry density gained the minimum value because the porosity-density relationship is an inverse relation [48]. According to directions for each pressure injection, the maximum average of porosity has been achieved at sample 300-35-C, which is 49% compared with SC300-35-R, SC300-35-L, SC300-35-U, and SC300-35-D, which are 48%, 47%, 48%, and 47%, respectively. The result for other parameters according to directions varied with the same approach in increasing and decreasing as presented in Fig. 15a.

Rotations of jet grout are detected as an important parameter to show the variation of density regards with locations, which is 25, 35, and 45 r/min for 400 bar pressure injection, as detailed in Fig. 15b. Results have been reported that the average porosity roughly varied with increasing rotations. Thus, the maximum average of density has been achieved at SC column sample SC400–45 (55%) compared with 400–25 and 400–35, which are 53% and 50%, respectively. According to directions for each pressure injection, the center of SC column has been measured the highest values for all rotations. 59% porosity has been recorded as the maximum result at sample SC400–25-C compared with SC400–25-R, SC400–25-L, SC400–25-U, and SC400–25-D, which are 51%, 51%, 51%, and 53%, respectively. The porosity values for other parameters according to directions achieved the same approach in variation which detailed in Fig. 15b. Thus, the present study compared with Muge (2016) study [49], were indicated that the average variation of porosity for silt and sandy soil were 27.27% and 24.70%, respectively. When the range of porosity values for silts and sands in the literature is evaluated, it is presumed that jet-grouted material has a lower porosity than original soil. Silt's porosity typically ranges between 35% and 50%, whereas sand's porosity ranges between 25% and 50% [51].

3.3. Surface friction of SC column in clayey soil

A direct shear test was conducted to study the interface friction of the SC with clayey soil with different pressure injections and rotations. Direct shear tests are generally presented in two graphs: (a) shear stress–horizontal displacement curves, and (b) shear strength envelopes, which indicate the interface shear strength parameters (adhesion [c], friction angle [φ]).

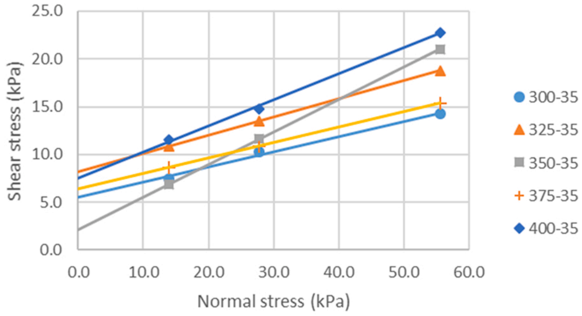
Fig. 16a and b show the shear stress versus normal stress of the SC column with clayey soil according to the pressure injection (300, 325, 350, 375, and 400 bar) and jet grout rotation (25, 35, and 45 rpm). These variations were drawn according to the shear stress and three normal stresses for each test, which were 13.9, 27.8, and 55.6 kPa, respectively. A linearity line was predicted for the normal stresses versus interface shear stress data. A 10% shear deformation was considered for strength values in all tests, which produced a straight line with an R^2 of approximately 1.0. The adhesion and friction angles were measured from the linear curve presented in Fig. 16a and b. The adhesion between clayey soil and grout specimens ranged from 0 to 8 kPa, which is considered small [20]. Generally, it was concluded that increasing normal stress leads to gradually increasing shear strength, and that all strengths can be determined according to the Mohr–Coulomb failure criterion regardless of the pressure injection and jet grout rotation. The maximum shear strength was obtained by sample SC400–35 with all normal stresses, which were 11.6, 14.8, and 22.8 kPa (Fig. 16a), and can be attributed to the rougher surface of SC400–35. The minimum shear strength was achieved by sample SC300–35 (7.5, 10.3, 14.2 kPa). According to the rotation, specimen SC400–45 obtained the minimum shear stress with all normal stresses, which were 5.4, 9.7, and 18.6 kPa, as shown in Fig. 16b. It is observed that the rotation has little effect on the shear stress compared with the pressure injection. Thus, it is concluded that the surface roughness directly affects the shear strength, which is consistent with findings in previous studies [20,52,53].

Fig. 17a and b show the variation of the interface friction angle with pressure injection and rotation. The interface friction angle varied slightly with increased pressure injection and rotation, which can be attributed to slight variation in frictional resistance between the clayey soil and SC column with pressure injection and rotation. For both parameters, the maximum interface friction angles were 19° and 18° for samples SC350–35 and SC400–45, respectively. The smallest surface friction angle was 9° for samples SC300–35 and SC375–35. The jet grout rotation does not have a significant effect on the interface friction angle of the SC column compared with the pressure injection. According to the literature, the interface friction increases with increasing cement content [54].

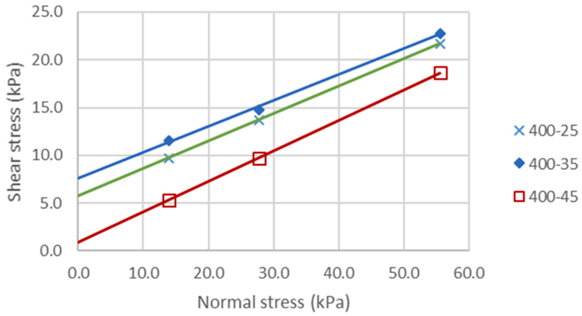
The variation in shear stress with horizontal displacement of the SC column was determined through injection in clayey soil with 300, 325, 350, 374, and 400 bar pressure injections with 25, 35, and 45 rpm jet grout rotations with 55.6 kPa, as shown in Fig. 16a and b. Generally, it can be seen from figures that the shear stress increases individually with increasing the horizontal displacement till the deformation keeps constant or it take a place. According to pressure injection, the maximum results have been achieved at sample SC400–35 as reported in Fig. 18a. Similar behavior was detected for different rotations of jet grout's parameter. As seen, the minimum shear stress has been observed at the sample SC400–45 compared with SC400–25 and SC40035. It can be attributed that the shear stress gradually decreased with increasing the jet grout's rotation, and the decreasing roughness surface of grout column at the same time, as shown in Fig. 18b. Thus, it can be explained that the shear stress has a direct relation with roughness surface, and the results acceptable compared with previous studies [20].

3.4. Diameter's variation of SC column and theoretical approach

In this study, the diameter of JGC has been measured after injection in clayey soil which located in location Şahitkamil - Gaziantep -Turkey at 37°08′47.76″ N and 37°22′24.96″ E coordination, to study the effect of pressure injection and jet grouting rotation on the diameter of grout column as detailed in Table 6. Generally, the full-scale of grout column was one-meter height and the diameter have been measured form the middle of the specimens. As seen, both parameters have been widely influenced on the diameter of grout column during to injecting in clayey soil, which are ranged between 32-to-51 cm for pressure injection, and 47-to-53 cm of rotation

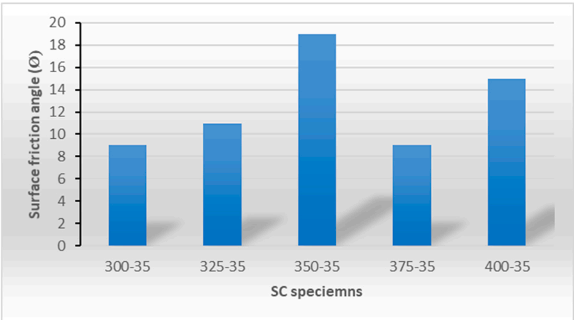


(a)

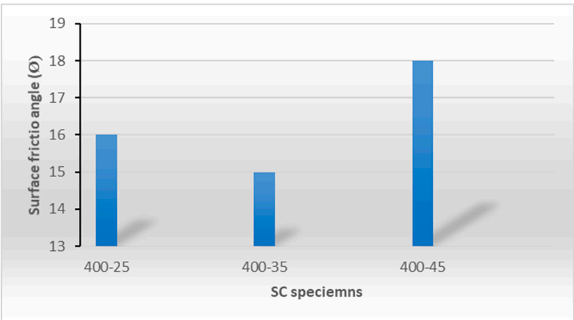


(b)

Fig. 16. Shear envelopes for the clayey soil– SC column interfaces for (a) pressure injection (b) rotation of jet grout.



(a)



(b)

Fig. 17. Interface friction of clayey soil– SC column interfaces of (a) pressure injection (b) rotation of jet grout.

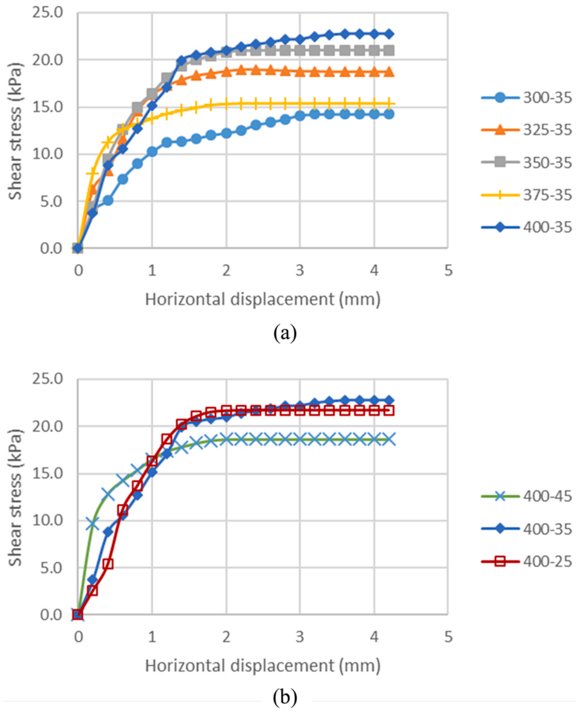


Fig. 18. Shear stress vs. horizontal displacement of SC column under 55.6 kPa: (a) pressure injection (b) rotation of jet grout.

Table 6
Diameter of SC column in clayey soil.

Parameter	Samples	Pressure (bar)	Rotation (r/m)	Diameter (m)
Pressure Injection	SC300-35	300	35	0.32
	SC325-35	325	35	0.38
	SC350-35	350	35	0.40
	SC375-35	375	35	0.41
	SC400-35	400	35	0.51
Jet grout rotations	SC300-25	400	25	0.47
	SC400-35	400	35	0.51
	SC400-45	400	45	0.53

parameters. Besides that, the diameter dramatically increased with increasing the pressure and rotations. According to the pressure injection, the maximum value of diameter has been observed in specimen SC400–35 which is 51 cm, while the minimum diameter gained at sample SC300–35 which is 32 cm, therefore, the rate of diameter's decreasing was exceeded 37% decreasing. Thus, these result have been considered as acceptable findings compared with study of [42]. During to comparison this study with previous work, it can be attributed the diameter of current study observed lower result compared with Aksoy [42] study, which are ranged between 49-to-74 cm for pressure injection 300-to-400 bar respectively, as well as, compared with wet and dry sand, he concluded that the diameter of clayey soil much smaller that wet and dry sandy soil which can be attributed that performance of water-cement works better in non-cohesive soil that cohesive, which the sandy soil contains with high void ratio compared with clayey soil that leads to vary the diameter during to fill these voids with grout past [42]. According to the rotation's parameter, this study reported that the rotation of jet grout normally affected the diameter of the column, while, not like the affection of pressure injection. As seen, the diameter of column increased with increasing the rotation that varied from 47-to-53 cm, therefore, the rate of increasing was exceeded 12%. In addition, the maximum diameter has been achieved at specimen SC400–45 which is 53 cm, while the smallest diameter observed at sample SC400–25.

Theoretical approach of diameter prediction also was being a part of this study. Several studies have joined to develop the theoretical method to expect the column diameter during the grouting specifications [24–27,55]. Furthermore, the full-scale grouting column results were confirmed to compare the measured diameter with the calculated diameter utilizing the existing relation. Flora et al. [56] concluded that the most overall relation, which considered the parameters of energy exerted during injection, soil type, and injection specifications, therefore the equation of diameter prediction for fine-grain soil had been presented as following:

$$Dm = D_{ref} \cdot \left(\frac{\alpha_E \quad . \quad A^* \quad . \quad E_n'}{7.5 * 10} \right)^{\beta} \cdot \left(\frac{q_c}{1.5} \right)^{\delta} \quad (1)$$

where q_c is the cone penetration resistance of the fine grain soil before improvement, E_n is the injection energy at the nozzle per unit length of grouting column (MJ/m), and α_E is a dimensionless parameter regarding the grout method, which is for double-fluid jet grouting measured as 6, which is D_ref is 0.5 for clayey soil. The dimensionless parameter is denoted as A^* and utilized according to the W/C ratio by wight (w) (which is A^*equal to 7.5 at w/c equal to one. Model parameters (β and δ) for clayey soil are equal to 0.2 and − 0.25, respectively [27]. In addition, the factors influencing the diameter of the JGC require careful consideration for a better prediction of column diameters [57]. Thus, this equation includes all requirement factors to predict the diameter. In this study, the average q_c of the present soil is equal to 1.0 MPa. As a confirmation of this equation during the present study, the measurement diameter was 0.997 m, and the possibility of using this equation in clayey soil was proven to be ranged between 0.32-to-0.53 m compared with the full-scale diameter of grout for both parameters (pressure injection and rotation). It has been predicted from this study that the diameter increased with increasing both pressure injection and rotation, which is the same as study stated in literature [58], In addition, the typical column diameters ranged between 0.5-to-0.9 m according to the soil type that categorized from clayey soil to gravelly soil as presented in Fig. 19 [28].

4. Conclusion

Despite jet-grouting's widespread use as a soil improvement method, the physico-mechanical properties of soilcrete material have not been investigated in detail up to now. In addition, most researches are not the latest and recent studies revealing the properties of full-scale soilcrete columns are very limited. Therefore, jet grouting techniques were used in clayey soil with different pressure injection and jet grouting rotations regards with direction which located from center to right-left and up-down, to study the property variation of grouting (SC) columns in the field. 7 different full-scale JGC constructed and measured the diameter to investigate the variation of mechanical (UCS, UPV, shear strength), and physical properties (water absorption, density, porosity) of the grout column. For each parameter, this study investigated the random variations from the center to all other directions, such as right-left and up-down. Thus, the geomechanical properties of SC were analyzed and the following conclusion was drawn:

- This study determined that the compressive strength indiscriminately varied with the pressure injection and jet grouting rotation. The maximum strength of 10 MPa was observed in sample SC300-35. The strengths of SC325-35, SC350-35, SC375-35, SC400-35, SC400-25, and SC400-45 were 8.2, 7.8, 7.2, 6.2, 6.8, and 6.4 MPa, respectively. The strength decreased with increasing pressure injection, indicating that the cement concentration decreased with increasing pressure injection.
- The UPV test was conducted to determine the variation in velocity with the pressure injection and rotation. The velocity ranged from 1938 to 2588 m/s, categorised as very low to low velocity. The UPV results differed somewhat from the compressive strength results, especially concerning the clay content. Sample SC375-35 exhibited the best performance (2588 m/s), which can be attributed to a greater density than other samples, leading to faster transport of waves.
- The water absorption of the SC was studied; the average water absorption ranged from 38% to 50% for both pressure injection and rotation. The water absorption percentage varied from 36% to 40% in SC300-35, 38–41% in SC325-35, 40–48% in SC350-35, 36–40% in SC375-35, 40–43% in SC400-35, 43–64% in SC400-25, and 48–53% in SC400-45.
- The variations in the dry density and porosity of the SC were studied. Generally, it was concluded that there is an inverse relationship between density and porosity. The minimum average density and maximum porosity were obtained in sample SC400-45,

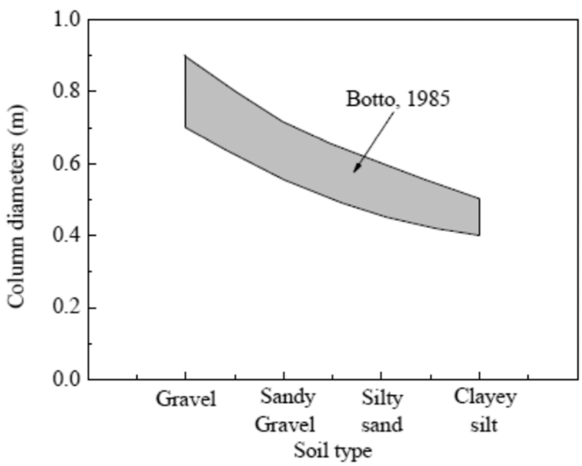


Fig. 19. Variation of column diameters according to different soil type [28].

1.098 g/cm^3 and 55%, respectively. SC375-35 produced the maximum density and minimum porosity, 1.26 g/cm^3 and 47%, respectively.

- The interface shear behaviour of the soil–jet grouting column and soil–soil were evaluated using a direct shear test method. The variation in the shear interface between the JGCs and clayey soil was reported with different pressure injections and jet grout rotations. The greatest shear strength was observed in sample SC400-35 with all normal stresses (11.6, 14.8, 22.8 kPa), attributed to the rougher surface of SC400-35 compared with other samples. SC400-45 produced the minimum shear stress with all normal stresses, 5.4, 9.7, and 18.6 kPa.
- The friction angle between the grout column and clayey soil varied significantly according to the pressure injection and rotation parameters. The friction angle ranged from 9° to 19° for pressure injection and from 15° to 18° for rotation. For both parameters, the maximum angles were 19° and 18°, produced by SC350-35 and SC400-45, respectively, indicating that these samples had rougher surfaces. The minimum friction angle was 9° for samples SC300-35 and SC375-35.
- Both parameters were greatly influenced by the diameter of the grout column, which ranged from 0.32 to 0.53 m. For the pressure injection, the maximum diameter was 0.51 m in SC400-35, while the minimum diameter was 0.32 m in SC300-35. The rate of diameter decrease exceeded 37%. For the rotation, the rate of increase exceeded 12%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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