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Full Length Research Paper

Improvement of granular soils by low pressure grouting

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Permeation grouting is a deep-soil improvement technique in which grout is injected into the voids, fissures and cavities in a soil formation in order to improve resistance to liquefaction, strength and durability and to reduce its permeability and deformability. The objective of this research is to investigate the parameters that affect the strength of cement grouted granular soils through laboratory testing. With this objective, cement grouting is applied, by using a special apparatus assembled for injection, into two different types of granular soil samples each of which is prepared to have 25, 50, 75 and 100% relative densities. Test samples are then grouted using cement grouts with different water/cement ratios by weight of 0.7, 1.0 and 1.5, by applying different levels of grouting pressures of 100, 150 and 200 kPa. At the end of the curing period, which is either 7 or 28 days, the test specimens are subjected to unconfined compression test. Large values of unconfined compression strength (as much as 19 MPa) reached by the test specimens verify the effectiveness of permeation grouting in granular soils. Test results also indicate that permeation grouting is most effective when the water/cement ratio is in the range of 0.7 to 1.0.

Key words: Soil improvement, granular soils, permeation grouting, low pressure grouting.

INTRODUCTION

Soil improvement is an important task in construction works, especially in those for buildings. In practice, many methods are used to improve *in-situ* properties of deep soil layers, such as, vibroflotation, dynamic compaction, stone columns, jet grouting, compaction grouting and wick-drains. However, these methods are generally expensive and occasionally necessitate costly mobilization of huge machinery and equipment. Requiring much lower mobilization cost, easy on application and cost effectiveness (Warner, 2004), permeation grouting has wider application areas in small-scale projects than many other soil improvement techniques. The presence of voids, soft ground, settlement and water inflow are just a few obstacles encountered where grouting can be employed to mitigate their effects during construction. Low-pressure permeation grouting is an efficient method for reducing permeability and for increasing stiffness and strength of coarse-to-medium grained soils with low initial properties (Dano et al., 2004). The effectiveness of this technique, however, appears to be influenced by various factors and relies substantially upon on-site experience and engineering judgments. Results of related studies on injection mechanism were generally not conclusive and the improvement of grouting on engineering properties of soils could not be practically quantified (Chang et al., 2005). Permeation grouting is a low-pressure form of cement grouting that involves grout injection into voids, fissures and cavities in soil or rock formations in order to improve their properties, specifically to reduce their permeability, to increase their strength and durability or to decrease their deformability (Anagnostopoulos, 2005). The adoption of low-pressure grouting as a ground improvement method is not new.

Many researchers (Andrus and Chung, 1995) have already used this technique in their studies. It is known that this method can effectively be applied to granular soils, which allow the permeation of grout into their voids. While it may not be easy to define the exact range implied by “low-pressure”, it can be said that the pressures that can be generated by small pumps, that is, pressures less than 1.0 MPa, can be regarded as low (Chang et al., 2005). For successful grouting, the grout has to be in its fresh state with high penetrability, stability

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and with limited or no bleeding. In order to achieve high penetrability, fine grout materials can be used. Nevertheless, the maximum diameter of the particles in the grout is not the only parameter that controls the penetrability performance of a grout. It is known that fine materials in a suspension can coagulate very easily due to inter-particular interactions (Toumbakari et al., 1999). For this reason, before carrying out grouting applications in the field, the groutability of the cement-based grout that is to be used in injection is often tested in the laboratory to determine its properties (Akbulut, 1999; Perret et al., 2000). Axelsson (2009) gave three main conclusions regarding the penetrability of cementitious grouts; i) the penetrability depends on the ratio between the opening and the maximum grains in the grout; ii) close to the limit of what is considered penetrable there is filtration of grout grains and iii) the water-to-cement ratio affects the filtration rate; more water means better penetrability. Hernquist et al. (2009) studied the grouting results for a tunnel at a depth of 450 m in crystalline rock. They investigated whether grout penetrations and inflow into the finished tunnel corresponds to predictions. The comparison between predicted and measured inflow into the tunnel, showed that the prediction was about four times than measured inflow. Their results indicated that cement based grout successfully sealed fractures down to a hydraulic aperture at about 50 µm but not 30 µm. In permeation grouting, a cement mixture is injected into a soil at pressures that do not alter the structure of the soil in such a way that the mixture diffuses into the cavities of the soil by flowing in irregular channels formed as a result of the combination of the cavities.

The basic parameters that influence the grouting process are: (i) grain-size distribution of the soil, (ii) size of the cement particles in the suspension grout, (iii) fines content (*FC*) of the soil passing through the 0.6 mm sieve, (iv) grouting pressure (*P*), (v) relative density (D_r) of the soil and (vi) water/cement ratio by weight *(w/c)* ratio (or viscosity) of the grout (Akbulut and Saglamer, 2002). The objective of this research is to investigate the parameters that affect the strength of cement grouted granular soils through laboratory testing. It is to be noted that, within the literature, many researchers (Akbulut and Saglamer, 2002; Burwell, 1958; Incecik and Ceren, 1995) have studied the groutability characteristics of soils and proposed different formulae for granular soils. However, the number of experiments in these studies has usually been very limited. In addition, since strength gain has not been the main objective in these studies, the effects of all parameters on the strength could not be investigated across wide ranges.

This study differs from previous studies in that it investigates in detail across a wide range of values the effects of: (i) grain-size of the soil, (ii) relative density of the soil (D_r), (iii) water/cement *(w/c)* ratio of the grout, (iv) grouting pressure *(P)* and (v) curing time on unconfined compressive strength (UCS) of cement grouted granular soils.

EXPERIMENTAL STUDY

This study investigates, in detail, the effects of: (i) grain-size of the soil, (ii) relative density of the soil (D_r), (iii) water/cement *(w/c)* ratio of the grout, (iv) grouting pressure *(P)* and (v) curing time on unconfined compressive strength (UCS) of cement grouted granular soils. For this purpose, two different soil samples with different gradations were prepared. In this study, these samples are classified as poorly graded gravel (*GP*) and poorly graded sand (*SP*) according to Turkish standards (TS 1500 to 2000) (According to unified soil classification system (*USCS*), both of the samples are classified as poorly graded sand (*SP*). It should be noted that the samples were produced with relative densities of 25, 50, 75 and 100%. The grout types injected into the soil samples were prepared to have *w/c* ratio values of 0.7, 1.0 and 1.5; and applied using three different grouting pressures, 100, 150 and 200 kPa. The values given in this study for *w/c* ratios are obtained "by weight". For the sake of simplicity, in the study, it will simply be called *w/c* ratio. The effect of the last parameter, that is, the curing time, on the strength of the grouted soil samples was investigated by preparing two samples from each soil group (that is, with specified gradation, *w/c* ratio, relative density and grouting pressure); the first sample was cured in water for 7 days and the second one for 28 days.

Following their curing periods, samples are subjected to unconfined compression tests. From each soil sample, at least three identical test specimens (that is, with the same gradation, D_r, *w/c* ratio, *P* value and curing time) were prepared and tested. Thus, the strength values that will be presented in the study are derived from the average of three strength values. It is worth noting that the variations in these averaged values are not more than 10%.

Soil properties

The soil samples used in this study were obtained from a quarry in the Kullar region of Kocaeli, in Turkey. These samples consisted of natural stream material. Test samples with two different soil gradations (*GP* and *SP* samples) were prepared by sieving these samples with ASTM 8.0, 4.76, 2.0, 1.0, 0.6 and 0.425 mm sized sieves and then mixing the materials retained over the sieves according to the ratios given in Table 1. In initial trial injections, it was observed that the groutability of the soil decreased when the amount of fines in the soil increased and that it was almost impossible to realize the injection if the percentage of fine grains was greater than 10%. As mentioned earlier, this is not an unexpected result since, as pointed out by Toumbakari et al. (1999), fine materials in the suspension tend to coagulate very easily due to inter- particular interactions. For this reason, in the present study, the amount of material passing through a 0.6 mm sieve was carefully selected not to exceed 10%. Test samples; that is, *GP* and *SP* samples, were selected in such a way that their particle size distributions remain inside the liquefaction zone, as proposed by the Japan Society of Civil Engineers (1977), as shown in Figure 1. It should be noted that it would be impractical to select a soil sample with grain size smaller than that in the SP sample, as such soils have a much lower permeability and therefore would not be grouted successfully.

The basic properties of the soil samples used in the experiments are given in Table 2. It can be seen from Table 2 that the dry unit weights γ_d of the soil samples vary from 15.1 to 17.2 kN/m^3. Similarly, the void ratio (*e*) values vary between 0.527 and 0.739. Typical grain sizes (D_{10}, D_{15}, D_{30} and D_{60}), specific weights (G_s) and coefficients of uniformity (c_u) and curvature (c_c) are also listed in the same table. The maximum and minimum dry unit weights (γ_{dmin} and γ_{dmax}) of the test samples are in agreement with ASTM D 4253 and D 4254 standards. The void ratios of the tested soil samples were calculated and are shown in Table 3 for different relative densities. It can be seen that void ratio decreases from 0.683 at 25% relative

Table 1. Grain size analysis of the test samples.

Sieve opening (mm)	GP (retained %)	SP (retained %)
8	7	3
4.75	5	4
2	55	42
1	30	40
0.6	2	7
0.425	1	4

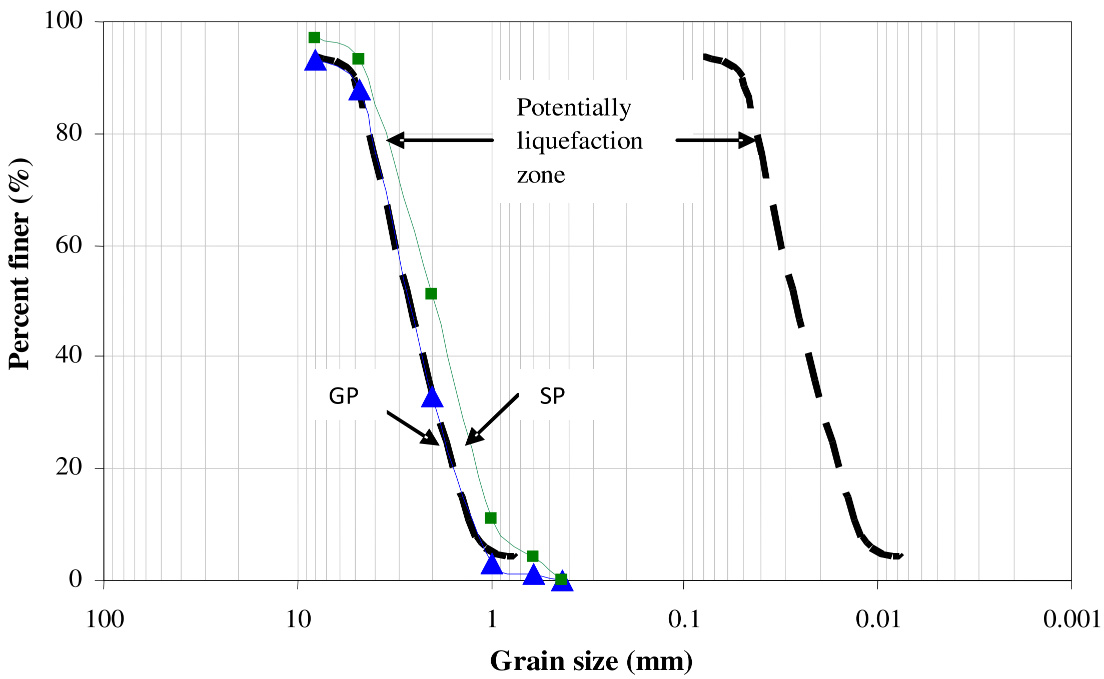

Figure 1. Particle size distribution of test samples.

Table 2. Basic properties of the soil samples.

Soil sample	γ_{dmax} (kN/m^3)	γ_{dmin} (kN/m^3)	e_{max}	e_{min}	D_{10} (mm)	D_{15} (mm)	D_{30} (mm)	D_{60} (mm)	c_u	c_c	G_s
GP	17.07	15.11	0.733	0.534	1.10	1.20	1.85	3.00	2.73	1.04	2.67
SP	17.20	15.10	0.739	0.527	0.99	1.06	1.52	2.30	2.32	1.02	2.68

density to 0.534 at 100% relative density for *GP* samples and from 0.686 to 0.527 for *SP* samples at the respective relative densities. The permeability values, which are also given in Table 3, range from 0.031 to 0.050 cm/s for *GP* samples and range from 0.062 to 0.035 cm/s for *SP* samples.

Physical and chemical properties of cement

The cement used in the experiments was an ordinary Portland cement (code CEM1-42.5-R), which was obtained from Turkish Nuh Cement Factory. This particular type of cement was selected for this study because it is widely used in similar injection works conducted in Turkey. The chemical and physical properties of the cement used in the experimental study are presented in Table 4.

Groutability

The groutability *N* of the test samples were computed using the following formulas proposed, respectively by Burwell (1958), Incecik and Ceren (1995) and Akbulut and Sağlamer (2002); denoted,

Table 3. Void ratio and permeability values of the test samples.

Sample	Relative density, D_r (%)	Permeability (cm/s)	Void ratio (e)
GP	25	0.050	0.683
	50	0.042	0.634
	75	0.037	0.584
	100	0.031	0.534
SP	25	0.062	0.686
	50	0.054	0.633
	75	0.042	0.580
	100	0.035	0.527

Table 4. Physical and chemical properties of cement.

Chemical properties	(%)	Physical properties	
SiO_2	20.34	Bulk density (g/cm^3)	3.17
Al_2O_3	4.24	Freezing time, start (vicat minutes)	181
Fe_2O_3	3.89	Freezing time, end (vicat minutes)	261
CaO	63.97	Volume stability, Le Chatelier (mm)	2
MgO	1.17	Specific surface, Blaine (cm^2/g)	3504
SO_3	2.57	Passing 50 µm (%)	92
Undissolvable solids	0.71	Passing 45 µm (%)	90
Heat loss	1.95	Passing 37 µm (%)	85
Free lime	0.96	Passing 30 µm (%)	78
Chloride	0.0089	2 day pressure resistance (MPa)	26.9
Lime standard (LSF)	99.2	7 day pressure resistance (MPa)	47.0
Hydraulic module (H.M.)	2.25	28 day pressure resistance (MPa)	59.9
Silicate module (S.M.)	2.5		
Ton module (Al_2O_3/Fe_2O_3)	1.09		
C_3S	60.55		
C_2S	12.63		
C_3A	4.65		
C_4AF	11.84		

respectively, as N_B, N_{IC} and N_{AS}:

$$N_B = \frac{D_{15}}{d_{85}} \quad (1)$$

$$N_{IC} = \frac{D_{10}}{d_{90}} \quad (2)$$

$$N_{AS} = \frac{D_{10}}{d_{90}} + 0.5\frac{w/c}{FC} + 0.01\frac{P}{D_r} \quad (3)$$

In Equations 1 to 3, D and d represent the grain size of the soil and the grout, respectively; FC is the fine content and the remaining symbols are as defined previously. The researchers also propose various limiting N values for the grouting operation to be successful. This limiting N value is 25 (that is, N>25) in Burwell (1958) formula, 10 (that is, N>10) in Incecik and Ceren (1995) formula and 28 (that is, N>28) in Akbulut and Sağlamer (2002) formula. It should also be noted that the least convenient conditions are assumed while calculating the N values for the tested soil specimens, by using the formula proposed by Akbulut and Sağlamer (2002) that is Equation 3. These least convenient conditions are w/c = 0.7, P = 100 kPa for all specimens. The FC values for GP and SP samples were 1 and 4%, respectively. The groutability values for the soil samples tested in this study, computed by using Equations 1 to 3, are given in Table 5. As can be seen from the table, all tested specimens have satisfactory N values, which are much larger than the afore-mentioned limiting values.

Test apparatus

A special apparatus was assembled for the laboratory grouting tests. This apparatus consists mainly of a pressure chamber, sample mold and compressor, as shown in Figure 2. The

Table 5. The groutability values of the samples.

Formula by	Limiting N	Computed N (GP)	Computed N (SP)
Burwell (1958)	>25	32	29
Incecik and Ceren (1995)	>10	24	22
Akbulut and Saglamer (2002)			
D_r = 25%	>28	106	41
D_r = 50%	>28	104	39
D_r = 75%	>28	104	39
D_r = 100%	>28	103	38

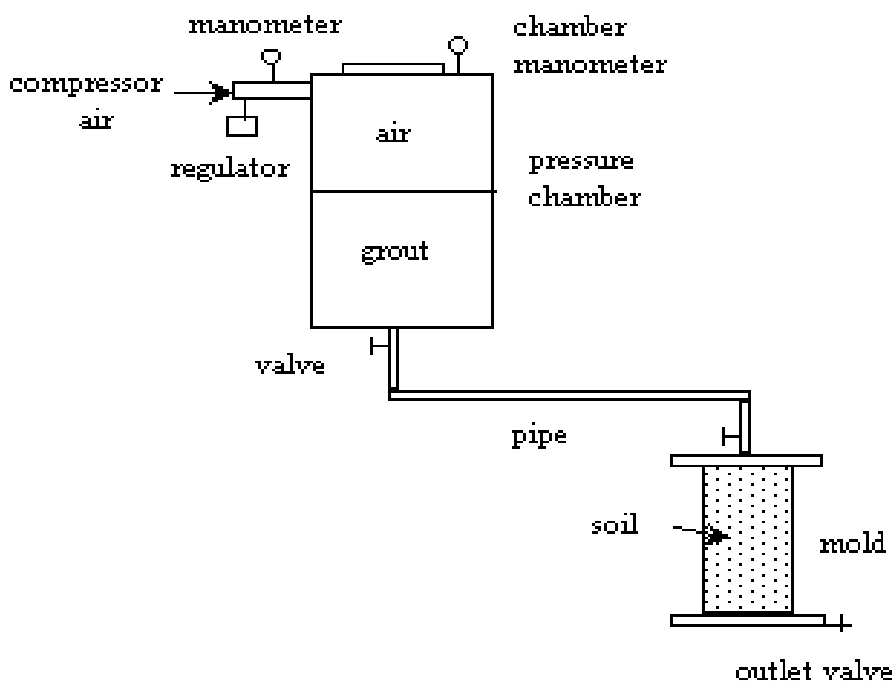

Figure 2. Test apparatus.

compressor is capable of providing a maximum pressure of 800 kPa. A pressure regulator is installed at the entrance of the pressure chamber and a manometer is mounted at the entrance of the pressure chamber to measure the pressure after regulation; another manometer is placed at the lid of the tank to monitor the pressure level. The valve located at the exit of the pressure chamber is designed to control the injection pressure. The connection between the pressure chamber and the molds is maintained by pressure resistant hydraulic pipes. The sample molds are 50 mm in diameter and 100 mm in height. To control the injection, another valve is installed at the lid of the molds. A similar valve is also installed at the base of the mold, to provide an air outlet.

Preparation of soil samples

As already mentioned, the grouting experiments were conducted on the soil samples with relative densities of 25, 50, 75 and 100%. The required relative densities were obtained using the following standard relative density expression:

$$D_r = \frac{\gamma - \gamma_{min}}{\gamma_{max} - \gamma_{min}} \times \frac{\gamma_{max}}{\gamma} \qquad (4)$$

Where γ is the necessary dry unit weight of the soil sample, γ_{dmax} and γ_{dmin} are computed for the studied soil gradations according to ASTM D-4253 and D-4254 standards (Table 2). Considering that the volume (*V*) of the mold where the soil is placed is constant, Equation 4 can be reformulated to obtain the weight (*W*), as:

$$W = \frac{V \cdot \gamma_{d\,max} \cdot \gamma_{d\,min}}{\gamma_{d\,max} - D_r \cdot (\gamma_{d\,max} - \gamma_{d\,min})} \qquad (5)$$

By substituting the required relative density (D_r) values used in the tests into Equation 5, the necessary dry unit weight (γ) values are computed. Then, for each sample, the material remaining on the sieves (Table 1) was oven dried at 105°C. These samples were weighed and mixed separately, in such a way that the required

Table 6. Average unconfined compression strength values for GP samples (MPa).

Relative density, D_r (%)		7 days curing			28 days curing		
	w/c	100 kPa	150 kPa	200 kPa	100 kPa	150 kPa	200 kPa
25	0.7	8.85	8.53	8.77	13.71	13.51	13.64
	1	2.40	2.53	2.24	4.83	4.59	4.89
	1.5	0.82	0.77	0.85	1.67	1.83	1.77
50	0.7	8.09	8.11	8.08	12.23	12.09	12.36
	1	2.72	2.79	2.62	3.48	3.66	3.51
	1.5	0.71	0.71	0.70	1.75	1.75	1.78
75	0.7	7.52	7.75	7.37	15.96	15.92	15.9
	1	2.94	2.84	2.99	7.35	7.45	7.25
	1.5	1.03	1.23	1.12	2.51	2.42	2.66
100	0.7	8.29	8.71	8.43	18.93	18.92	18.95
	1	3.15	3.74	3.34	5.46	5.11	5.30
	1.5	1.55	1.39	1.75	3.68	4.29	3.71

relative density was obtained in each mold. The prepared samples were then placed into the molds through skewers. O-rings were installed around the outer surface of the molds to seal them against leaks.

Preparation of cement mixtures

Cement mixtures with *w/c* ratios of 0.7, 1.0 and 1.5 were used in the grouting process. After placing the water, cement was added to the mix it. The mixture was then mixed for 10 min with a mixer at a speed of 1400 rpm. When grouting with a *w/c* ratio of 0.7, a superplasticizer was also added, at a ratio of 1% cement weight, to reduce the viscosity of the mixture. In these cases, the superplasticizers are added to the water before the addition of the cement. Once the mixing stage was completed, the cement was transferred into the pressure chamber.

Grouting applications

The pressure chamber, which is leak proofed after the placement of the mixture is pressurized by the compressor. The pressure to be obtained inside the chamber is adjusted by the regulator located at the entrance to the chamber. Once the required pressure level is achieved, the outlet valve is opened and the grouting process is started. During the grouting process, the pressure inside the chamber is continuously controlled and stabilized. The valve beneath the chamber is opened and the air inside the chamber is released. When all air is released from the valve located at the bottom of the mold and the cement mixture is observed to come out, the grouting process is ended.

Curing

Upon completion of the grouting operation, the samples are left inside the molds for 24 h in order to let them set. The samples are then removed from the molds and cured in water at 21°C for either 7 or 28 days.

Unconfined compression tests

At the end of the curing periods, the test specimens were subjected to unconfined compression tests to determine their unconfined compressive strength. Each test specimen was covered with caps that give smooth surfaces at its top and bottom faces. Unconfined compression tests were performed at a rate of 0.85 mm/min.

RESULTS AND DISCUSSION

Tables 6 and 7 present the average unconfined compression strength (UCS) values obtained from the unconfined compression tests of *GP* and *SP* samples, respectively. UCS values of up to 19 MPa were recorded for both types of soil. As can be seen from results, the UCS of test specimens may depend significantly on the gradation and relative density of the soil, the water/cement ratio of the cement grout and the curing period. However, it can be rather difficult to independently evaluate the influence of each parameter on strength values. In the following paragraphs, the effect of each parameter will be evaluated separately by plotting the variation of UCS of test specimens with that parameter while keeping the other parameters constant. However, it should be kept in mind that the effect of one parameter may depend considerably on the other parameters and, for this reason, the resulting conclusions may not always be general but, instead, specific to the range of parameters investigated in this study. It should also be noted that in order to limit the discussion to a reasonable length, only some representative plots are presented in the paper (Mutman, 2007). The strength and modulus of elasticity values of both grouted *GP* and *SP* samples

Table 7. Average unconfined compression strength values for SP samples (MPa).

Relative density, D_r (%)	w/c	7 days curing 100 kPa	7 days curing 150 kPa	7 days curing 200 kPa	28 days curing 100 kPa	28 days curing 150 kPa	28 days curing 200 kPa
	0.7	11.69	10.8	11.52	18.02	17.88	18.40
25	1	4.14	4.85	4.64	7.79	8.25	7.97
	1.5	1.44	1.45	1.43	2.10	2.04	2.03
	0.7	10.97	11.22	10.69	19.44	19.2	19.83
50	1	4.30	4.17	4.47	5.68	5.12	5.38
	1.5	1.57	1.72	1.68	2.36	2.36	2.35
	0.7	7.59	7.85	7.77	13.03	13.67	13.26
75	1	4.05	4.05	3.81	7.53	7.45	7.20
	1.5	1.42	1.35	1.41	2.37	2.41	2.39
	0.7	6.39	6.44	6.38	10.38	10.12	10.73
100	1	3.13	3.08	3.23	6.24	5.88	6.46
	1.5	1.78	1.59	1.66	2.43	2.80	2.64

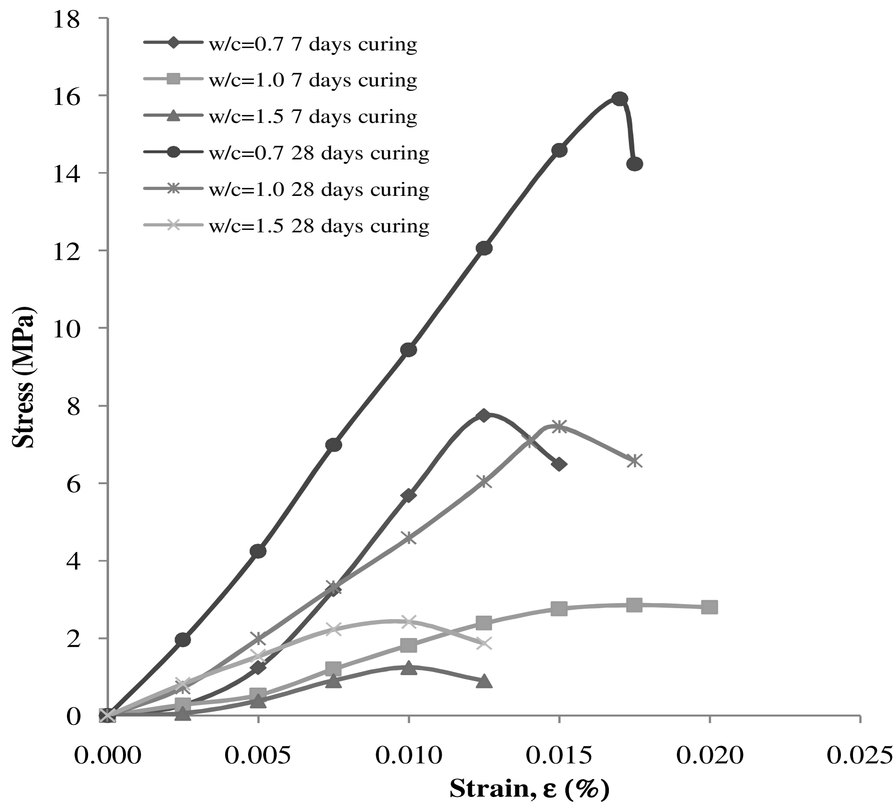

Figure 3a. Unconfined compression strengths of GP sample (D_r = 75% and P = 150 kPa).

increase as w/c ratio decreases (Figures 3a and b). The slopes of the stress-strain graphs increases and the curves of the graphs become steeper leading to increase of modulus of elasticity. Similar graphs can easily be

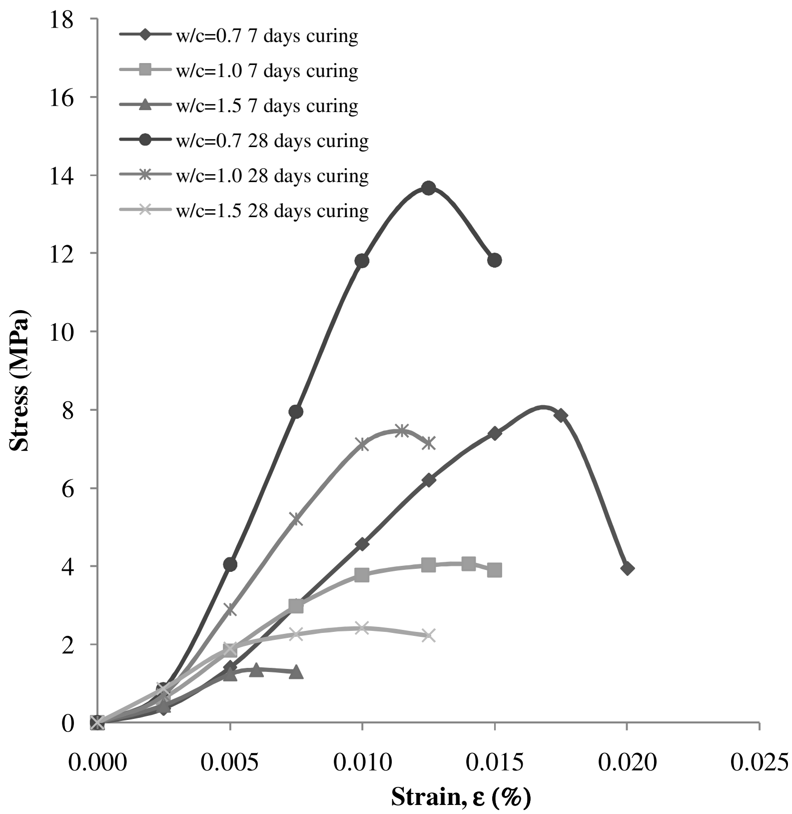

Figure 3b. Unconfined compression strengths of SP sample (D_r = 75% and P = 150 kPa).

plotted from the values listed in Tables 6 and 7. Figures 3a and b shows stress-strain relations of test specimens obtained from unconfined compression tests.

As will be discussed in detail, since the strength values are not influenced by grouting pressure, for the range of pressures considered in the study, only the graphs for one typical value of grouting pressure (150 kPa) are presented. These graphs provide information not only on the unconfined compressive strengths of the test specimens, but also on their elastic modulus. For easier comparison, the "average" UCS values are also listed in Tables 6 and 7. As can be seen from both the figures and tables, UCS of test specimens may depend significantly on the gradation and relative density of the soil, water/cement ratio of the cement grout and the curing period.

The effect of soil gradation on UCS

From Tables 6 and 7, it can be seen that, independent from *w/c* ratio, curing time and grout pressure, the UCS of *SP* samples are always larger than those of *GP* samples if $D_r \leq 50\%$. This is also the case when $D_r = 75\%$ if the samples are cured for only seven days before the tests. On the other hand, when $D_r = 100\%$ and $w/c = 0.7$, the *UCS* of *GP* samples exceed those of *SP* samples, irrespective of the curing period. It is interesting to see that, when $w/c = 1.0$, *SP* samples have higher strengths than *GP* samples if they are cured for 7 days, while the reverse is true if they are cured for 28 days. It can be noted that, in the range of the parameters investigated in this study, *SP* samples reached their maximum strength value, 19.83 MPa, when $D_r = 50\%$, $w/c = 0.7$, $P = 200$ kPa and curing period = 28 days. On the other hand, the largest strength value attained by the *GP* samples, 18.95, MPa, was at $D_r = 100\%$, $w/c = 0.7$, $P = 200$ kPa and 28 day curing. It can easily be realized that, despite occurring at different D_r values, both *GP* and *SP* samples showed very similar maximum strength values of approximately 19 MPa.

The effect of grouting pressure on UCS

Figures 4a and b present typical graphs ($D_r = 50\%$) showing the effect of grouting pressure, for various *w/c* ratios, on unconfined compression strength of tested samples. It can clearly be seen that neither of the samples was influenced by the grouting pressure. Thus, it can be concluded that there is no advantage to be gained in applying high grouting pressure to increase the

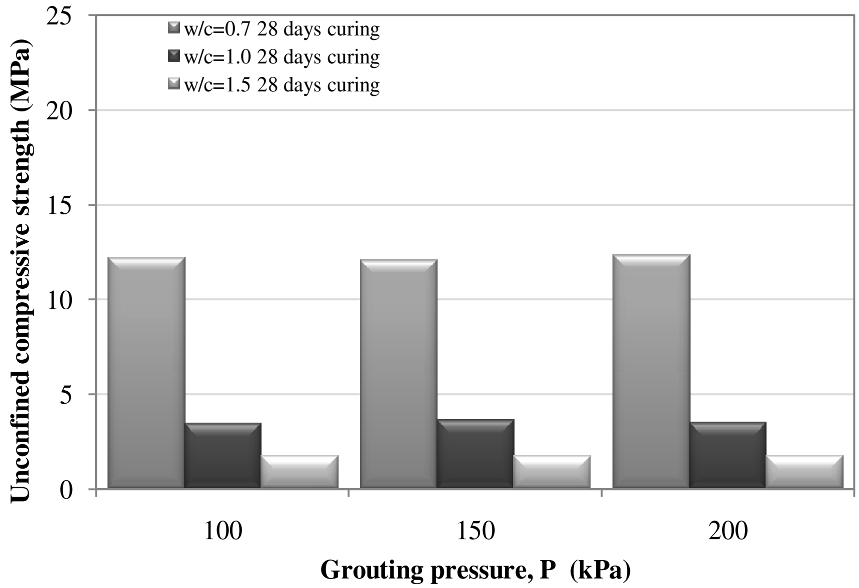

Figure 4a. Variation of unconfined compressive strength with grouting pressure for GP sample with $D_r = 50\%$.

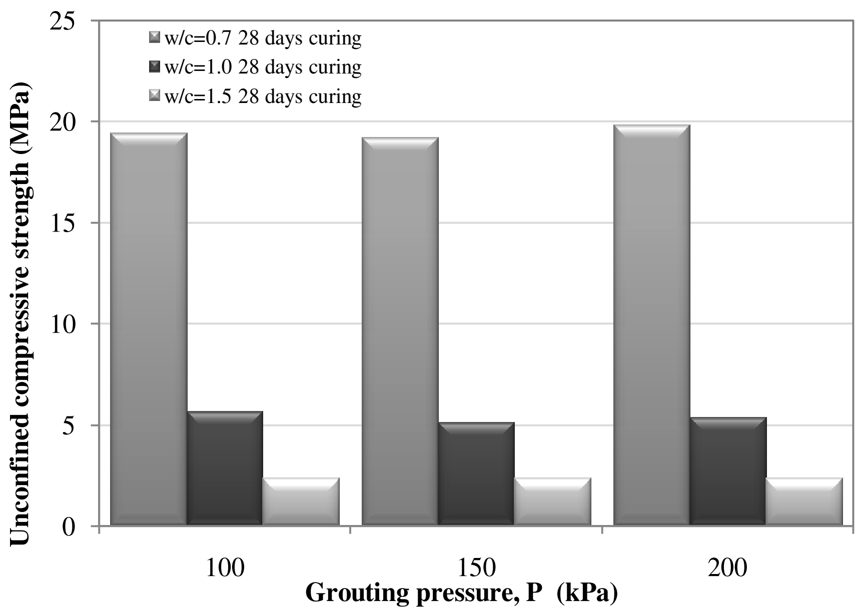

Figure 4b. Variation of unconfined compressive strength with grouting pressure of SP sample with $D_r = 50\%$.

unconfined compression strength. When an adequate injection pressure is applied in permeation grouting, the strengths of the samples are independent of the applied pressure. However, it should not be forgotten that field applications might differ from laboratory tests in that the use of larger pressure will influence greater volume of soil in the field due to the fact that grout with higher energy spreads over a larger area. Since UCS values of the tested samples are observed to be independent of the applied grouting pressures, in the following discussions, the grouting pressure will be kept constant, typically, 100 kPa.

Specific values for 150 and 200 kPa pressure can be obtained from Tables 6 and 7.

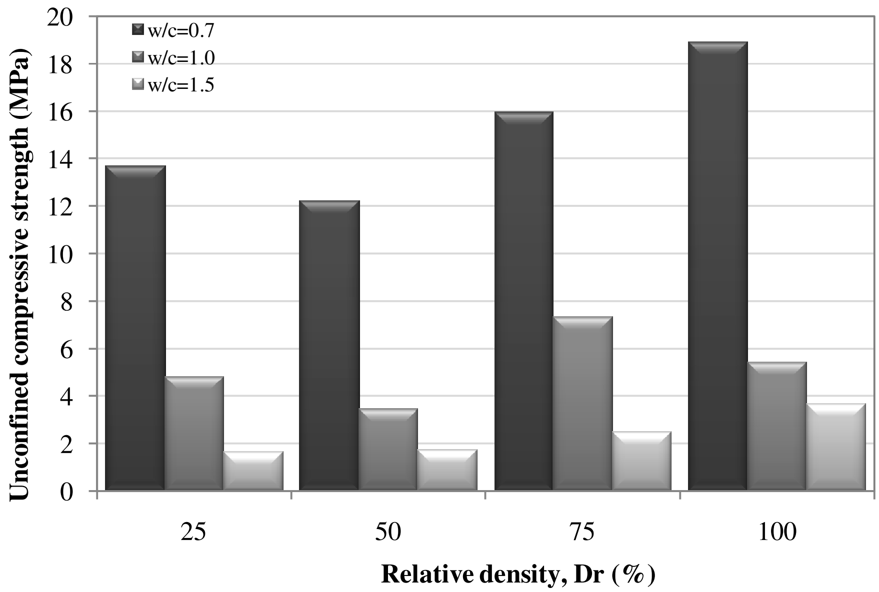

Figure 5a. Variation of unconfined compressive strength with relative density for GP samples.

The effect of water/cement ratio on UCS

From Figures 4a and b, it can be observed that UCS increases as *w/c* ratio decreases. At this stage, it is worth noting that the lowest *w/c* ratio investigated in this study, that is, *w/c* = 0.7, was selected on the basis of the observation, in the initial trial tests, that the penetrability of the grout into the soil samples cannot be achieved if the *w/c* ratio is smaller than 0.7. This is also the case even when a superplasticizer is used in the samples. In these trial tests, it was also realized that proper diffusion cannot be achieved if the *w/c* ratio is increased considerably, to the point when water is observed to accumulate on the top surface of the samples and the grouting operation is observed to fail. For this reason, the highest *w/c* ratio selected for this study was 1.5. Based on these initial trial tests and the results presented in Tables 6 and 7, it can be concluded that, for the tested samples, *w/c* ratio is most suitable if it is in the range of 0.7 to 1.0.

The effect of relative density (D_r) on UCS

Figures 5a and b show the variation of UCS values of the tested samples with relative density for various *w/c* ratios and for 28-day-curing periods. It is seen that, as expected, UCS decreases as *w/c* ratio increases for all relative density values examined in this study. What was less expected were the different patterns achieved by *SP* and *GP* samples in these variations although the maximum unconfined compression strength is attained at 100% relative density for *GP* samples, the maximum unconfined compression value for *SP* sample was found to occur at 50% relative density. This result can be attributed to the fact that dense *GP* samples with voids and high permeabilities show stable characteristics when grouted with cement, and attain very high strength values, as much as 18.95 MPa, at 100% relative density. However, for *SP* samples, the permeability at 100% D_r is insufficient and these samples reach their maximum strength of 19.83 MPa at 50% relative density.

The effect of curing time of the samples on UCS

The variation of unconfined compressive strength with curing time, which is either 7 or 28 days for the test specimens is shown in Figure 6, which plots the ratio of unconfined compressive strength of 28 to 7-day-cured specimens, denoted respectively as q_{u28} and q_{u7}. As shown in the figure, the q_{u28}/q_{u7} ratio for *SP* samples varies from 1.54 to 1.68 with an overall average of 1.64, which is the average of 216 UCS test results. For *GP* samples, the same ratio varies from 1.85 to 2.36 with an average of 2.02, which is again computed from 216 UCS test results. It is notable that the effect of relative density on q_{u28}/q_{u7} is not more than 10% for all *SP* samples and less than 20% for all *GP* samples. From Figure 6, it can be concluded that 28-day-cured specimens have at least 1.5 times the strength of 7-day-cured specimens. This strength ratio is slightly larger in *GP* samples than *SP* samples if $w/c \leq 1.0$. On the other hand, when $w/c = 1.5$, the difference becomes considerable.

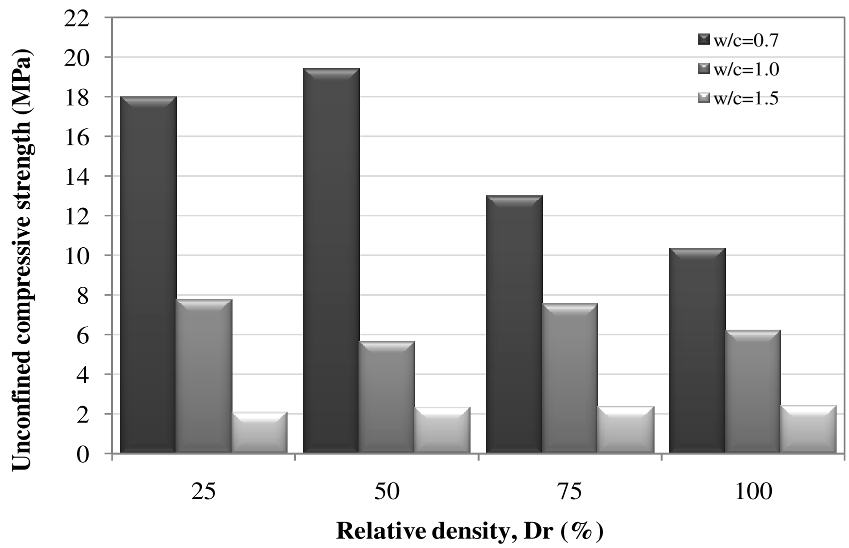

Figure 5b. Variation of the unconfined compressive strength with relative density for SP samples.

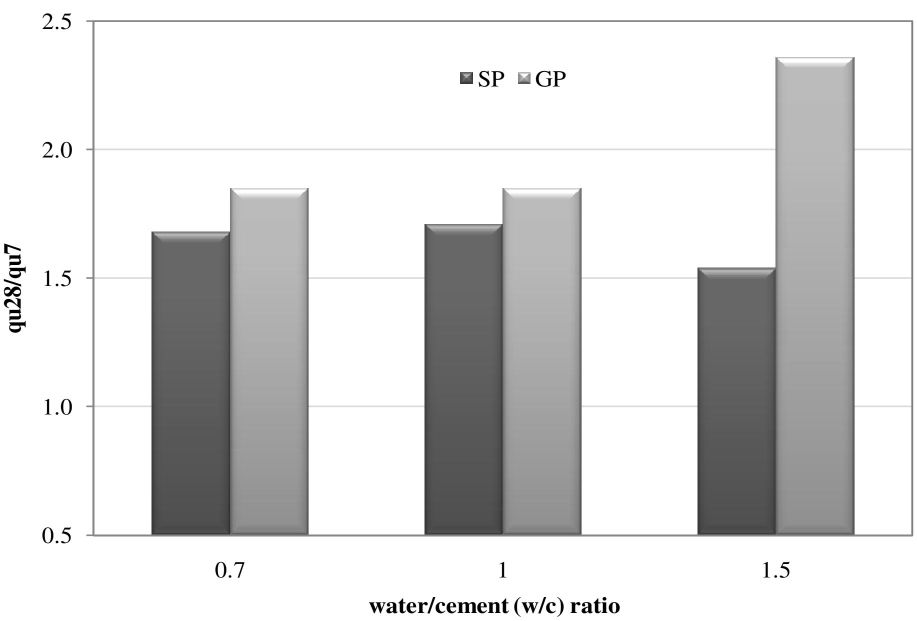

Figure 6. Variation of unconfined compressive strength of 28 and 7-day-cured specimens (denoted as q_{u28} and q_{u7}) with water/cement ratio.

CONCLUSIONS

Grouted sands in the study present the general characteristics of cemented soils and can be considered as an intermediate material between soil and concrete (Dano et al., 2004). The results of the unconfined compression tests indicate that the grain-size of the soil samples affects the "satisfaction" of the grouting operation more than it affects their unconfined compressive strength; test samples in which less than 10% of material passes through a 0.6 mm sieve give satisfactory results for grouting. UCS decreases as water/cement (*w/c*) ratio by weight increases. The most appropriate *w/c* ratio was found to be within the range of 0.7 to 1.0. The effect of relative density on UCS showed different characteristics for *SP* and *GP* samples. Although the maximum unconfined compression strength was attained at 100% relative density for *GP* samples, the maximum unconfined compression value for *SP* samples was found to occur at 50% relative density. This result can be attributed to the fact that dense *GP* samples with voids and high permeabilities show stable characteristics when grouted with cement, and attain very high strength values (up to 18.95 MPa) at 100% relative density. The results of UCS tests also indicate that the UCS of the tested soil samples is not affected significantly by the grouting pressure, as long as it is sufficiently low. In laboratory conditions, since the head difference over the sample is not dominant and the test apparatus allows free drainage of the grout, the stabilized samples are almost fully saturated with cement grout and no significant variation in UCS is observed. It should be noted that, if the injection pressure used on-site is greater than the low-pressure values necessary for permeation grouting, the pressure equilibrium between the grout and the environment occurs at greater distances from the nozzle and the diffusion volume of grouting in the soil increases. If the applied pressure is very high and/or the stability cannot be attained, plastic and/or permanent deformations can occur in the soil. This type of improvement is called compaction grouting, which also improves granular soils but not as much as permeation grouting.

The effect of curing time of the samples on UCS values was examined using the q_{u28}/q_{u7} ratio. It was concluded that 28-day-cured specimens have at least 1.5 times greater strength than 7-day-cured specimens. This strength ratio is slightly larger in *GP* samples than *SP* samples if $w/c \leq 1.0$. On the other hand, when $w/c = 1.5$, the difference becomes considerable. Injection ability and final strength of the soil is very important for grouting in site applications. The results of the present study support those reported in the literature, which suggest that an adequate laboratory study should be performed to verify the injection ability and the strength of the injected soil medium before permeation grouting is applied in the field.

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