Journal of African Earth Sciences 116 (2016) 190–197

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Experimental studies on the physico-mechanical properties of jet-grout columns in sandy and silty soils

Muge K. Akin

Abdullah Gül University, Department of Civil Engineering, Kayseri, Turkey

ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form
5 January 2016
Accepted 7 January 2016
Available online 8 January 2016

Keywords:
Jet-grout
Soil stabilization
Uniaxial compressive strength (UCS)
P-wave velocity
Soilcrete
Physico-mechanical properties

ABSTRACT

The term of ground improvement states to the modification of the engineering properties of soils. Jet-grouting is one of the grouting methods among various ground improvement techniques. During jet-grouting, different textures of columns can be obtained depending on the characteristics of surrounding subsoil as well as the adopted jet-grouting system for each site is variable. In addition to textural properties, strength and index parameters of jet-grout columns are highly affected by the adjacent soil. In this study, the physical and mechanical properties of jet-grout columns constructed at two different sites in silty and sandy soil conditions were determined by laboratory tests. A number of statistical relationships between physical and mechanical properties of soilcrete were established in this study in order to investigate the dependency of numerous variables. The relationship between q_u and γ_d is more reliable for sandy soilcrete than that of silty columns considering the determination coefficients. Positive linear relationships between Vp and γ_d with significantly high determination coefficients were obtained for the jet-grout columns in silt and sand. The regression analyses indicate that the P-wave velocity is a very dominant parameter for the estimation of physical and mechanical properties of jet-grout columns and should be involved during the quality control of soilcrete material despite the intensive use of uniaxial compressive strength test. Besides, it is concluded that the dry unit weight of jet-grout column is a good indicator of the efficiency of employed operational parameters during jet-grouting.

1. Introduction

A number of soil improvement methods have been developed in engineering practice to overcome various geotechnical problems. Jet-grouting or high pressure grouting is remarkably highlighted primarily for both its efficiency and cost-effectiveness. The basic concept of jet-grouting is to inject controlled quantities of cement grout through very small diameter nozzles on a rotating drill rod with significantly high pressures (300–600 bar). The injected water–cement grout creates cemented geometries of so-called soilcrete with improved physico-mechanical properties. The range of jet-grout column diameter may vary between 40 and 140 cm depending on the soil type and employed operational parameters (Lunardi, 1997). Furthermore, the physical and mechanical properties of the high-modulus columns are considerably variable due to two variables namely the effectiveness of replacing soil with cement and the composition of the foundation soil (Croce et al., 2014). Besides, the water–cement ratio is the major factor controlling the physico-mechanical parameters of the soilcrete. Although a water/cement ratio of 1.0 is mostly considered in jet-grout applications, a lower water/cement ratio should be preferred in which there is substantial groundwater flow as well as in order to get columns with high elasticity modulus (Lunardi, 1997; Kashevarova et al., 2013; Croce et al., 2014; Akan et al., 2015).

Several studies concerning the physico-mechanical properties of the jet-grout columns constructed in different soil types were conducted (Xanthakos et al., 1994; Croce and Flora, 1998; Van der Stoel, 2001; Fang et al., 2004; Correia et al., 2009; Bzowka, 2012; Lambert et al., 2012; Akan et al., 2015). However, the significance of the empirical correlations are reasonably crucial since an unknown parameter can be estimated using the identified factor (Correia et al., 2009). In addition, the behavior of soil-cement mixtures can be well-understood and the quality control process can be improved by empirical relations of various parameters (Tinoco et al., 2011). In this study, physico-mechanical properties of jet-grouted material were investigated by means of laboratory testing on core samples drilled from jet-grout columns constructed

E-mail address: muge.akin@agu.edu.tr.

http://dx.doi.org/10.1016/j.jafrearsci.2016.01.011
1464-343X/

in sandy and silty soils. Accordingly, unit weight, porosity, P wave velocity in dry and saturated conditions and uniaxial compressive strength of sandy and silty soilcrete material were distinguished respectively. Additionally, several statistical relations were developed to reveal the relationship between physical and mechanical properties of high modulus columns. The results were also compared with the existing formulations. The jet-grout core samples tested in this study were extracted from in-situ columns erected in foundation soils during soil stabilization applications.

2. Physico-mechanical properties of jet-grouted material in silty and sandy deposits

2.1. Unit weight of jet-grout columns

Different textures of soilcrete obtained during jet-grouting due to the fact that the characteristics of surrounding subsoil and the adopted jet-grouting system for the specific site are variable. Moreover, the texture of jet-grout column is typically heterogeneous involving coarse soil particles or untreated fragments (Croce et al., 2014). Two different jet-grouted materials in this study also reveal inhomogeneous textural properties as shown in Fig. 1.

The NX-size (54.7 mm) jet-grout cores were collected from columns of 0.8 m in diameter by coring with a drilling rig from two different construction sites. The operational parameters employed during jet-grouting are very similar at both sites and summarized in Table 1. Additionally, the classification and physical properties of the foundation soils at two specific sites are presented in Table 2. And also it should be noted that the groundwater level at the sampling sites is shallow being around 3–5 m.

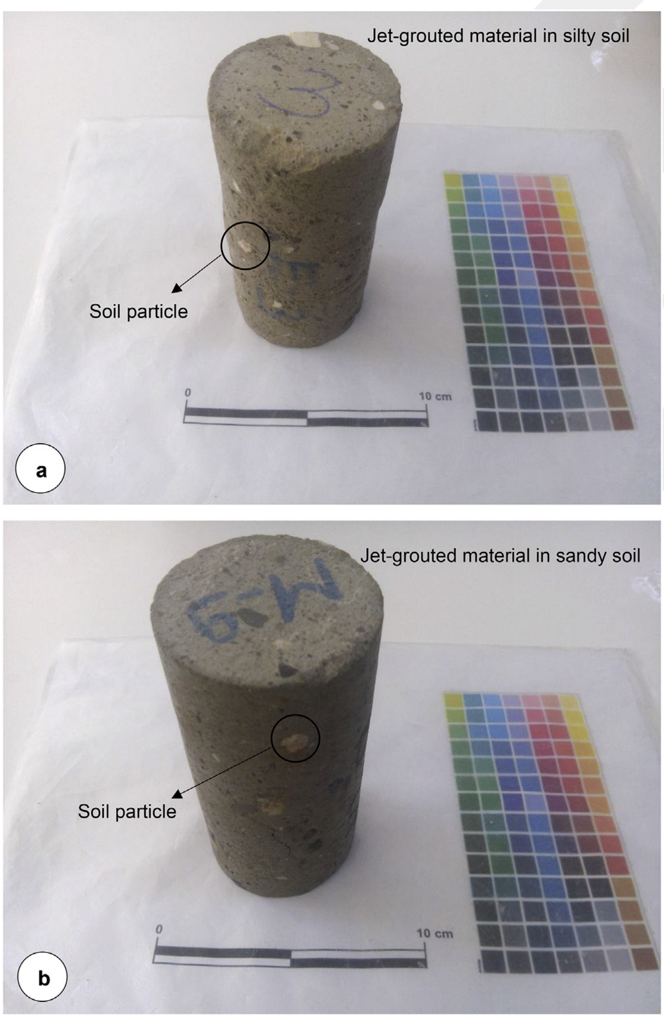

Fig. 1. Close-up views of test materials: jet-grouted materials in silty soil (a) and sandy soil (b).

Although the mechanical properties of the jet-grouted materials have been studied in detail, comparatively little attention has been paid to the unit weight of soilcrete in the literature. However, the unit weight of the jet-grout columns is very significant for the geotechnical designs such as sealing plugs or earth-retaining walls where the self-weight of the jet-grout column plays a substantial role (Croce and Modoni, 2007; Rollins et al., 2008; Eramo et al., 2012; Croce et al., 2014). Moreover, the unit weight of the column should be assessed as an indicator of the efficiency of the employed operational parameters (Croce et al., 2014). The average dry unit weight values for various soil types presented in the literature are summarized in Table 3.

A gradual increase of dry unit weight with the escalating grain size is obvious in Table 3 except pyroclastic sand. In general, the dry unit weight of columns erected in fine grained soils (clay, silt) varies between 16.0 and 17.5 kN/m^3, whereas a minimum dry unit weight of 18 kN/m^3 is reasonable in coarse grained soils. However, it should be kept in mind that different threshold values are also presented in the literature for various soils (Croce et al., 1994; Croce and Flora, 1998; Fang et al., 2004). Furthermore, despite the effect of operational parameters applied during high pressure grouting, it is reported in the literature that the jet-grouted material reveals similar unit weight values with the surrounding soil (Croce et al., 2014).

Variation of dry and saturated unit weight values of jet grout columns in sandy and silty soils is presented in Table 4. As a particular note, all jet-grout core specimens tested in this study are older than 60 days and completed their curing process. As seen in Table 4, the average dry unit weight of jet-grout columns in silty (ML) and sandy soils (SM-SW) are 15.86 and 16.95 kN/m^3, respectively. Slightly lower values were obtained for both sample groups than the literature when compared to the results presented in Table 3. However, the average dry unit weight of soilcrete in sand is still higher than that of silt. A maximum of 19.05 kN/m^3 dry unit weight was found for silty soils and it can be as low as 12.40 kN/m^3 as well. Oppositely, sandy soils reveal very similar minimum and maximum threshold values to silty layers which can be attributed to the silt content of sandy deposits. Besides dry unit weight, saturated unit weight may sometimes be essential when jet-grout columns are constructed under groundwater as sealing plugs. The same trend with the dry unit weight was obtained for saturated unit weight of tested core specimens. The average saturated unit weight of columns in silty and sandy soils are found to be 19.06 and 19.93 kN/m^3, which are noticeably higher than the average dry unit weight values.

Table 1
Several operational parameters used for jet-gouting at two sampling sites.

	Site 1 (silty soil)	Site 2 (sandy soil)
Jet-grout column diameter	0.8 m	0.8 m
Jet-grout method	Jet-1 (single fluid)	Jet-1 (single fluid)
Water/cement ratio	1.0	1.0
Injection pressure	450 bar	400 bar
Dosage	450 kg/m^3	430 kg/m^3
Uplift speed	7.5–10 s/4 cm	7–8 s/5 cm
Nozzle diameter	2.2 mm	2.2 mm

Table 2
Soil classification and average physical properties of the foundation soils where jet-grout cloumns were constructed.

	Site 1	Site 2
Soil classification (USCS)	ML	SW-SM
Plasticity Index (%)	5.1	NP
Natural unit weight (kN/m^3)	16.3	17.1
Water content (%)	27.3	12.6
Fine content (%)	52.1	13.9

The permeability coefficient (k) of soilcrete varies between 10^{-7} and 10^{-10} cm/s as stated by Bell (1993) and Croce et al. (2014). Nevertheless, the overall permeability of jet-grouted columns may be much higher than those of specimens in the laboratory (Croce and Modoni, 2007). Therefore, an overlapping jet-grout design is implemented under dam-type structure in practice and an effective overlapping of the jet-columns is the most crucial requirement to prevent water flow through soilcrete. Otherwise, leakage with very high seepage rates and eventually piping may occur as a result of high hydraulic gradients (Croce et al., 2014). Thus, great attention should be paid for the performance of jet-grout columns for water sealing purposes under water-retaining structures particularly in coarse grained soils.

Table 3
Average dry unit weight of soilcrete for different soil types (after Croce et al., 2014).

Soil type	Dry unit weight (kN/m^3)	Variation coefficient (CV)	Reference
Clay	16.25	0.05	Botto and Capolupo (1989)
Silt	16.00	0.08	Eramo et al. (2012)
Silty clay	16.81	0.04	Xanthakos et al. (1994)
Silty sand	18.32	0.04	Xanthakos et al. (1994)
Sandy silt	17.89	0.08	Croce et al. (2004)
Pyroclastic sand	13.89	0.07	Croce and Flora (1998)
Gravel	22.80	0.04	Mongiovi et al. (1991)

Table 4
Dry and saturated unit weight values of jet grout columns in sandy and silty soils determined in this study.

Soil type	# of samples	Dry unit weight (kN/m^3)				Saturated unit weight (kN/m^3)			
		Min.	Max.	Average	Std. Dev.	Min.	Max.	Average	Std. Dev.
Silt	42	12.40	19.05	15.86	1.76	16.65	21.28	19.06	1.18
Sand	16	13.00	18.80	16.95	2.30	17.02	21.08	19.93	1.65

2.2. *Porosity of jet-grout columns*

No data have been reported about the porosity properties of jet-grout columns in the literature. Nevertheless, in addition to sealing plugs in engineering projects, jet-grouting can also be used as water flow barriers like grout curtains under dams or small-scale water-retaining structures (Burke, 2007). Therefore, porosity of jet-grout columns is of great importance for the permeability assessment. The apparent porosity values of jet-grout columns in silty and sandy soils are depicted in Table 5. Porosity of soilcrete in sandy and silty soils are quite similar due to the fact that the tested specimens for sandy deposits contain considerable amount of silt size grains. The average porosity values of columns in silt and sand are 27.27% and 24.70%, respectively. Although tested specimens were extracted from columns constructed by single-fluid system, the results reveal a porous media. However, it is assumed that the porosity of jet-grouted material is lower than that of original soil when the range of porosity values for silts and sands in the literature are considered. The porosity of silt commonly varies between 35% and 50% while the porosity of sand fluctuates between 25% and 50% (Freeze and Cherry, 1979).

As mentioned before, the jet-grout columns are used as sealing barriers or cut-off walls under water-retaining structures. Despite high porosities of soilcrete in sandy and silty soils, the permeability of jet-grouted material is reported to be very low in the literature.

Table 5
Apparent porosity of jet-grout columns in silty and sandy soils.

Soil type	# of samples	Porosity (%)			
		Min.	Max.	Average	Std. Dev.
Silt	42	17.46	35.37	27.27	5.19
Sand	10	19.24	37.48	24.70	7.66

2.3. *P-wave velocity of jet-grout columns*

Similar to porosity, very few laboratory testing was performed on jet-grout cores to determine the velocity of sonic waves in the literature (Fang et al., 1994). However, sonic velocity may be a good indicator of the quality of jet-grout columns and the efficiency of the jet-grout operating parameters. Accordingly, P-wave velocity of jet-grout cores was determined for both dry and saturated conditions using a Pundit Lab ultrasonic instrument in the laboratory. The results of P-wave velocity measurements are summarized in Table 6.

Although the minimum and maximum values of P-wave velocity both in dry and saturated conditions are quite similar, the average values slightly diverse for different soil types as seen in Table 6. The average P-wave velocity of jet-grout cores of silty and sandy soils in dry state are around 2965 and 3339 m/s. Moreover, the P-wave velocities very slightly rise in saturated soils.

The obtained P-wave velocity (V_p) of jet-grout columns for silty and sandy soils indicates low-velocity rock (V_p between 2500 and 3500 m/s) in accordance with Anon (1979). Conversely, the P-wave velocity of soilcrete is considerably higher than that of loose sand (1800 m/s) reported by Clark (1966). As a result, it can be stated that the soilcrete material reveals intermediate properties between soil and rock regarding P-wave velocity.

2.4. *Strength of jet-grout columns*

Strength is one of the major parameters of jet-grout columns

Table 6
P-wave velocity of jet-grout cores for silty and sandy soils.

Soil type	# of samples	P-wave velocity (m/s) - dry				P-wave velocity (m/s) - saturated			
		Min.	Max.	Average	Std. Dev.	Min.	Max.	Average	Std. Dev.
Silt	42	2395	3765	2965.29	376.76	2508	3682	3014.98	363.29
Sand	10	2354	3739	3338.50	570.54	2648	3683	3370.50	430.20

very much investigated in the literature (Correia et al., 2009; Laefar et al., 2009; Nikbakhtan and Osanloo, 2009; Gladkov et al., 2011; Tinoco et al., 2011; Akan et al., 2015). There is a scientific consensus on the variability of strength of jet-grout columns because of heterogeneity of soil and effectiveness of operating parameters considered during jet-injection. The strength of soilcerete is mostly expressed with respect to uniaxial compressive strength (q_u) of jet-grout column. The uniaxial strength of jet-grout columns in fine grained soils roughly varies between 1.5 and 10 MPa, while strength of soilcrete in coarse grained soils may range between 10 and 30 MPa in accordance with Xanthakos et al. (1994). As a particular note, while the initial strength of soilcrete is strongly time-dependent, the final strength of jet-grout column is achieved after curing for a duration of almost a month. A couple of graphs illustrating the variation of uniaxial compressive strength for different soil types according to time and cement ratio are depicted in Fig. 2. As seen in graphs in Fig. 2, the strength of soilcrete escalates with the increasing particle size.

Within the context of this study, a number of uniaxial compressive strength tests were performed on jet-grout cores having a length to diameter ratio of 2:1 to reveal the strength of soilcrete consisting of silty and sandy soils. The variation of uniaxial compressive strength (q_u) of jet-grout columns are shown in Table 7. The minimum and maximum q_u of jet-grout cores from silty soils are 6.5 and 34.4 MPa, respectively. The average q_u for the same specimens was found to be 16.1 MPa. Furthermore, the average q_u of soilcrete from sandy soils is 25.1 MPa, whilst the minimum and maximum values are 10.9 and 37.7 MPa. The average q_u values obviously reveal that the jet-grout cores of sandy soils exhibit higher strength than that of cores in silty soils.

The variation of uniaxial compressive strength of jet-grout cores versus cement consumption for silty and sandy soils is depicted in Fig. 3. As reported in Table 1, the dosage used for the execution of jet-grout columns in silty soils is 450 kg/m^3 and a volume of 430 kg/m^3 cement per volume was added into the grout in sandy deposits at the study area. The scattering of the uniaxial compressive strength of jet-grout cores obtained from sandy soils is mostly consistent (except a couple of specimens) with the threshold lines of graph presented in Croce et al. (2014). However, the strength range of cores from silty layers is rather large and does not exactly fit the limit boundaries. Although most samples distribute in silt and silty sand group, a considerable amount of cores scatter in sands and gravels and even in silty clay zone. Consequently, it can be concluded that there are some other additional factors such as jet-injection type (Van der Stoel, 2001), cement–water ratio and operational parameters controlling the strength of jet-grout columns and cement consumption. Moreover, depth may also positively affect the strength of columns (Arroyo et al., 2007 in Croce et al., 2014).

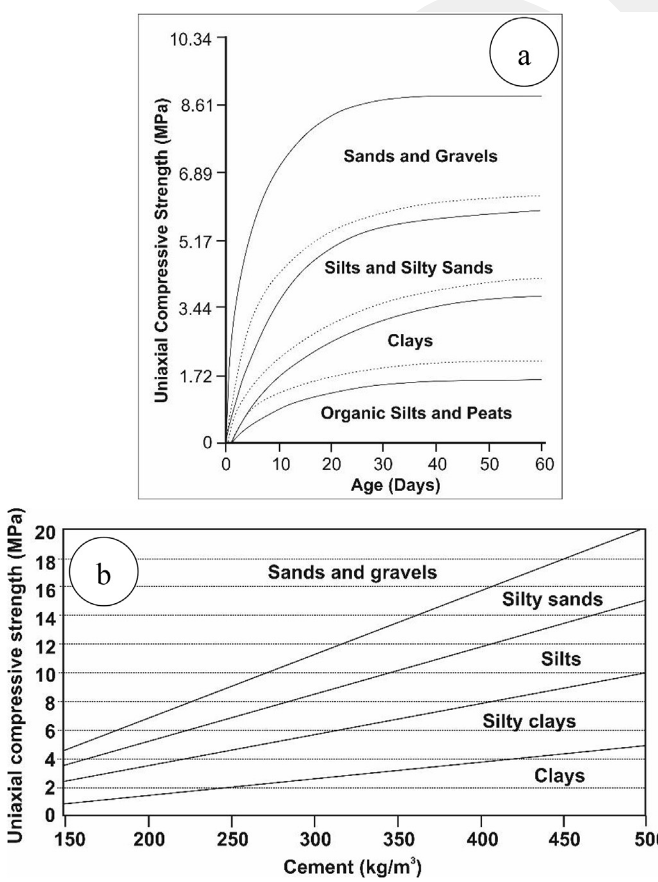

Fig. 2. Variation of uniaxial compressive strength for different soil types versus time (a) (modified after Hussin, 2014) and cement ratio (b) (modified after Croce et al., 2014).

3. Statistical relationships between physical and mechanical parameters of jet-grout columns

Correlations between two variables may be of use if the value of one variable is easier to determine than the other in statistics and accordingly, the rate of other parameter can be assessed. Therefore, some statistical relationships between physical and mechanical properties of soilcrete were established in this study in order to investigate the dependency of various variables. In addition, revealed correlations may also lead to estimate strength parameters during the quality control of jet-grout columns.

In the literature, strength and unit weight of soilcrete are much more investigated than other parameters. However, statistical relationships even between these two parameters are very limited. One of the most comprehensive studies regarding the relationship between uniaxial compressive strength and dry unit weight of jet-grout columns in different soil groups is presented in Croce et al.

Table 7
Uniaxial compressive strength of jet-grout columns in silty and sandy soils.

Soil type	# of samples	Uniaxial compressive strength (q_u) (MPa)			
		Min.	Max.	Average	Std. Dev.
Silt	29	6.5	34.4	16.1	6.9
Sand	11	10.9	37.7	25.1	8.5

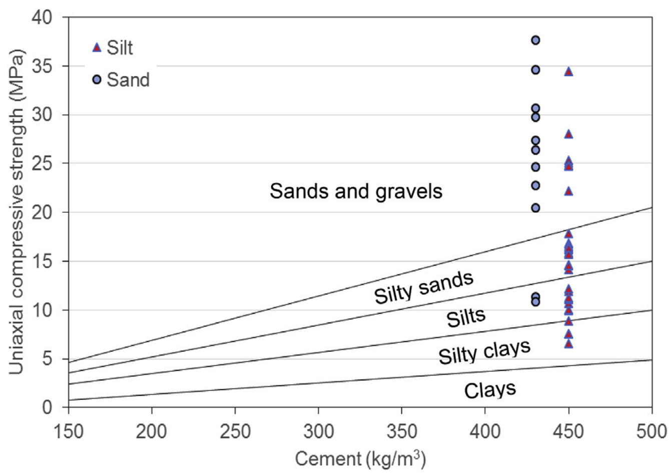

Fig. 3. Variation of uniaxial compressive strength versus cement consumption for jet-grout cores of silty and sandy soils in this study.

(2014). The q_u-γ_d graph showing the results of several researches as well as the specimens of this study is illustrated in Fig. 4.

A widely scattered relationship between q_u and γ_d pairs for jet-grout columns constructed in different soils is noticeable in Fig. 4. It is clear that the soilcrete consisting of gravelly soils is stronger than other soils according to the study of Mongiovi et al. (1991). The q_u of gravelly jet-grout columns mostly varies between 10 and 50 MPa, whereas the γ_d of same specimens is higher than 20 kN/m^3. Furthermore, a wide-ranging scatter of q_u and γ_d pairs was reported by Croce et al. (1994) for the soilcrete in silty sand. The q_u of jet-grout columns in silty sand may be as low as 0.5 MPa and a maximum strength of 20 MPa is obvious for the γ_d values ranging between 15 and 20 kN/m^3 Croce and Flora (1998) described a rather different relationship for silty sands. Accordingly, the q_u and γ_d values of columns in silty sand fluctuates between 5 and 15 MPa, 12 and 16 kN/m^3, respectively. Fang et al. (2004) mentioned a very similar relationship for silty and sandy soilcrete with that of Croce and Flora (1998). Hence, the q_u of sandy and silty jet-grout column may be as high as 10 MPa and the γ_d values range between 12 and 16 kN/m^3 with respect to Fang et al. (2004). The q_u and γ_d pairs of silty soilcrete obtained in this study slightly overlap with the results of Croce and Flora (1998). Nonetheless, the data do not match with the outcomes presented in Croce et al. (1994). In general, the q_u of silty soilcrete in this study is considerably higher than those of previous studies on silt and silty sand. Significantly higher strength and unit weight values than other researches were determined for sandy jet-grout columns except a couple of q_u and γ_d pairs. Despite lower unit weight, the strength of sandy columns is as high as gravels indicated in Mongiovi et al. (1991). It can be briefly stated that the strength and unit weight of jet-grout columns generally rise with the increasing particle size of adjacent soil strata where the columns are constructed.

Simple regression analyses were carried out to determine the degree of relationship between several physical and mechanical properties of the jet-grout columns in silty and sandy deposits. Regression analysis is a statistical technique to predict a dependent variable considering change in one or more independent variables. Regression analysis can also be used to establish a predictive model amongst relevant material properties (Mishra and Basu, 2013). Simple regression analysis between q_u and γ_d for the soilcrete in silt and sand is presented in Fig. 5. An exponential relationship is evident for q_u and γ_d pairs of silty and sandy soilcrete. The determination coefficients (R^2) were found to be 0.86 and 0.5 for sand and silt, respectively. It can be specified that the relationship between q_u and γ_d is more reliable for sandy soilcrete than that of silty columns considering the determination coefficients.

No significant relationship was achieved for q_u and porosity pairs for sand (Fig. 6). On the other hand, a linear relationship with a determination coefficient of 0.55 is apparent for silty soilcrete. However, it is apparent that the relationship between q_u and porosity is less meaningful than q_u and γ_d for jet-grout columns.

P-wave velocity (Vp) is frequently used to predict the uniaxial compressive strength of intact rock material in rock mechanics. However, there is very limited application of ultrasonic velocity in the quality control of jet-grout columns. Despite its ignorance, P-wave velocity can be a good tool to estimate the q_u of soilcrete material. Therefore, statistical relationship between q_u and Vp was also investigated in the content of this study. Simple regression analysis between q_u and Vp (in dry conditions) for the soilcrete in silt and sand is presented in Fig. 7. A linear statistical relationship with a determination coefficient of 0.61 can be seen for silty soilcrete in Fig. 7, whereas the relationship for sand is quite insignificant. Though, it is believed that more significant relationships for sandy material can be retrieved with additional data.

The relationship between P-wave velocity and a couple of physical properties (unit weight and porosity) was investigated in

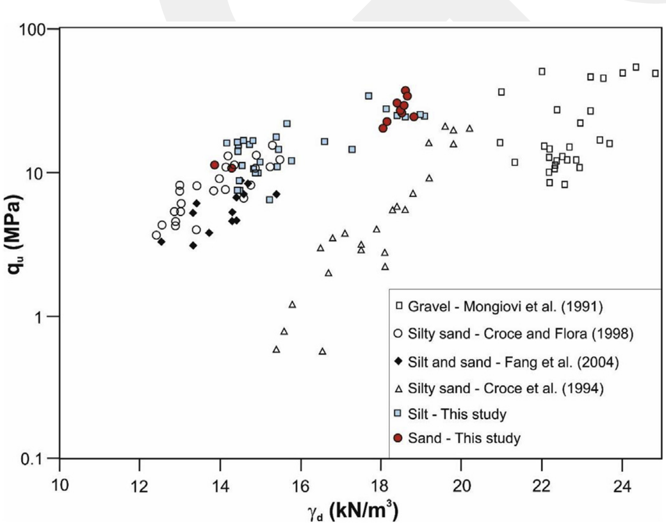

Fig. 4. Relationship between uniaxial compressive strength (q_u) and dry unit weight (γ_d) of jet-grout columns in different soil types (modified after Croce et al., 2014).

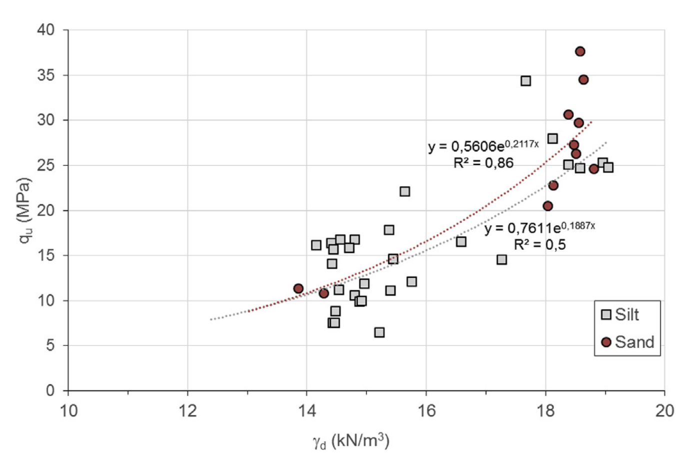

Fig. 5. Simple regression analysis between q_u and γ_d for the jet-grout columns in silt and sand.

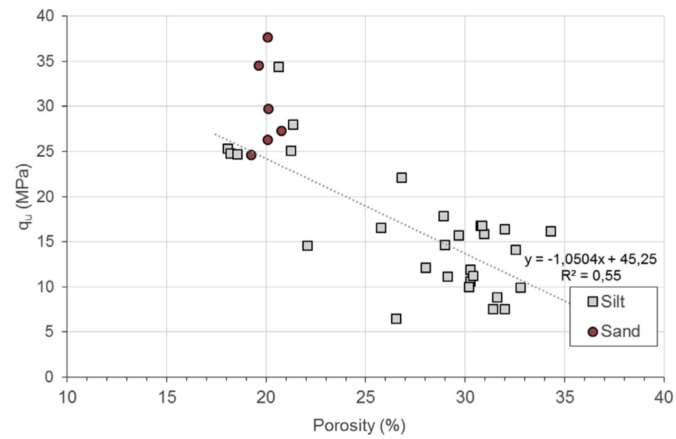

Fig. 6. Simple regression analysis between q_u and porosity for the jet-grout columns in silt and sand.

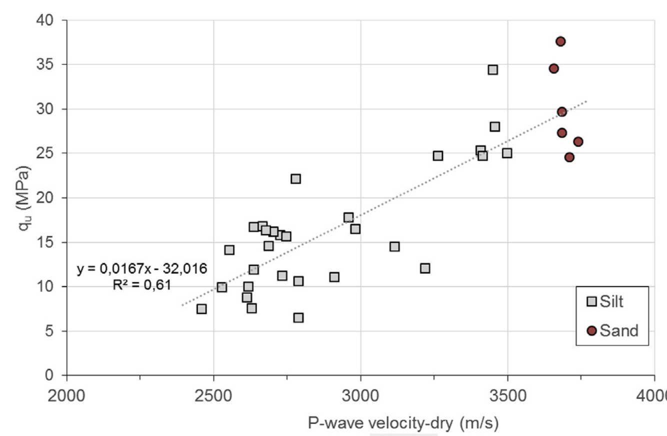

Fig. 7. Simple regression analysis between q_u and P-wave velocity (Vp) for the jet-grout columns in silt and sand.

this study as well. Positive linear relationships between Vp and γ_d with very high determination coefficients (0.81 and 0.94) are visible for the jet-grout columns in silt and sand as shown in Fig. 8. Similarly, very strong negative linear relationships between Vp and porosity were retrieved after regression analysis (Fig. 9). A decrease in ultrasonic velocity is very significant with the increasing

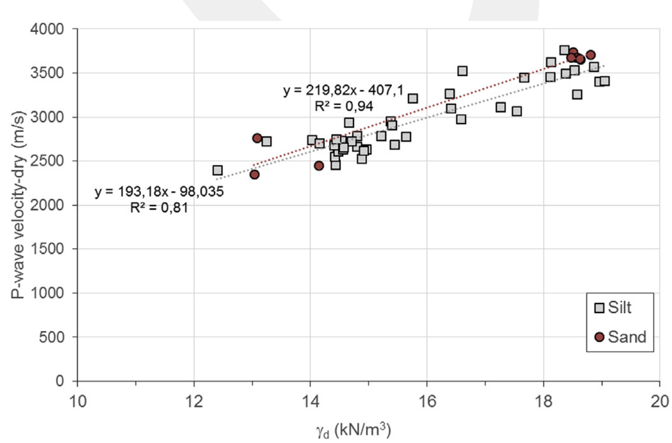

Fig. 8. Simple regression analysis between P-wave velocity (Vp) and γ_d for the jet-grout columns in silt and sand.

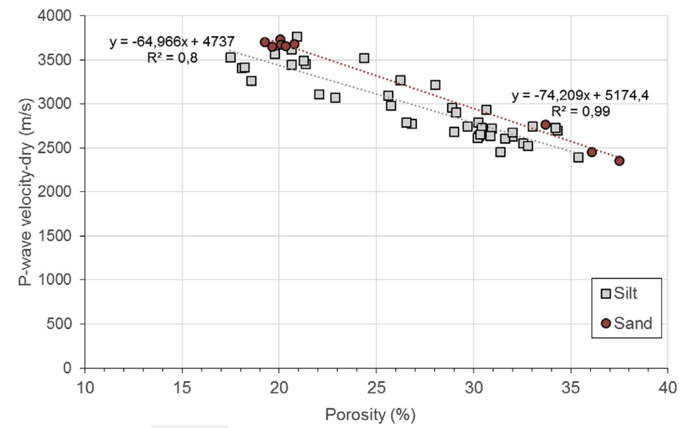

Fig. 9. Simple regression analysis between P-wave velocity (Vp) and porosity for the jet-grout columns in silt and sand.

porosity. These regression analyses indicate that P-wave velocity can be successfully used for the estimation of physical and mechanical properties of jet-grout columns. Moreover, the significance of relationships can be improved with additional studies on different soilcrete materials.

Statistical relationship between porosity and unit weight of jet-grout columns in silt and sand is depicted in Fig. 10. The determination coefficients are very high (0.96 and 0.97) indicating a meaningful linear relation between these two index properties. Therefore, the porosity of a jet-grout column can be estimated regarding the unit weight value, which may be quite useful for the design of impermeable barriers in hydraulic works. A summary of derived equations using simple regression analyses for different physico-mechanical parameters of silty and sandy soilcrete is listed in Table 8.

In addition to simple regression analyses, multiple regression analyses were also carried out to investigate the dependency of multiple variables. In statistics, multiple regression analyses are employed to derive a predictive model amongst relevant variables. Accordingly, predictive equations were established for silty and sandy jet-grout columns amongst uniaxial compressive strength (q_u), dry unit weight (γ_d) and P-wave velocity in dry conditions (Vp). Thus, uniaxial compressive strength of a jet-grout column in silt and sand can be estimated using the following equations, respectively. Moreover, the determination coefficients of the

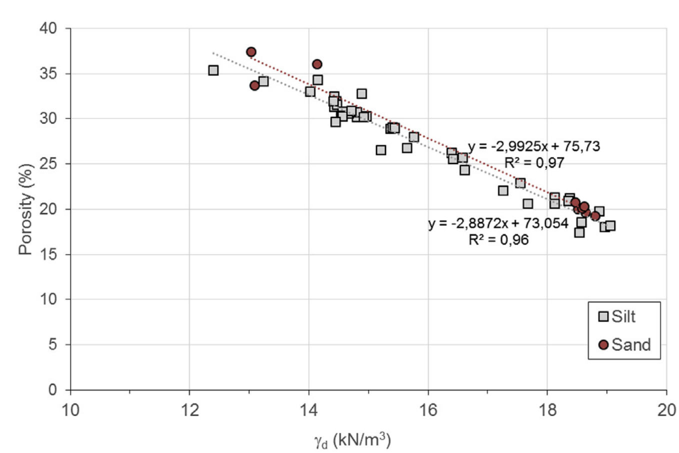

Fig. 10. Simple regression analysis between porosity and γ_d for the jet-grout columns in silt and sand.

Table 8
Summary of statistical relationships between physical and mechanical properties of jet-grout columns in silty and sandy soils.

Variables	Soil type	Equation	Determination coefficient (R^2)
q_u - γ_d	Sand	$q_u = 0.56.e^{0.21.\gamma d}$	0.86
q_u - γ_d	Silt	$q_u = 0.76.e^{0.19.\gamma d}$	0.50
q_u - n	Silt	$q_u = -1.05.n + 45.25$	0.55
q_u - Vp	Silt	$q_u = 0.017.Vp\text{-}32.02$	0.61
Vp - γ_d	Silt	$Vp = 193.18.\gamma_d\text{-}98.04$	0.81
Vp - γ_d	Sand	$Vp = 219.82.\gamma_d\text{-}407.1$	0.94
Vp - n	Silt	$Vp = -64.97.n + 4737$	0.80
Vp - n	Sand	$Vp = -74.21.n + 5174.4$	0.99
n - γ_d	Silt	$n = -2.89.\gamma_d + 73.05$	0.96
n - γ_d	Sand	$n = -2.99.\gamma_d + 75.73$	0.97

q_u: Uniaxial compressive strength (MPa).
γ_d: Dry unit weight (kN/m^3).
n: Porosity (%).
Vp: P-wave velocity-dry (m/s).

relations are 0.63 and 0.50 which are supposed to be slightly higher than those of silty samples in simple regression analyses using γ_d. However, the determination coefficient of multiple regression is very low for sands considering the relation between q_u and γ_d.

$$q_u = -35,18 + (1,18.\gamma_d) + (0,011.Vp)(\text{for silt})$$

$$q_u = 614,06 - (7,10.\gamma_d) - (0,122.Vp)(\text{for sand})$$

Plots of estimated q_u against measured q_u from simple and multiple regression analyses were prepared to illustrate the prediction capability of derived equations (Fig. 11). Dry unit weight and P-wave velocity were employed to calculate the predicted uniaxial compressive strength in Fig. 11a and 11b. It should be noted that no data are shown for sands in q_u and Vp relation (Fig. 11b) as there is no significant relationship for sands. In addition, the predicted q_u values were determined using γ_d and Vp values with respect to equations derived from multiple regression analyses in Fig. 11c. The accuracy of the predicted value is represented by the distance between the data point and 1:1 diagonal line and a data point just on this line indicates a precise estimation. As seen in Fig. 11a–c, although they distribute in the reasonable area between 1:2 and 2:1 diagonal lines except one sample, data points are scattered and do not exactly fit the 1:1 line both for simple and multiple regression analyses. This suggests that great attention should be considered during the prediction of q_u by using various physico-mechanical parameters.

On the contrary, a significantly better fit was achieved for the P-wave velocity (in dry condition) prediction on the basis of dry unit weight using related equations in Table 8 both for silty and sandy soilcrete specimens (Fig. 12). This result supports that the P-wave velocity of jet-grout column may be a good indicator during the quality control phase of jet-grouting applications. Additionally, P-wave velocity can be simply estimated by various index parameters.

4. Conclusions

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 jet-grout columns are very limited. The experimental studies carried out on silty and sandy jet-grout columns in this research indicate that the physico-mechanical properties of soilcrete material are strongly affected by the adjacent soil properties during jet-grouting. Moreover, it should be recognized that besides adjacent soil properties, the operating parameters such as injection pressure, rotating and withdrawal (lifting) rate have also impact on the physico-mechanical parameters of the jet-grouted material. Although uniaxial compressive strength of jet-grout columns can be estimated to some extent by various index parameters, high standard errors should be considered in terms of the established

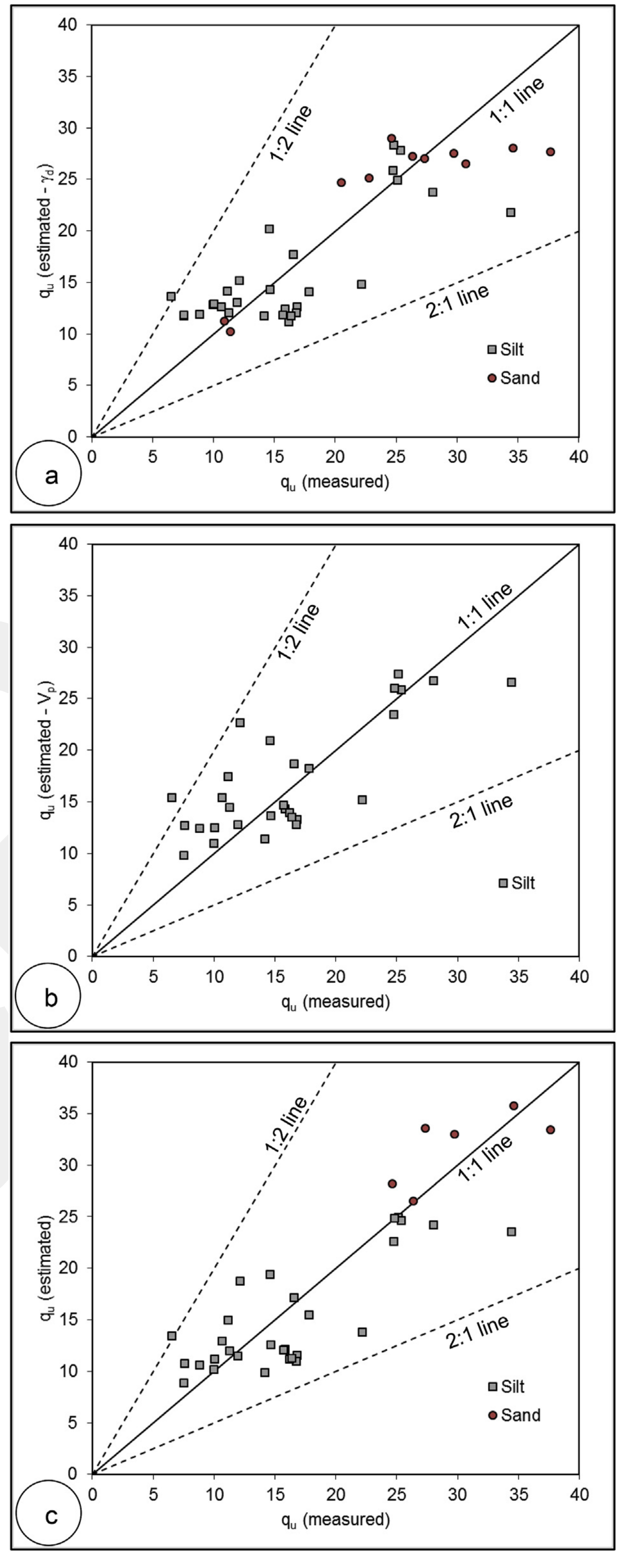

Fig. 11. Plots of estimated q_u against measured q_u from simple (a, b) and multiple regression analyses (c).

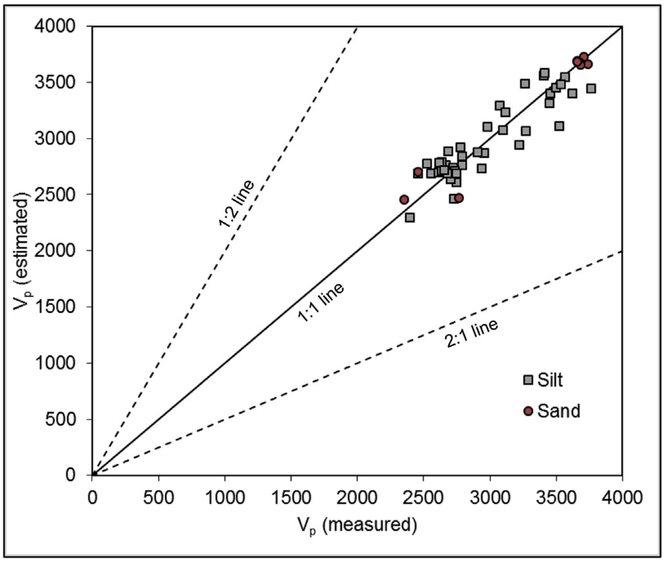

Fig. 12. Plots of estimated Vp against measured Vp from simple regression analyses.

statistical relations in this study. Conversely, the use of P-wave velocity is strongly recommended for the quality assessment of jet-grout columns as better results were derived after statistical analyses between the ultrasonic velocity rates of soilcrete material and other index properties. Besides, P-wave velocity can be easily measured on jet-grout columns in laboratory conditions and it can be easily estimated by dry unit weight or porosity as well.

Acknowledgments

Sesil Karatekin is greatly acknowledged for her efforts during the laboratory testing of jet-grout columns. Dr. Samad Joshani-Shirvan is also acknowledged for his comments on the use of language. The author would also like to express her thanks to the anonymous reviewers of this journal for their constructive comments and suggestions on the manuscript.

References

Akan, R., Keskin, S.N., Uzundurukan, S., 2015. 2015. Multiple regression model for the prediction of unconfined compressive strength of jet grout columns. Procedia Earth Planet. Sci. 15, 299–303. http://dx.doi.org/10.1016/j.proeps.2015.08.072.
ANON, 1979. Classification of rocks and soils for engineering geological mapping. Part 1: rock and soil materials. Bull. Int. Assoc. Eng. Geol. IAEG Bull. 19, 364–371.
Arroyo, M., Gens, A., Alonso, E., Modoni, G., Croce, P., 2007. Informes Sobre Tratamientos de Jet Grouting. ADIF LAV Madrid-Barcelona-Francia, Tramo Torrasa-Sants. Report of the Universidad Politecnicha de Catalunya, p. 110 ([in Spanish]).
Bell, A.L., 1993. Jet grouting. In: Moseley, M.P. (Ed.), Ground Improvement. Blackie, Boca Raton, FL, pp. 149–174.
Botto, G., Capolupo, F., 1989. Trattamenti colonnari di gettiniezione normale (jet grout monofluido) in formazioni argillose per le fondazioni della centrale gas dell'Agip di Falconara: ricerca della tecnologia ottimale a mezzo di campo prove. In: Proceedings of the 12th Nationali Geotechnical Conference, Taormina, Italy, April 26–28, 1989. Associazione Geotecnica Italiana, pp. 47–53 ([in Italian]).
Burke, G.K., 2007. Vertical and horizontal groundwater barriers using jet-grout panels and columns (GSP 168). In: Proceedings of Geo-Institute's Geo-Denver: New Peaks in Geotechnics, Denver, CO, February 18–21, 2007, p. 10.
Bzowka, J., 2012. Analysis of bearing capacity and settlement of jet grouting columns. Archit. Civ. Eng. Environ. 5 (2), 41–54.
Clark, S.P., 1966. Handbook of Physical Constants. Geological Society of America, Memoir, p. 587.
Correia, A. Gomes, Valente, T., Tinoco, J., Falcão, J., Barata, J., Cebola, D., Coelho, S., 2009. Evaluation of mechanical properties of jet-grouting columns using different test methods. In: Hamza, M., et al. (Eds.), Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering. © 2009 IOS Press. http://dx.doi.org/10.3233/978-1-60750-031-5-2169.
Croce, P., Flora, A., 1998. Effects of jet grouting in pyroclastic soils. Riv. Ital. Geotec. 2, 5–14.
Croce, P., Modoni, G., 2007. Design of jet grout cut-off Walls. Ground Improv. 11 (1), 11–19. 5.
Croce, P., Gajo, A., Mongiovì, L., Zaninetti, A., 1994. Una verifica sperimentale degli effetti della gettiniezione. Riv. Ital. Geotec. 2, 91–101 ([in Italian].).
Croce, P., Flora, A., Modoni, G., 2004. Jet Grouting: Tecnica, Progetto e Controllo. Benevento, Italy, p. 221 ([in Italian]).
Croce, P., Flora, A., Modoni, G., 2014. Jet-grouting-technology, Design and Control. CRC Press, Taylor and Francis Group, p. 283.
Eramo, N., Modoni, G., Arroyo, M., 2012. Design control and monitoring of a jet-grouted excavation bottom plug. In: Viggiani, G. (Ed.), Proceedings of the 7th International Symposium on the Geotechnical Aspects of Underground Construction in Soft Ground. Taylor & Francis Group, London, pp. 611–618.
Fang, Y., Liao, J., Lin, T., 1994. Mechanical properties of jet grouted soilcrete. Q. J. Eng. Geol. Hydrogeol. 27 (3), 257–265.
Fang, Y.S., Kuo, L.Y., Wang, D.R., 2004. Properties of soilcrete stabilized with jet grouting. In: Proceedings of the 14th International Offshore and Polar Engineering Conference, Toulon, France, May 23–28, 2004, pp. 696–702.
Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ, p. 604.
Gladkov, I.L., Malinin, A.G., Zhemchugov, A.A., 2011. Strength and deformation characteristics of soil-concrete as a function of jet-grouting parameters. In: Geotechnical Engineering: New Horizons Proceedings of the 21st European Young Geotechnical Engineers' Conference Rotterdam, pp. 75–78.
Hussin, J.D., 2014. Methods of soft ground improvement. In: Gunaratne, M. (Ed.), The Foundation Engineering Handbook, second ed. Taylor and Francis Group, pp. 607–645.
Kashevarova, G.G., Makovetsky, O., Khusainov, I., 2013. Experience in application of "Jet grouting" for installation of substructures of estates. Front. Geotech. Eng. (FGE) 2 (2). June 2013.
Laefar, D.B., O'Neill, D., O'Mahony, C., 2009. Impact of clay on early jet-grouting strength. In: DFI Proceedings of the 34th Annual Conference on Deep Foundations.
Lambert, S., Rocher-Lacoste, F., Le Kouby, A., 2012. Soil-cement columns, an alternative soil improvement method, ISSMGE. In: TC 211 International Symposium on Ground Improvement IS-GI Brussels 31 May & 1 June 2012.
Lunardi, P., 1997. Ground improvement by means of jet-grouting. Proc. Inst. Civ. Eng. - Ground Improv. 1 (2), 65–85. http://dx.doi.org/10.1680/gi.1997.010201.
Mishra, D.A., Basu, A., 2013. Estimation of uniaxial compressive strength of rock materials by index tests using regression analysis and fuzzy inference system. Eng. Geol. 160, 54–68.
Mongiovi, L., Croce, P., Zaninetti, A., 1991. Analisi sperimentale di un intervento di consolidamento mediante gettiniezione. In: Proceedings of the 2nd National Conference of the Researchers of Geotechnical Engineering, pp. 101–118 ([in Italian]).
Nikbakhtan, B., Osanloo, M., 2009. Effect of grout pressure and grout flow on soil physical and mechanical properties in jet-grouting operations. Int. J. Rock Mech. Min. Sci. 46, 498–505.
Rollins, K.M., Adsero, M.E., Brown, D.A., 2008. Use of jet grouting to increase lateral pile group resistance in soft clay. In: Proceedings 14th World Conf. On Earthquake Engineering, Beijing, China, p. 7. Paper 03—04-02-0093, CD-Rom.
Tinoco, J., Gomes Correia, A., Cortez, P., 2011. Application of data mining techniques in the estimation of the uniaxial compressive strength of jet grouting columns over time. Constr. Build. Mater. 25 (3), 1257–1262.
Van der Stoel, A.E.C., 2001. Grouting for Pile Foundation Improvement. PhD thesis. Delft University Press, p. 217.
Xanthakos, P.P., Abramson, L.W., Bruce, D.A., 1994. Ground Control and Improvement. a Wiley-interscience publication John Wiley & Sons, Inc.