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Laboratory Study on the Effect of Water-Cement Ratio on Strength Characteristics of Jet Grouting Columns

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ABSTRACT

Jet grouting is one of the most widely applied soil improvement techniques. It is suitable for most geotechnical problems, including improving bearing capacity, decreasing settlement, forming seals, and stabilizing slopes. One of the difficulties faced by designers is determining the strength and geometry of elements created using this method. Jet grouted soil-cement columns in soil are a complicated issue because they are dependent on a number of parameters such as soil type, grout and water flow rate, rotation and lifting speed of monitor, nozzle jetting force, and water to cement ratio of slurry. This paper discusses the effect of the water-cement ratio on the physical and mechanical characteristics of soilcrete. In the laboratory, sandy soil mixed with cement grout with water-cement ratio varies from (0.7:1 to 1.4:1). To evaluate the characteristics of soilcrete, 96 specimens were prepared in the laboratory and tested at different curing times. The results indicate that the Uniaxial Compressive Strength (UCS) of soilcrete decreases with increasing the (W/C) ratio of the grout, where the soilcrete strength of W/C ratio of 0.7 is higher about 237% of W/C ratio of 1.4 at 28-day; the evolution of the (UCS) is proportional to the logarithm of the curing time; the ratio between the modulus of elasticity (E_{tg50}) to the maximum UCS varies from 113 to 175; when the water-cement ratio increases, the dry density of soilcrete decreases, as a result, the (UCS) of soilcrete decreases.

Keywords: Soilcrete, Jet Gro uting, water-cement ratio, uniaxial compressive strength.

دراسة مختبرية لتأثير نسبة الماء الى الاسمنت على خصائص المقاومة لاعمدة الحقن النفاتة

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الخلاصة

يعتبر الحقن النفات أحد أكثر تقنيات تحسين التربة تطبيقاً. إنها مناسبة لمعظم المشاكل الجيو تقينية ، بما في ذلك تحسين قدرة التحمل ، وتقليل الهطول ، وتشكيل الجدران الساندة ، وتثبيت المنحدرات. من اهم الصعوبات التي يواجهها المصممون عند استخدام

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طريقة الحقن النفث هي تحديد مقاومة وابعاد العناصر التي يتم إنشاؤها باستخدام هذه الطريقة. تعتبر أعمدة الأسمنت والترتبة المتكونة بالحقن في التربة مشكلة معقدة لأنها تعتمد على عدد من المتغيرات مثل نوع التربة ، ومعدل تدفق مادة الحقن والماء ، وسرعة دوران ورفع انبوب الحقن ، ونسبة الماء إلى الأسمنت للمحلول الاسمنتي. يناقش هذا البحث تأثير نسبة الماء إلى الأسمنت على الخصائص الفيزيائية والميكانيكية لخرسانة التربة. حيث تم خلط التربة الرملية بالمحلول الاسمنتي مع نسبة الماء إلى الأسمنت تختلف من (0.7 : 1 إلى 1.4 : 1) في المختبر. لتقييم خصائص خرسانة التربة ، تم تحضير 96 عينة في المختبر واختبارها في أوقات معالجة مختلفة. تشير النتائج إلى أن مقاومة الانضغاط احادية المحور لخرسانة التربة UCS يتناقص مع زيادة نسبة (W/C) للمحلول الاسمنتي ، حيث تكون قوة خرسانة التربة عند نسبة الماء إلى الاسمنت البالغة 0.7 أعلى بنحو % 237 من نسبة الماء إلى الاسمنت البالغة 1.4 في عمر 28 يوم من الانضاج؛ يتناسب تطور (UCS) طرديا مع لوغاريتم وقت المعالجة ؛ تتراوح النسبة بين معامل مرونة (E_{tg50}) إلى الحد الأقصى لـ UCS من 113 إلى 175 ؛ عندما تزداد نسبة الماء إلى الأسمنت ، تنخفض الكثافة الجافة مما يؤدي إلى انخفاض مقامة خرسانة التربة.

الكلمات الرئيسية: خرسانة التربة بالحقن النفث، نسبة الماء إلى الاسمنت، قوة الانضغاط أحادي المحور.

1. INTRODUCTION

The Jet Grouting technique is one of the soil improvement techniques. It is a technique where the injection of a fluid jet produces structural elements of soil-cement with different geometries (columns, panels, slabs) with high energy, promoting the disintegration, mixing, and partial replacement of the soil by a cementitious agent. Compared to other soil improvement techniques, the Jet Grouting technique has greater flexibility of applicability. It can be used successfully in various types of soils, from clayey to sandy, with high or low permeability (Pearlman, 1998, Giménez, 2004). This technique can also be applied in any direction and in the strictly necessary soil strata (Falcão, Pinto and Pinto, 2000), being used successfully in reinforcing structural foundations, with several existing applications for reinforcing foundations of historical and current buildings, works of art, road and railway structures, and tunnels. The uniaxial compressive strength and geometry of the jet-grouted element are two parameters of great importance in the design of jet grouting columns. According to Sližytė *et al.*, 2010 and based on previous researches by researchers, soil-cement compressive strength generally depends on four factors: soil type, cement content, water-cement ratio, and hardening time. The amount of cement in the improved soil has a significant impact on its strength. This directly influences costs and should be considered to optimize the project and balance the cost and strength (Kimpritis, 2013). According to Nikbakhtan and Ahangari, 2010, the strength and diameter of soilcrete are dependent on jet grouting parameters such as grout pressure, withdrawal and rotating speed, nozzle number and diameter, water to cement (W/C) ratio, and in-situ soil characteristics. The grout mixture is water and cement dosed in weight ratios (W/C), typically ranging between 0.6 and 1.3. The W/C ratio that is most appropriate for each project should be determined, taking into account that raising the W/C ratio results in increased erosion efficiency but decreased strength of the jet-grouted material (Croce, Flora and Modoni, 2014). The effect of the water-cement ratio on the consolidated soil's behavior is consistent with the principles of concrete engineering. In general, decreasing the grout's water-cement ratio results in an increase in strength and hardening time. KUTZNER, 1996 reported a 50% increase in compressive strength when the water-cement ratio of the injected grout was reduced from 1.5 to 1. Field and laboratory testing have established a relationship between the improved soil's compressive strength and the water-cement ratio (Lunardi, 1997). Van der Stoel, 2001 conducted a thorough experimental investigation on jet-grouted material derived from sandy and clayey soils. As a result, the relationship between the water-cement ratio and compressive strength was investigated. The relation between the W/C ratio and uniaxial compressive strength is shown in the following equations for $0.6 < wcr < 1.4$:

$$f_c = 7 + 8.1(wcr)^2 \quad (\text{Jet grouted sand}) \quad (1)$$



$$f_c = 2 + 3.6(wcr)^2 \quad (\text{Jet grouted clay}) \quad (2)$$

Where:

wcr = water-cement ratio (-)

f_c = compressive strength (MPa)

It is essential to understand that these relationships provide only a rough estimate, as many jet-routing parameters that affect strength are not involved in the relationships. On the other hand, these relationships can be a helpful rule of thumb for similar grouting operations (**Van der Stoel, 2001**). **Ökmen, 2003** conducted an experimental investigation to determine the soilcrete's characteristic properties at water-cement ratios ranging from 0.75 to 2.75. The unconfined compressive strength of sandy soil ranged between 5 and 23 MPa, whereas the unconfined compressive strength of clayey soil was between 1 and 5 MPa.

The choice of the execution parameters to be used in this technique should be aided by a laboratory study of the formulations to design the mixtures to be used on-site, allowing a technical-economic analysis of them. The performance of the formulations is evaluated through the mechanical (strength and deformability) and physical (density and permeability) characterization of soil-cement specimens. However, the laboratory study is still insufficient to fully reproduce the physical and mechanical properties of in-situ soil being improved, so that being necessary to carry out trial or test columns to adjust the formulations defined in the laboratory.

The main purpose of this study is to investigate the effect of the water-cement ratio on the uniaxial compressive strength of the soilcrete specimens made in the laboratory simulating jet grouting.

2. MATERIALS AND METHODS

The experimental program consisted of two stages. First, the physical and mechanical properties of the soil and cement were determined; then, extensive unconfined compression tests at different curing durations were used to determine the strength of soilcrete specimens prepared with various water-cement ratios. The results of which are explained in detail in the following section.

2.1 Materials

According to the Unified Soil Classification System, the soil used is fine, poorly graded sand, containing fines (silt and clay) passing sieve no. 200 of 4% and specific gravity (G_s) of 2.63. The soils used in this study are naturally sandy soil from Karbala Province in Iraq. The grain size distribution curve of the soil is shown in **Fig. 1**. The chemical, physical and mechanical properties of the soil are shown in **Table 1** and **Table 2**. The cement used in the mixture is Portland cement (sulfates resistance type), and potable water was used in grout preparation.

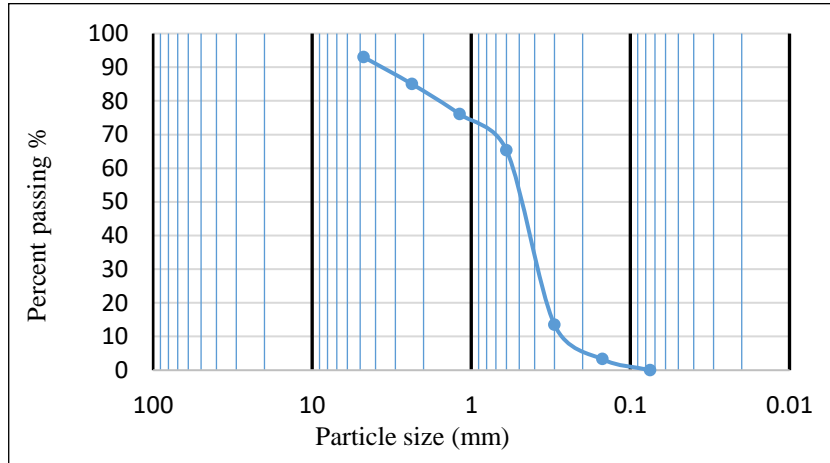


Figure 1. Grain size distribution curve of selected soil.

Table 1. The chemical properties of the tested sand.

Test	SO ₃ %	Gypsum %	O.M%	Cl%
Value	5.54	11.91	0.84	0.041

Table 2. The physical and mechanical properties of the tested sand.

Property	Unit	Value	Specification
Specific gravity, G _s	-	2.63	(ASTM D854 - 14)
Classification (USCS)	-	SP	(ASTM D2487 - 17e1)
Maximum, γ _{d,max.}	kN/m ³	17.67	(ASTM D4253 - 16e1)
Minimum, γ _{d,min.}	kN/m ³	12.4	(ASTM D4254 - 16)
Test unit weight, γ _{d test}	kN/m ³	14.6	-
Angle of internal friction (Ø) at relative density (50%)	degree	34	(ASTM D3080 - 11)

2.2. Mixture and Samples Preparation

The mixture was prepared by adding the cement slurry to the soil. After that, the soilcrete material was mechanically mixed and poured into the molds. The soil dosage is 1460 kg/m³ (medium dense sand), and the cement dosage is 430 kg/m³. The water to cement ratio (W/C) adopted in this study was 0.7 to 1.4. **Table 3** illustrates the proportion of soil, cement, and water was adopted to formulate soilcrete samples for each water/cement ratio.



Firstly, the grout was prepared by adding the water to the cement and mechanically mixed for 5 minutes. Then, the grout was added to the sandy soil and mechanically mixed for 5 minutes to simulate the adopted procedure at constructing jet grouting columns in the field .

Finally, the mixture was placed in PVC cylinder molds without any type of compaction with a diameter of 70 ± 2 mm and a height of 140 ± 2 mm for the uniaxial compressive strength test. A mold ratio of height to diameter of 2:1 according to (ASTM D1633 - 17). The specimens were extracted from PVC molds after 24 hours and submerged in water in a plastic container in the laboratory with temperatures varying from 20°C to 23°C. **Figure 2** shows the steps to prepare soilcrete material and samples.

Table 3. Soilcrete mixture ingredients.

Water/cement ratio (W/C)	Sand (Kg)	Cement (Kg)	Water (Kg)
0.7	12.150	3.578	2.504
0.8	12.150	3.578	2.862
0.9	12.150	3.578	3.220
1.0	12.150	3.578	3.578
1.1	12.150	3.578	3.935
1.2	12.150	3.578	4.293
1.3	12.150	3.578	4.651
1.4	12.150	3.578	5.009

2.3. Testing Program

Most of the experimental programs documented in the literature have used unconfined compression tests to evaluate the effectiveness of cement stabilization or to determine the importance of certain elements in determining the strength of soil-cement mixtures. Accumulated expertise with this kind of test for concrete may explain this (Da Fonseca, Cruz and Consoli, 2009). The test is quick and straightforward, as well as reliable and inexpensive. The specimens

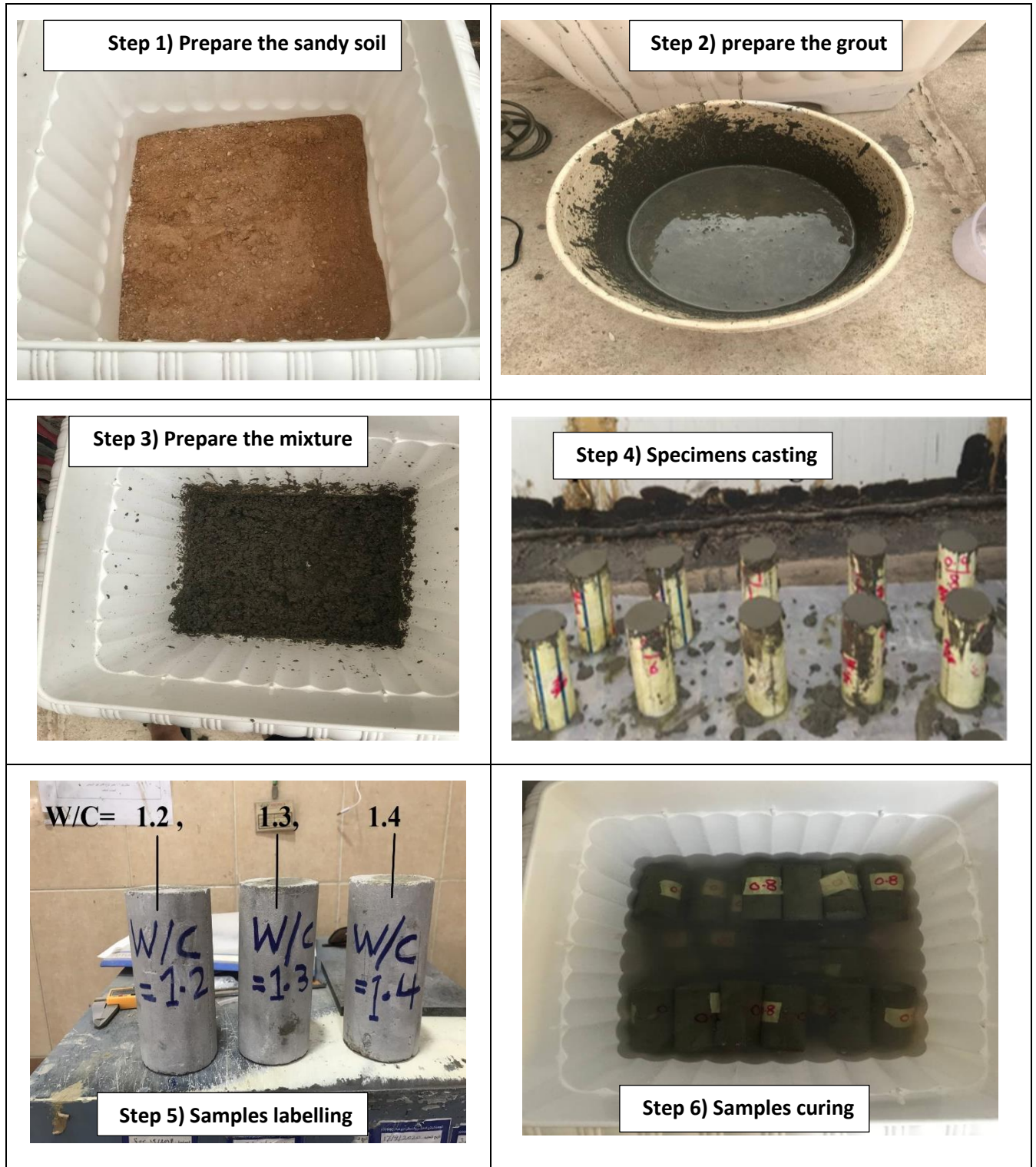


Figure 2. Mixture and specimens preparation procedure.

were subjected to axial stress until they failed, with the maximum load reached (q_u) of each sample precisely recorded. A total of 96 samples were used in the testing program (8 mixtures x 4 test days x 3 samples per day) for uniaxial compressive strength tests (UCS). The compression tests were carried out at 7, 14, 28, and 56 days using a (microcomputer controlled electronic universal testing machine) at a rate of 1mm/min according to (ASTM D1633–2017). This machine



automatically records stress, axial strain, force, and axial deformation. After being extracted from the submersion bath, all samples were analyzed. When samples looked to have dried, this was due to surface drying, which was ignored because suction had no discernible effect on the results. As a result, all strength values recorded are presumed to be saturated (**Cardoso, Ribeiro and Néri, 2017**). The 56 days of curing were programmed to determine the module of deformation, tangent module at 50% of the maximum strength (E_{tg50}) for 3 specimens of each water to cement ratio, where E_{tg50} corresponds to the slope of the tangent of the stress-strain curve at the point corresponding to 50% of the maximum stress.

Correlations between two variables can be valuable if one variable's value is easier to determine statistically than the other. As a result, the value of the other parameter can be calculated. The strength and unit weight of soilcrete have received far more attention in the literature than other factors. Even so, statistical correlations between these two factors are limited (**Akin, 2016**).

In this study, the statistical correlations between the physical (dry density) and mechanical (UCS) properties of soilcrete were studied to evaluate various variables' dependence. The dry density and water content were determined of samples for each water-cement ratio (W/C) for all curing ages according to (**ASTM D2216 - 10**).

3. RESULTS AND DISCUSSION

3.1. Effect of Water to Cement Ratio on Uniaxial Compressive Strength (UCS)

The results of the UCS tests conducted on all specimens are analyzed first. **Table 4** shows the UCS of samples prepared with a water to cement ratio from 0.7 to 1.4 at different curing times. **Figure 3** illustrates the relationship between the average UCS and water to cement ratio (W/C) for specimens at 28- days of curing time. It is clear from **Fig. 3** that the (W/C) ratio is a significant parameter that affects the UCS of soilcrete. The UCS decreases with increasing the (W/C) ratio with a linear relationship ($R^2 = 0.69$), as shown in Eq. (3):

$$q_u = -5.3537(W/C) + 12.057 \quad (3)$$

where q_u is the uniaxial compressive strength at 28 days in (MPa), and (W/C) is the water to cement ratio. Several UCS demonstrates that the mass of water utilized during the mixing stage affects the strength characteristics. This is comparable to the structure found in compacted fine soils due to the compaction process (**Cardoso, Ribeiro and Néri, 2017**). The average UCS are 9.31 and 3.92 MPa for (W/C) ratio of 0.7 and 1.4, respectively. A cement content of a W/C ratio of 0.7 is greater than that of the W/C ratio of 1.4. As a result, soilcrete samples strength of W/C ratio of 0.7 is higher about 237% of W/C ratio of 1.4. The average UCS of all W/C ratios was 6.43 MPa might be adopted for a W/C ratio equal to 1.0 is in good agreement with previous studies, e.g., (**Kimpritis, 2013**). **Kimpritis, 2013** studied the effect of the W/C ratio on the strength of jet grouting columns were constructed in sandy soil with a W/C ratio ranges from 0.8 to 1.3. the results of this study were a mean value of approximately 6.0 MPa might be adopted for a water/cement ratio equal to 0.9 (UCS values range between 2.0 and 9.0 MPa for water/cement ratios 1.3 and 0.8, respectively).



Table 4. Uniaxial compressive strength test results of soilcrete specimens.

W/C ratio	Curing time	No. of specimens	UCS average (qu)	Standard deviation	Coefficient of variation
-	days	-	MPa	MPa	%
0.7	7	3	5.95	0.07	1.188
	14	3	7.02	0.18	2.702
	28	3	9.31	0.07	0.773
	56	3	8.269	0.77	9.322
0.8	7	3	6.52	0.96	14.74
	14	3	6.35	1.04	16.38
	28	3	6.80	0.38	5.712
	56	3	6.98	1.015	14.535
0.9	7	3	4.70	0.28	6.018
	14	3	6.75	0.13	1.940
	28	3	6.61	1.29	19.552
	56	3	7.44	0.79	10.659
1.0	7	3	4.25	0.63	14.974
	14	3	4.46	0.32	7.223
	28	3	6.0	0.38	6.45
	56	3	6.16	0.16	2.726
1.1	7	3	4.73	0.22	4.785
	14	3	5.78	0.92	15.914
	28	3	7.47	1.74	23.41
	56	3	7.70	1.37	17.823
1.2	7	3	4.25	0.43	10.27
	14	3	5.21	0.11	2.165
	28	3	5.77	0.55	9.674
	56	3	5.82	0.76	13
1.3	7	3	3.98	0.55	13.818
	14	3	4.38	0.22	5.078
	28	3	5.56	0.62	11.319
	56	3	5.71	0.85	14.945
1.4	7	3	4.75	0.21	4.466
	14	3	3.85	0.51	13.357
	28	3	3.92	0.13	3.343
	56	3	5.99	0.99	16.586

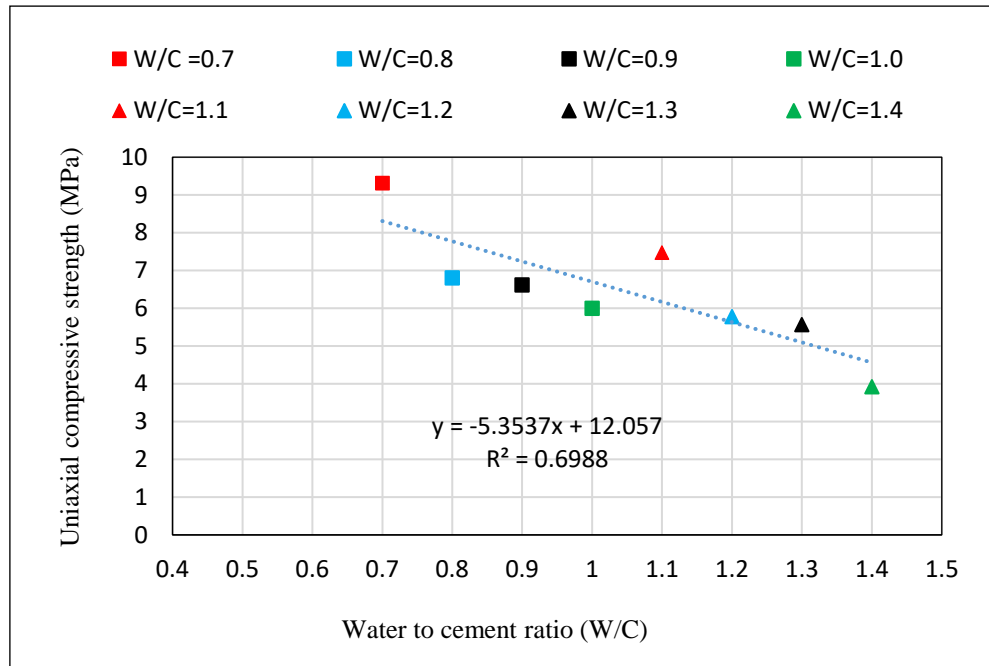


Figure 3. Simple regression analysis between the average uniaxial compressive strength and water to cement ratio at 28 days.

3.2 Development of UCS with Curing Time

Fig. 4 presents the UCS and curing time relationship at 7, 14, 28, and 56 days for all (W/C) ratios. The points in Fig. 4 were created using the average values of each curing time for each (W/C) ratio studied. It can be concluded that the behavior of all (W/C) ratios are approximately similar with curing time. The UCS increases logarithmically with time for all (W/C) ratios except

the (W/C) ratio of 1.4, decreasing from 4.75 to 3.92 MPa at 7 and 28 days. The highest UCS indicated by the points in Fig. 4 can be regarded as the greatest compressive strength obtained. Since the specimens were made using the same amount of sand but varying amounts of water for a fixed dosage of cement.

From Fig. 4, it is possible to deduce that the strength evolution of the treated soil over time has been demonstrated to be non-linear, increasing with curing age as this is a characteristic of cement-treated soils, mortar, and concrete (Kosmatka and Panarese, 1988; Consoli, Cruz and Floss, 2011). Strength increases with curing time were greater in the early periods than in the later periods. UCS had shown the tendency to stabilize after 14 days of cure in some (W/C) ratios and after 28 days in others. The observed scattering accurately reflects the difficulties in obtaining homogenous specimens. Table 5 summarises the strength gains associated with various curing durations for all (W/C) ratios. Where (q_{u14}/q_{u7}) varies from 0.81 to 1.43, (q_{u28}/q_{u14}) varies from 0.97 to 1.34, and (q_{u56}/q_{u28}) varies from 0.89 to 1.54. It is now possible to study the evolution of the UCS of soilcrete material during curing time. Considering that the evolution of uniaxial compressive strength (UCS) is proportional to the logarithm of the curing time, an empirical

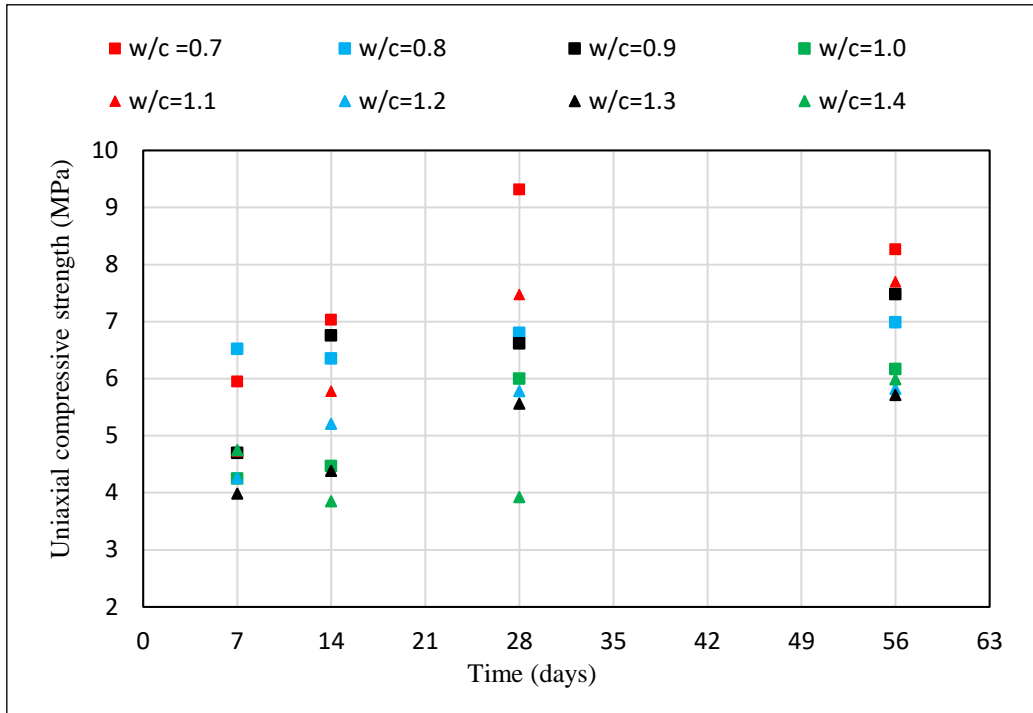


Figure 4. Uniaxial compressive strength of soilcrete specimens versus curing time for all (W/C) ratios.

Table 5. Strength gains between different curing times.

W/C Ratio	qu_{14}/qu_7	qu_{28}/qu_{14}	qu_{56}/qu_{28}
0.7	1.18	1.32	0.89
0.8	0.97	1.07	1.03
0.9	1.43	0.97	1.13
1.0	1.05	1.34	1.03
1.1	1.22	1.29	1.03
1.2	1.22	1.10	1
1.3	1.09	1.26	1.02
1.4	0.81	1.01	1.54

relationship capable of predicting the UCS for a given period and water-cement ratio can be proposed. The following equation defined the relationship between UCS and curing time:



$$qu(t) = a \cdot \ln(t) + b \tag{4}$$

where $qu(t)$ is the uniaxial compressive strength of the samples at time t ; a and b are empirical parameters, and t is the curing age in days. The parameters a , b , and the corresponding correlation factor (R^2) for each W/C ratio are listed in **Table 6**. Experimental error due to nonhomogeneity of samples explains the correlation factors' low values, particularly for the W/C ratio of 1.4. Due to the different characteristics of the bonding, it is unlikely that the evolution of the UCS over time will follow a similar path for the various water-cement ratios used in this study. Really, the cement minerals form a network of bonds around the sand particles. The geometry of these bonds is related to the amount of water used to prepare the mixture.

Table 6. The values of empirical parameters a , b , and the correlation factor R^2 for fitting the evolution of UCS along curing time for the different (W/C) ratio.

W/C Ratio	Parameter (a)	Parameter (b)	R^2
0.7	1.346	3.627	0.67
0.8	0.283	5.829	0.72
0.9	1.184	2.853	0.79
1.0	1.070	2.035	0.88
1.1	1.528	1.860	0.93
1.2	0.759	3	0.86
1.3	0.918	2.168	0.91
1.4	0.572	2.936	0.25

3.3. Modulus of Elasticity (E_{tg50})

Laboratory tests indicate a linear relationship between the elastic modulus of the soilcrete material and the UCS. The tangent modulus (E_{tg50}) to 50% of the ultimate UCS of soilcrete samples was calculated from the stress-strain curve at 56 days of curing age. The (E_{tg50}) results are shown in **Table 7**, where 3 specimens were tested for each water-cement ratio. A relationship between UCS and Young's module (E_{tg50}) can be proposed with linear regression using the following equation ($R^2 = 0.86$):

$$E_{tg50} = 235.15qu - 586.86 \tag{5}$$

where E_{tg50} and qu in (Mpa). The relationship between the (E_{tg50}) and UCS is presented in **Fig. 5**. In general, the (E_{tg50}) increase almost linearly with an increase in the UCS. The ratio between the (E_{tg50}) to the maximum UCS varies from 113 to 175. This ratio is considered relatively low if compared with the ratios presented in previous studies, e.g. (**Fang, Kuo and Wang, 2004**) where the ratio between the (E_{tg50}) to (UCS) in this study is 300-750 for silty sand soil. The inaccuracy



in the measurement was due to existing initial gaps between the load cell of the test equipment and the specimen, which may affect the results of elasticity modulus for the samples.

Table 7. Modulus of elasticity (E_{tg50}) at 56 days of curing age.

W/C Ratio	No. of sample	E_{tg50} (average)	Standard deviation	Coefficient of variation
-	-	MPa	MPa	%
0.7	3	1424	75	5.26
0.8	3	1046	64	6.15
0.9	3	1218	99	8.16
1.0	3	765	30	4
1.1	3	1133	165	14.56
1.2	3	688	168	24.45
1.3	3	840	179	21.33
1.4	3	948	220	23.31

3.4. Statistical Relationships Between the Dry Density and UCS of Soilcrete Specimens

The dry density (ρ_d) at 7, 14, 28, and 56 days of curing age of soilcrete samples were determined for each water-cement ratio. The results for 28 days of curing age are illustrated in **Table 8**. Simple regression analysis between average q_u and average (ρ_d) of specimens at a curing time of 28 days is shown in **Figure 6**. A polynomial relationship is evident for ρ_d and UCS. The coefficients of determination (R^2) were determined to be 0.79, the relation between these parameters is shown in Eq. (6):

$$q_u = 0.0001(\rho_d)^2 - 0.5071(\rho_d) + 450.51 \tag{6}$$

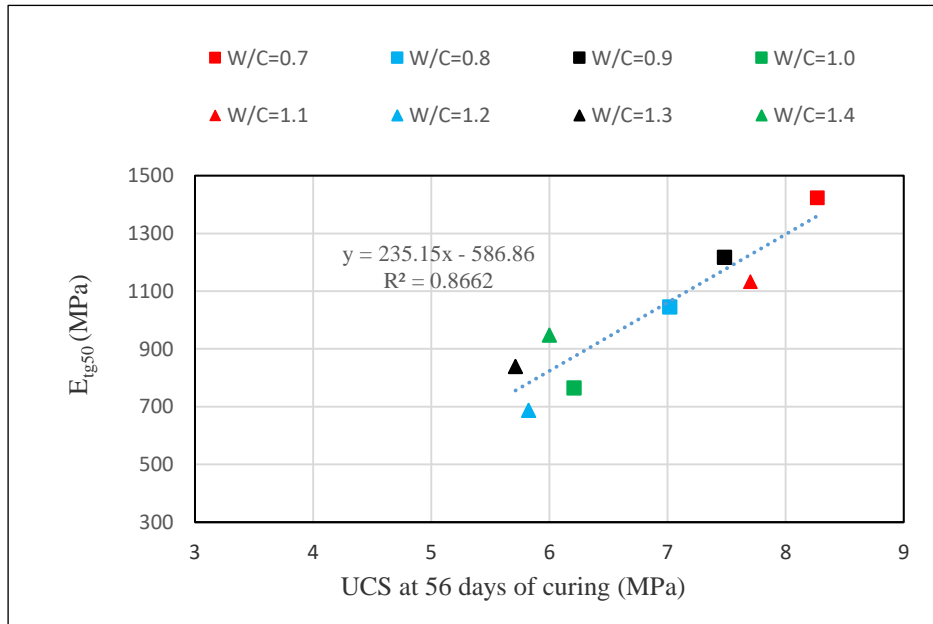


Figure 5. Tangent modulus E_{tg50} versus unconfined compressive strength of soilcrete specimens at 56 days.

Table 8. The dry density of soilcrete specimens at 28 days of curing age.

W/C Ratio	No. of sample	Dry density	Standard deviation	Coefficient of variation
-	-	(kg/m ³)	(kg/m ³)	%
0.7	3	1924	19.75	1
0.8	3	1889	13.97	0.74
0.9	3	1861	5.54	0.298
1.0	3	1849	4.42	0.239
1.1	3	1858	15.88	0.855
1.2	3	1793	64.90	3.618
1.3	3	1751	15.87	0.907
1.4	3	1773	33.66	1.899

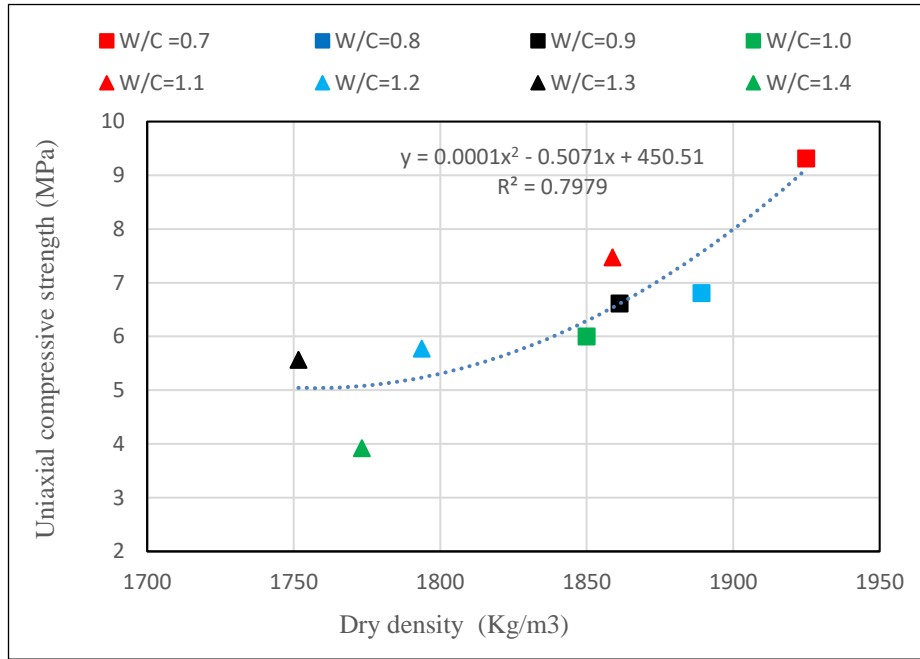


Figure 6. Simple regression analysis between UCS and dry density of soilcrete specimens.

where q_u in MPa and ρ_d in kg/m³. It is clear from **Table 8** and **Fig. 6** that when the water-cement ratio increases, the dry density decreases; as a result, the UCS decreases where maximum dry density was 1924 kg/m³ for W/C ratio of 0.7 and minimum dry density was 1751 kg/m³ for W/C ratio of 1.3. The increase in the W/C ratio leads to an increase in the volume of voids and consequently the reduction of dry density. The average dry density of all W/C ratios equal to 1837 kg/m³ might be adopted to a W/C ratio of 1.0. The minimum dry unit weight of 1832 kg/m³ is reasonable in coarse-grained soils improved by using the jet-grouting method was found in the literature, e.g. (Xanthakos, Abramson and Bruce, 1994).

4. CONCLUSION

In the present study, an investigation into the mechanical and physical properties of soilcrete material produced in the laboratory to simulate the jet grouting process has been performed. Where 96 specimens of the soilcrete material were prepared with a W/C ratio varying from 0.7 to 1.4 because this range of water-cement ratios represents the range usually adopted in literature and recommended by researchers. The results indicate the following findings:

- 1- The water-cement ratio is one of the critical parameters that affect the strength of jet grouted materials. The water-cement ratio should be appropriately selected for a specific project based on the design strength required.
- 2- The relationship between the water-cement ratio and the UCS was negative linear, where the larger the W/C ratio, the greater the drop in compressive strength of soilcrete samples at 28-day. The average UCS are 9.31 and 3.92 MPa for (W/C) ratio of 0.7 and 1.4, respectively. A cement content of a W/C ratio of 0.7 is greater than that of the W/C ratio of 1.4. As a result, soilcrete samples strength of W/C ratio of 0.7 is higher about 237% of W/C ratio of 1.4.



- 3- Concerning the mechanical properties development, a logarithmic relation between uniaxial compressive strength and time is proposed until 56 days of curing.
- 4- The relationship between the UCS and tangent modulus (E_{tg50}) was positive linear, where the E_{tg50} increases with increases in the UCS. The ratio between the E_{tg50} to the maximum UCS varies from 113 to 175. The tangent modulus values are higher for the low water-cement ratio and decrease significantly when the W/C ratio increases.
- 5- The dry density is one of the significant physical properties of jet grouted materials and consider a good indication of soilcrete material quality. In this study, a polynomial relationship was found between the dry density and the UCS at 28-day of curing, where the dry density decreases with increases in W/C ratio. As a result, the UCS decreases, where maximum dry density was 1924 kg/m³ for W/C ratio of 0.7 and minimum dry density was 1751 kg/m³ for W/C ratio of 1.3. The increase in the W/C ratio leads to an increase in the volume of voids and consequently the reduction of dry density.
- 6- Although the laboratory study is itself insufficient to fully reproduce the mechanical and physical properties of in-situ soil improved by the jet grouting method, still, the data obtained from the laboratory study can be used to make preliminary estimates of the water-cement ratio and cement dosage needed to achieve the desired mixture strength for the projects will be constructed on similar soils.

NOMENCLATURE

E_{tg50} = tangent modulus of deformation, MPa.

q_u = uniaxial compressive strength, MPa.

t = time of curing, days.

W/C = water to cement ratio, dimensionless.

ρ_d = dry density, kg/m³.

a, b = empirical parameters, dimensionless.

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