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Factors Affecting Engineering Properties of Microfine Cement Grouted Sands

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Abstract An experimental investigation was conducted in order to evaluate the influence of distance from the injection point and of parameters pertinent to the cement, the suspension and the sand on the effectiveness of microfine cement grouts. Three different cement types, each at three different gradations having nominal maximum grain sizes of 100, 20 and 10 μm, were used. Grouting effectiveness was evaluated by injecting suspensions with water to cement (W/C) ratios of 1, 2 and 3, by weight, into five uniform sand fractions with different grain sizes and eight composite sands with different gradations, using a specially constructed apparatus. Unconfined compression and permeability tests were conducted on the resulting grouted sand specimens, after curing for 28 and 90 days. Microfine cement grouted sands obtained unconfined compression strength values of up to 14.9 MPa and permeability coefficients as low as 1.3×10^{-6} cm/s or by up to 5 orders of magnitude lower than those of clean sands. The W/C ratio and the bleed capacity of suspensions as well as the effective grain size and the permeability coefficient of sands are very important parameters, since they affect substantially the grouted sand properties and are correlated satisfactorily with them. The strength and permeability of grouted sands can increase, decrease or remain constant with distance from the injection point depending on the easiness of suspension penetration into the sands. The improvement of grouted sand properties with increasing distance from the injection point is consistent with the observed increase of the cement content of grouted sands.

Keywords Grouting · Microfine cements · Laboratory investigation · Grouted sands · Permeability · Strength

1 Introduction

The safe construction and operation of many structures frequently requires improvement of the mechanical properties and behavior of soils by permeation grouting using either suspensions or chemical solutions. Suspensions have lower cost and are harmless to the environment but can not be injected into soils with gradations finer than coarse sands. Chemical solutions can be injected in fine sands or coarse silts but are more expensive and, some of them pose a health and environmental hazard. Therefore, a number of “microfine” or “ultrafine” cements has been developed and marketed in the last decades and the improvement of soil properties by means of microfine cement grouting has been practiced, in order to extent the application range of ordinary cement grouts and to

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reduce the use of harmful chemical solutions. The quantification of the effectiveness of microfine cements in permeation grouting and the investigation of the effect of various factors on the grouted sand properties have been the objectives of numerous research efforts, mostly based on the results obtained from unconfined compression and permeability tests (e.g. Zebovitz et al. 1989; De Paoli et al. 1992; Schwarz and Krizek 1994; Santagata and Collepardi 1998; Dano et al. 2004; Schwarz and Chirumalla 2007; Mollamahmutoglu and Yilmaz 2011). However, the effect of certain factors, such as the cement type and fineness, the suspension properties, the curing time (>28 days), the sand gradation and the degree of saturation of sand prior to grouting, on the strength and permeability of microfine cement grouted sands needs further documentation. Moreover, the available, limited in number, means of estimation of the microfine cement grouting effectiveness include a correlation between the unconfined compression strength and the permeability coefficient of microfine cement grouted sands (Zebovitz et al. 1989) as well as an equation relating the grouted sand strength to the cement to water ratio of microfine cement suspension (Dano et al. 2004).

The experimental investigation reported herein is part of an extensive research effort aimed toward the development of a relatively fine-grained material, suitable for permeation grouting, obtained by pulverization of ordinary cements produced in Greece. Suspensions of three different cement types, each at three different gradations, were tested. Scopes of this paper are: (a) to quantify the improvement of the strength and permeability of sands by grouting with these coarse- and fine-grained cements, (b) to document the effect of cement type and fineness, grout composition (water to cement ratio, superplasticizer addition) and properties (bleed capacity, strength), curing time (>28 days), sand characteristics (grain size, gradation, relative density, degree of saturation prior to grouting) and distance from injection point on the effectiveness of these cement grouts, (c) to correlate the grouted sand properties with parameters pertinent to the grout (water to cement ratio, bleed capacity) and the sand (effective grain size, permeability coefficient) and, (d) to investigate the potential connection between the cement content and the observed behavior of grouted sands. The 340 unconfined compression tests and the 230 constant head permeability tests required for the present investigation, were conducted on grouted sand specimens produced using a specially constructed grouting apparatus.

2 Materials

For the purposes of this laboratory investigation, 62 sand columns were injected with suspensions of coarse- and fine-grained cements of three different types having water to cement (W/C) ratios of 1, 2 and 3, by weight. Five uniform, clean sands with different grain sizes were used alone or in various proportions to obtain eight additional soils, with different gradations, for grouting.

2.1 Suspensions

Three cement types (Portland, Portland-composite and pozzolanic cement, code-named CEM I, CEM II/B-M and CEM IV/B, respectively, according to European Standard EN 197-1) were selected because of production cost differences. The amount of clinker used for the production of the CEM I cement (90 %) is significantly higher in comparison with 63 and 58 % for CEM II/B-M and CEM IV/B cements, respectively, while the pozzolan content increases from 0 % (CEM I) to 23.5 % (CEM II/B-M) and 38 % (CEM IV/B). Each ordinary cement was pulverized, by performing dry grinding in a special laboratory mill, to produce additional cements with nominal maximum grain sizes (d_{max}) of 20 and 10 μm. Characteristic grain sizes and Blaine specific surface values for all cements are presented in Table 1. In terms of gradation, all cements with nominal $d_{max} = 10$ μm can be considered as “microfine” since they satisfy the requirements of Standard EN 12715 ($d_{95} < 20$ μm and specific surface over 800 m^2/kg) as well as definitions adopted by ISRM, ACI Committee 552 and PCA (Henn and Soule 2010). Also, cements with nominal $d_{max} = 20$ μm have adequately small characteristic grain sizes to be considered, marginally, as “microfine”.

All suspensions tested during this investigation were prepared using potable water since it is considered appropriate for preparing cement-based suspension grouts (Littlejohn 1982; Eriksson et al. 2003). The W/C ratio of the suspensions was set equal to 1, 2 and 3 by weight, because suspensions with a W/C > 3 would have prohibitively large bleeding, long setting times

Table 1 Gradation of ordinary and microfine cements

Grain sizes	Cement type								
Specific surface	CEM I			CEM II/B-M			CEM IV/B		
d^{a}_{max} (μm)	100	20	10	100	20	10	100	20	10
d_{95} (μm)	57.0	11.5	8.2	45.5	13.6	9.1	48.0	12.8	9.8
d_{50} (μm)	16.6	4.2	3.2	14.0	5.8	4.2	14.2	4.4	3.9
d_{10} (μm)	3.0	1.2	1.0	2.2	1.4	1.1	3.0	1.3	1.2
Blaine (m^2/kg)	384	710	920	466	735	942	452	715	923

[a] Nominal maximum cement grain size

and low strengths, while suspensions with a W/C < 1 would have prohibitively high viscosity (Littlejohn 1982; Bruce et al. 1997; Lombardi 2003). A superplasticizer (patented new generation of admixture based on polycarboxylate chemistry), at a dosage of 1.4 % by weight of dry cement, was used to improve the suspension properties of the microfine cements. This fixed superplasticizer dosage was determined following a laboratory evaluation of the effect of various dosages on the apparent viscosity and the rheological characteristics of the pulverized cement suspensions (Pantazopoulos et al. 2012). Suspension preparation required a total mixing time of 10 min in high-speed mixers, of the type used for the preparation of soil specimens for hydrometer testing, with a speed of 10,000 rpm at no load. For suspensions with superplasticizer, the appropriate amount of cement and 70 % of the required water were placed in the mixer together with the superplasticizer dosage and mixed for 5 min. Then, the rest of the water was added and mixing continued for another 5 min. This procedure was recommended by the superplasticizer producer. The experimental documentation of the suspension properties, in terms of apparent viscosity, rheological properties, bleed capacity, setting times, unconfined compression strength and groutability, of the cements used in this investigation indicates that microfine cement suspensions, enhanced with superplasticizer, have acceptable apparent viscosity, behave as Bingham fluids, are stable for W/C = 1, have reasonable setting times for field applications and can be injected into medium-to-fine sands (Pantazopoulos et al. 2012).

2.2 Sands

A limestone sand with angular grains was used for the preparation of two types of soils, utilized in the present research. With appropriate treatment (washing and sieving), five clean, uniform sand fractions (type I sands) with grain sizes limited between ASTM sieve sizes Nos. 5 and 10, 10 and 14, 14 and 25, 25 and 50, and 50 and 100, were produced. The properties of the sand fractions, designated using the aforementioned sieve Nos. and tested with the purpose of evaluating the effect of sand grain size on the engineering properties of microfine cement grouted sands, are presented in Table 2. Permeability coefficient values of the sands were obtained from constant head permeability tests in dense and loose specimens. Summarized in Table 3 are the compositions, selected gradation characteristics and permeability coefficient values (dense specimens) of the composite (type II) sands, prepared with the abovementioned sand fractions. Type II sands were tested with the aim of investigating the effect of sand gradation on the effectiveness of microfine cement grouting. They were produced in order to have common grain size limits but different uniformity coefficients (Table 3), which are higher than the ones of type I sands (Table 2).

The resulting eight composite sands are divided into four 5–50 and four 5–100 sands with grain sizes limited between ASTM sieve sizes Nos. 5 and 50, and 5 and 100, respectively, and grain size distributions presented in Fig. 1. More specifically, 5–50 (1) and 5–100 (1) sands were prepared by mixing successive sand fractions in equal proportions and, as a result, they attained smoother gradations compared to the other equivalent sands (Fig. 1). All the other composite sands were produced using a basic sand, easily groutable with microfine cement suspensions (5–25 sand), in which a “tail”, containing all sand fractions (if more than one required) in equal proportions, was added in three alternative total percentages (10, 15 and 20 %). For example, 5–100 (3) sand consists of 5–25 basic sand (containing equal proportions of sand fractions 5–10, 10–14 and 14–25) and 25–100 “tail” (containing equal proportions of sand fractions 25–50 and 50–100) in overall percentages of 85 and 15 %,

Table 2 Properties of sand fractions

Sand fraction	Grain size limits (mm)	d_{10} (mm)	Uniformity coefficient	Specific gravity	Void ratios		Permeability coefficient[a] (cm/s)	
					e_{min}	e_{max}		
5–10	4.00–2.00	2.15	1.40	2.71	0.66	1.06	4.1×10^{0}	2.3×10^{0}
10–14	2.00–1.40	1.45	1.19	2.72	0.67	1.03	1.8×10^{0}	8.0×10^{-1}
14–25	1.40–0.71	0.77	1.43	2.72	0.67	1.07	5.3×10^{-1}	2.2×10^{-1}
25–50	0.71–0.30	0.34	1.56	2.70	0.70	1.06	8.5×10^{-2}	4.0×10^{-2}
50–100	0.30–0.15	0.16	1.43	2.72	0.72	1.12	2.9×10^{-2}	1.3×10^{-2}

[a] Left column: loose sands ($D_r = 32$ %), Right column: dense sands ($D_r = 96$ %)

Table 3 Composition and properties of composite sands

Sand designation	Contained sand fractions (%)					d_{10} (mm)	C_u	Permeability coefficient[a] (cm/s)
	5–10	10–14	14–25	25–50	50–100			
5–50 (1)	25.0	25.0	25.0	25.0	0.0	0.43	3.77	5.3×10^{-1}
5–50 (2)	26.7	26.7	26.7	20.0	0.0	0.46	3.63	2.1×10^{-1}
5–50 (3)	28.3	28.3	28.3	15.0	0.0	0.53	3.26	6.1×10^{-1}
5–50 (4)	30.0	30.0	30.0	10.0	0.0	0.71	2.51	8.5×10^{-1}
5–100 (1)	20.0	20.0	20.0	20.0	20.0	0.21	6.67	5.7×10^{-2}
5–100 (2)	26.7	26.7	26.7	10.0	10.0	0.30	5.57	1.4×10^{-1}
5–100 (3)	28.3	28.3	28.3	7.5	7.5	0.40	4.33	2.5×10^{-1}
5–100 (4)	30.0	30.0	30.0	5.0	5.0	0.71	2.51	3.6×10^{-1}

[a] Sands in dense condition ($D_r = 93$ %)

respectively. The term “tail” is derived from the gradation shape of these sands, which, as shown more clearly in Fig. 1b, can be idealized as bilinear with a coarser part represented by the basic sand and a finer part represented by the “tail”. All sands were grouted at a dense condition (mean value of relative density, D_r, 98 ± 1 %) and were dry prior to grouting. Sand 25–50 was also grouted in loose condition ($D_r = 42$ %) or was saturated prior to grouting in order to assess the effect of sand relative density and saturation on the effectiveness of microfine cement grouting.

3 Experimental Procedures

The special apparatus shown in Fig. 2 was constructed and used for injecting sand columns with cement suspensions. It allows for adequate laboratory simulation of the injection process and investigation of the influence of the distance from injection point on the properties of the grouted sand. The grouting column was made of thick PVC tube with an internal diameter of 75 mm and a height of 1,440 mm and was formed by placing at each end a 50 mm thick gravel layer, between two screens of suitable aperture, and filling the remaining length (1,340 mm) with dry sand in a dense or loose condition. The sand was saturated, when required by the testing program, by upward flow of water pumped from the grout tank. The rate of discharge of the pump was regulated to be constant and equal to 60 L/h. Injection was stopped when either the volume of the injected grout was equal to two void volumes of the sand in the column or when the injection pressure became equal to 700 kPa. After injection, the grouted column remained on its base for 24 h, then its ends were sealed with plastic and was stored in a vertical position. After curing for 28 days, the grouted columns were cut in alternating lengths of 160 and 90 mm. As a result, six specimens with a length of 160 mm and distance of the mid-height of each specimen from the injection point equal to 80, 330, 580, 830, 990 and 1,240 mm, respectively, as well as four specimens with a length of 90 mm and

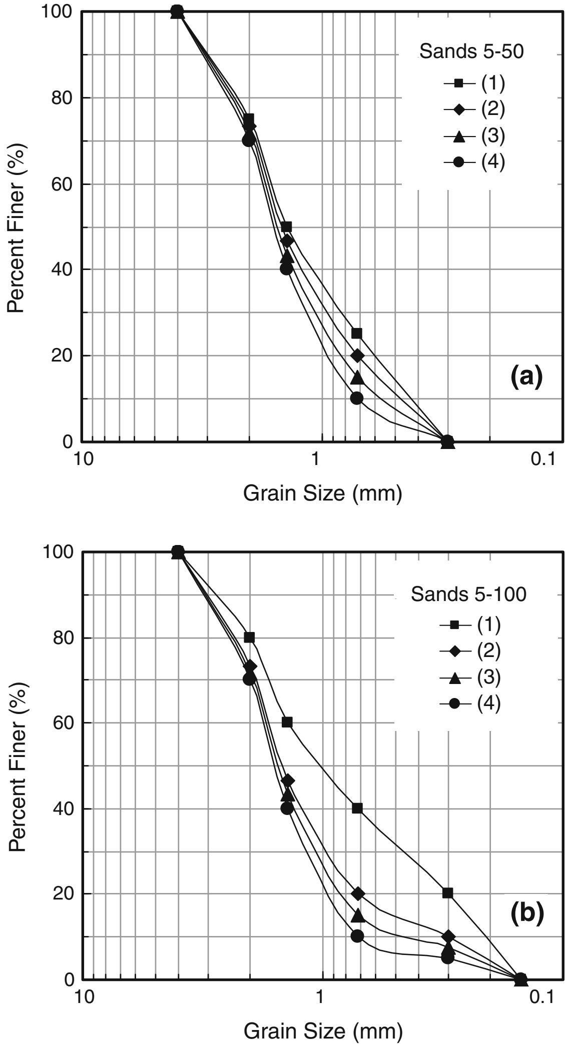


Fig. 1 Grain size distributions of **a** 5–50 and, **b** 5–100 composite sands

distance of the mid-height of each specimen from the injection point equal to 205, 455, 705 and 1,115 mm, respectively, were obtained from each grouted column.

The specimens with a length of 160 mm were tested in unconfined compression at an axial strain rate equal to 0.05 %/min. The loading surfaces of each specimen were capped, prior to testing, using a cement-based low strength compound. The selection of the axial strain rate used in the unconfined compression tests was based on the findings of a former research (Dano et al. 2004) according to which, the variation of axial strain rate from 0.0125 to 12.5 %/min has no effect on the unconfined compression strength of grouted sand.

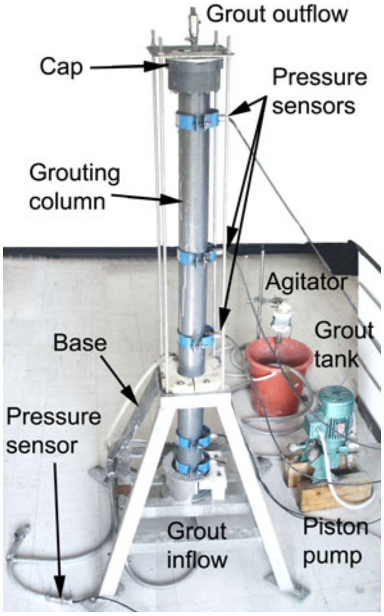


Fig. 2 Laboratory equipment for grouting sand columns

The specimens with a length of 90 mm were utilized for constant head permeability testing under water pressures ranging from 10 to 200 kPa, using the special apparatus shown in Fig. 3. The pressure control system of the apparatus is identical to ones used in triaxial compression testing and allows for the simultaneous but independent testing of two grouted sand specimens. The two specially constructed permeameters were designed to facilitate the testing of grouted sand specimens in their PVC tubes. The problem of sidewall leakage associated with this procedure, was eliminated using the specimen configuration shown in Fig. 3. More specifically, a cut was made along the PVC tube of the specimen, the specimen was then extracted carefully from the PVC tube, vaseline layers were spread on the peripheral surface of the specimen and on the inner side of the PVC tube, subsequently, the specimen was put back into the PVC tube, the void caused by the cut was filled with an elastic water-tight strip and, finally, the PVC tube was brought back to its initial diameter by the tightening of three clamps. For the investigation of the effect of curing time on grouted sand properties, selected grouted sand columns were cured for 90 days, unconfined compression and permeability tests were conducted on the resulting specimens and the results were compared with the ones obtained from grouted sand columns with equivalent compositions, cured for

28 days. It is clarified that the unconfined compression strength and permeability coefficient values of grouted sands are presented in relation to the distance of specimens from the injection point, only in the corresponding section. In all the other sections, average strength and permeability values are employed, which were obtained using the results from all specimens of each grouted column.

4 Cement Type and Fineness

The effect of cement type on the strength of grouted sand is quantified in terms of the unconfined compression strength ratio, defined as the ratio of the unconfined compression strengths of equivalent sand specimens, grouted with suspensions of different cement types having the same W/C ratio. The results presented in Fig. 4, indicate a strength increase due to grouting with CEM I suspensions. The other two cement types give comparable but inferior results. Variations in the unconfined compression strength of grouted sands due to the cement type used in the suspensions have been also reported by other researchers (Legendre et al. 1987; Henn et al. 2005). The high pressure (600 kPa) required for the injection of CEM IV suspension with W/C = 1 into 14–25 sand relative to the lower pressures of 90 and 100 kPa needed for the injection of CEM I and CEM II suspensions with the same W/C ratio, respectively, is probably the reason why this CEM IV grouted sand presents equal or higher unconfined compression strength in comparison with CEM I and CEM II grouted sands, respectively (Fig. 4). The superiority of CEM I suspensions improves with increasing W/C ratio of the grouts and can be attributed to the composition of the cements, since as stated earlier, CEM I is a pure Portland cement consisting of a larger proportion of clinker in comparison with the other two cement types and does not contain pozzolanic materials. Cement type appears to affect grouted sand permeability as well, since it was observed that the permeability of sands grouted with CEM I suspensions is always the highest, while the one of sands grouted with CEM IV suspensions is always the smallest. However, the observed differences are generally low since they do not exceed half an order of magnitude.

The effect of cement fineness, expressed as Blaine specific surface, on the strength and permeability of sands grouted with CEM II/B-M suspensions, is shown in Fig. 5. It can be observed (Fig. 5a) that the unconfined compression strength of grouted sands is not affected by cement fineness. It is known (De Paoli et al. 1992; Shibata 1996) that the use of microfine cements can lead to higher unconfined compression strength values of grouted soil in comparison with

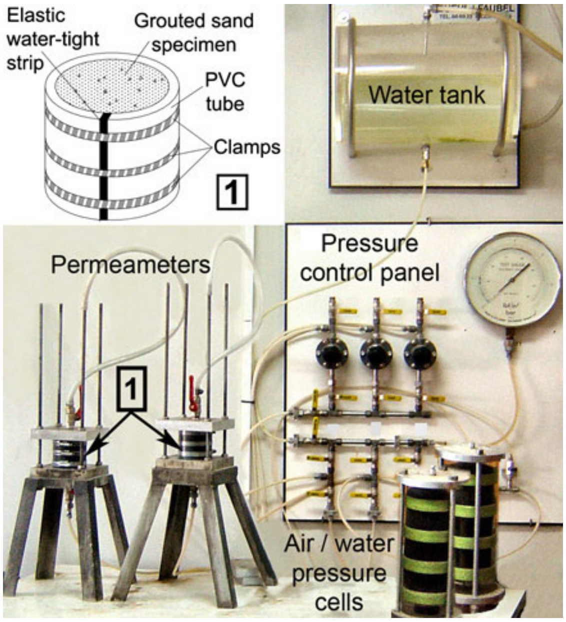


Fig. 3 Apparatus and specimen configuration for the determination of permeability coefficient of grouted sands

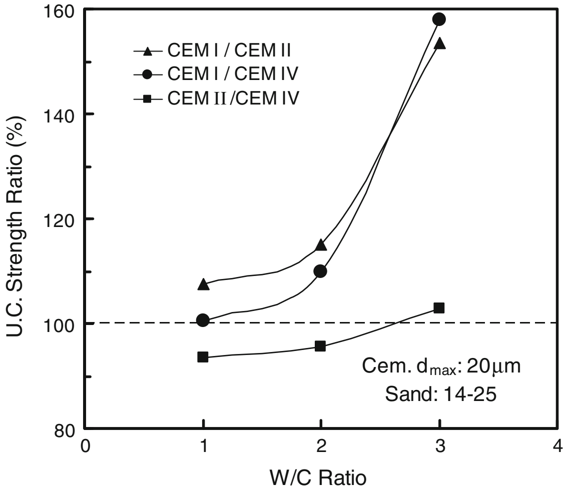


Fig. 4 Effect of cement type on the unconfined compression strength of grouted sand

ordinary Portland cements. This observation was not verified by the findings of the present research due to the relatively high W/C ratios (equal to 2 and 3) of the suspensions used in the injections. Using suspensions of the same cement, Pantazopoulos et al. (2012) observed that the unconfined compression strength of the grouted sands increases with increasing cement fineness and that the effect of cement fineness is most pronounced for the thicker cement suspensions (W/C = 1) and is negligible (±20 %) for W/C = 3. However, it must be stated that suspensions with W/C ratio equal to 1 were not used in the injections reported herein because of their low injectability in the case of cements with $d_{max} = 100\ \mu m$. Although the differences are not significant (lower than half an order of magnitude), the data shown in Fig. 5b indicate a consistent trend of decrease in permeability coefficient values with increasing cement Blaine specific surface, in agreement with the observations of other researchers (De Paoli et al. 1992; Shibata 1996). The effect of cement fineness on the permeability of grouted sands is attributed to the lower bleed capacity (final proportion of the volume of bleed water to the total initial volume of the suspension) of microfine cement suspensions which leads to the more effective filling of sand voids with grout solids. This justification is confirmed by the results of the present investigation since, as it is documented in the next section, it was verified that permeability coefficient values of the grouted sands decrease with decreasing bleed capacity of the suspensions used in the injections.

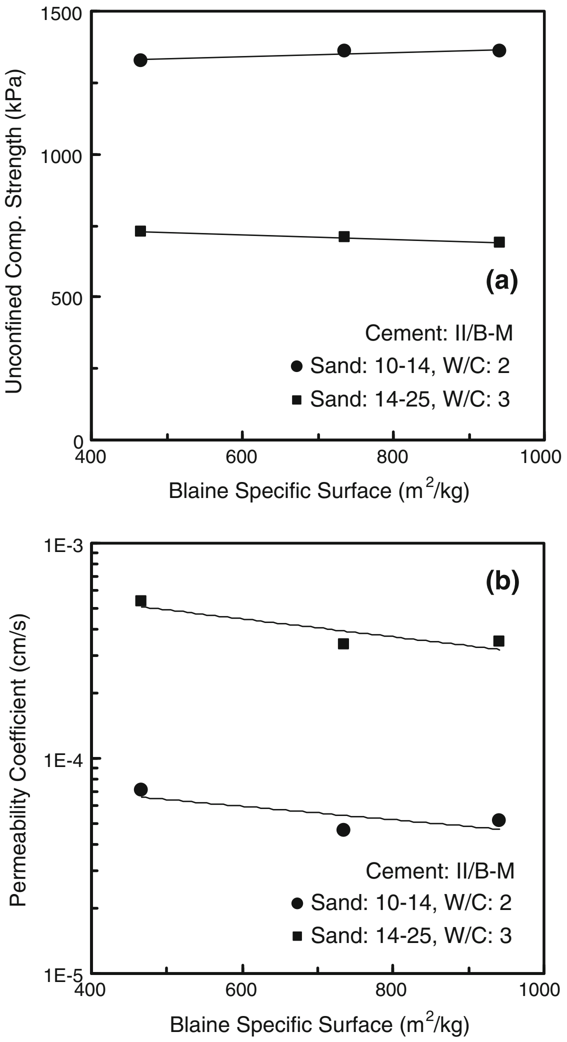


Fig. 5 Effect of cement fineness on **a** the unconfined compression strength and, **b** the permeability coefficient of grouted sands

5 Grout Composition and Behavior

The average values of the unconfined compression strength and the permeability coefficient of grouted sand fractions, obtained from 41 sand columns injected with suspensions of ordinary and microfine cements of all three types, are presented in Fig. 6 in connection with the W/C ratio of the suspensions used in the injections. The unconfined compression strength of grouted sand increases significantly and the permeability coefficient of grouted sand decreases considerably with decreasing W/C ratio of the suspensions, in agreement with the results of numerous other research efforts (e.g. Zebovitz et al. 1989; Krizek and Helal 1992; Schwarz and Krizek 1994; Shibata 1996; Santagata and Collepardi 1998; Dano et al. 2004; Schwarz and Chirumalla 2007). As also indicated in Fig. 6a, b, respectively, the unconfined compression strength and the permeability coefficient of grouted sands are correlated well with the W/C ratio of suspensions (correlation coefficients, R^2, equal to 0.884 and 0.876, respectively). The equation resulting from the correlation of the unconfined compression strength of grouted sand with suspension W/C ratio (Fig. 6a), is of the same form with the one developed by Dano et al. (2004).

Summarized in Table 4 are the minimum and maximum values of the unconfined compression strength and the permeability coefficient of microfine cement grouted sand fractions, after curing for

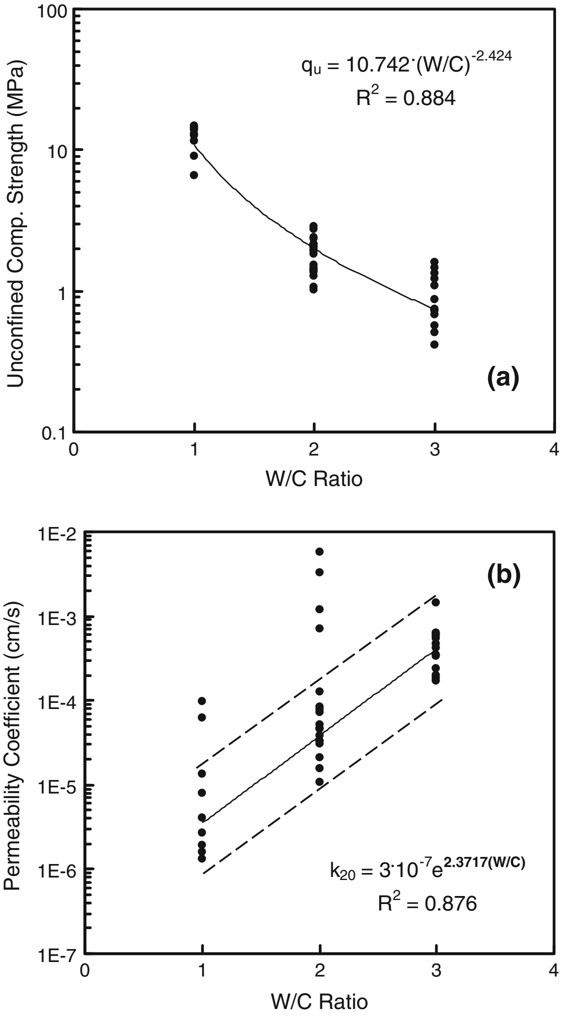


Fig. 6 Correlation of **a** the unconfined compression strength and, **b** the permeability coefficient of grouted sands to the water to cement ratio of suspensions

28 days, with respect to the W/C ratio of the suspensions. A large difference is observed in the unconfined compression strength of the sands grouted with suspensions of W/C = 1 in comparison with those grouted with suspensions having W/C ratios equal to 2 and 3. More specifically, the unconfined compression strength of sands grouted with suspensions of W/C = 1, ranges from 11.6 to 14.9 MPa and is generally from 4 to 15 times and from 7 to 36 times higher than those obtained using suspensions with W/C ratios equal to 2 and 3, respectively. As also shown in Table 4, the permeability coefficient of grouted sands decreases by 1 order of magnitude with decreasing the suspension W/C ratio from 3 to 2 and from 2 to 1, respectively, and attains values ranging from 1.3×10^{-6} to 8.0×10^{-6} cm/s, when suspensions of W/C = 1 are used. The improvement (reduction) of sand permeability achieved by grouting with suspensions of W/C = 1, is equal to 5 orders of magnitude and is up to 2 and up to 3 orders of magnitude higher than the ones obtained using suspensions with W/C ratios equal to 2 and 3, respectively. The ranges of strength and permeability values of microfine cement grouted sands presented in Table 4 are in good agreement with the values found in the literature for soils grouted with other microfine cements (e.g. Zebovitz et al. 1989; De Paoli et al. 1992; Schwarz and Krizek 1994; Sano et al. 1996; Santagata et al. 1997; Dano et al. 2004; Schwarz and Chirumalla 2007). Thus, the end effect of grouting with the suspensions used in this investigation is comparable to that accomplished by grouting with other microfine cement suspensions.

The results obtained from the 41 columns of four uniform sand fractions grouted during this investigation, with suspensions of ordinary and microfine cements of all three types, having W/C ratios equal to 1, 2 and 3, are plotted in Fig. 7 in relation to the bleed capacity values of the suspensions used in the injections. It is easily observed (Fig. 7a, c) that the unconfined compression strength of grouted sand decreases and the permeability coefficient of grouted sand increases with increasing bleed capacity of the suspensions. As also shown in Fig. 7, the grouted sand properties are correlated satisfactorily with suspension bleed capacity since the obtained correlation coefficients, R^2, are >0.8. The resultant equations can be useful for the design of grouting applications because they can provide in advance, an estimation of the grouting effectiveness based on the suspension bleed capacity, which can be easily determined experimentally. From the correlation of the strength ratio (ratio of the 28-day unconfined compression strengths of grouted sand and pure grout used in the injection), σ_{GS}/σ_{PG}, with the bleed capacity of pure grout presented in Fig. 7b, it is evident that a value of strength ratio equal to 1.0 is attained for bleed capacity approximately equal to 20 %. This means that a suspension with bleed capacity lower than 20 % has to be injected into the sand, so that the resulting 28-day unconfined compression strength of grouted sand to be greater than the 28-day unconfined compression strength of the grout used in the injection and that

Table 4 Range of strength and permeability values of microfine cement grouted sands

W/C ratio	Unconfined compression strength (MPa)		Permeability coefficient (cm/s)		Permeability reduction (orders of magnitude)	
	Min	Max	Min	Max	Min	Max
1	11.65	14.91	1.3×10^{-6}	8.0×10^{-6}	5	5
2	1.02	2.86	1.1×10^{-5}	7.9×10^{-5}	3	5
3	0.41	1.61	1.7×10^{-4}	6.0×10^{-4}	2	3

bleed capacity values higher than 20 % can lead to very low strength ratio values. All the aforementioned observations indicate that bleed capacity: (a) is the suspension property controlling the effectiveness of cement grouting, (b) justifies the influence of suspension W/C ratio and cement fineness on cement grouting effectiveness because these two factors affect bleed capacity as well and (c) provides assistance in the comprehension of the mechanisms involved in the cement grouting effectiveness. Consequently, the mechanism of permeability reduction is based on the reduction rate of soil voids induced by grouting, as it has also been stated by other researchers (Krizek and Helal 1992; Schwarz and Chirumalla 2007). The mechanism of strength increase appears to be associated with the amount of cement channeled into the sand voids and the efficient cementation of sand grains. This conclusion is also supported by the fact that the bleed capacity of pure cement suspensions mostly decreases when the W/C ratio of them is decreased and that the bleeding reduction achieved with the addition of bentonite in microfine cement suspensions, led to grouted soil with higher strength and lower permeability coefficient values (De Paoli et al. 1992).

A direct consequence of the dependence of grouted sand strength and permeability on the bleed capacity of suspensions is the adequate correlation ($R^2 = 0.81$) between the unconfined compression strength and the permeability coefficient of grouted sands, illustrated in Fig. 8. Accordingly, the increase of grouted sand strength implies a simultaneous decrease of grouted sand permeability and vice versa. A similar, independent of sand type, satisfactory relationship ($R^2 = 0.875$) between the two properties of microfine cement grouted sands was determined by Zebovitz et al. (1989), after a linear regression analysis of experimental results.

In grouting practice, ordinary cement suspensions are generally injected without superplasticizer while, in most cases, the use of this type of additive is necessary in microfine cement suspensions. Although, as stated earlier in the “suspensions” section, this rationale was also adopted in the present research effort, it is worthwhile investigating the effect of superplasticizer on the grouted sand properties. For this purpose, columns of 10–14 sand were grouted with CEM II/B-M suspensions of ordinary ($d_{max} = 100$ μm) and microfine ($d_{max} = 10$ μm) cement having W/C = 2. Both suspensions were injected either without superplasticizer or with superplasticizer at the fixed dosage of 1.4 % by weight of dry cement. The use of superplasticizer has negligible effect on the properties of microfine cement grouted sand since the unconfined compression strength values are equal to 1.40 MPa and 1.36 MPa and the permeability coefficient values are equal to 5.5×10^{-5} and 5.1×10^{-5} cm/s for the suspension without and with superplasticizer, respectively. This result is justified by the comparable bleed capacity values (14 and 19 %, respectively) of the two suspensions based on the analysis of the effect of bleed capacity presented previously. The insignificant effect of superplasticizer on the unconfined compression strength of microfine cement grouted sand reported herein, is in agreement with the negligible strength reduction due to superplasticizer, reported recently (Mollamahmutoglu and Yilmaz 2011) and in disagreement with the strength increase because of superplasticizer, detected previously (Santagata and Collepardi 1998). This discrepancy is probably generated by material and/or dosage differences. On the contrary, the properties of ordinary cement grouted sand were influenced by the use of superplasticizer since the unconfined compression strength values are equal to 1.33 and 1.80 MPa and the permeability coefficient values are equal to

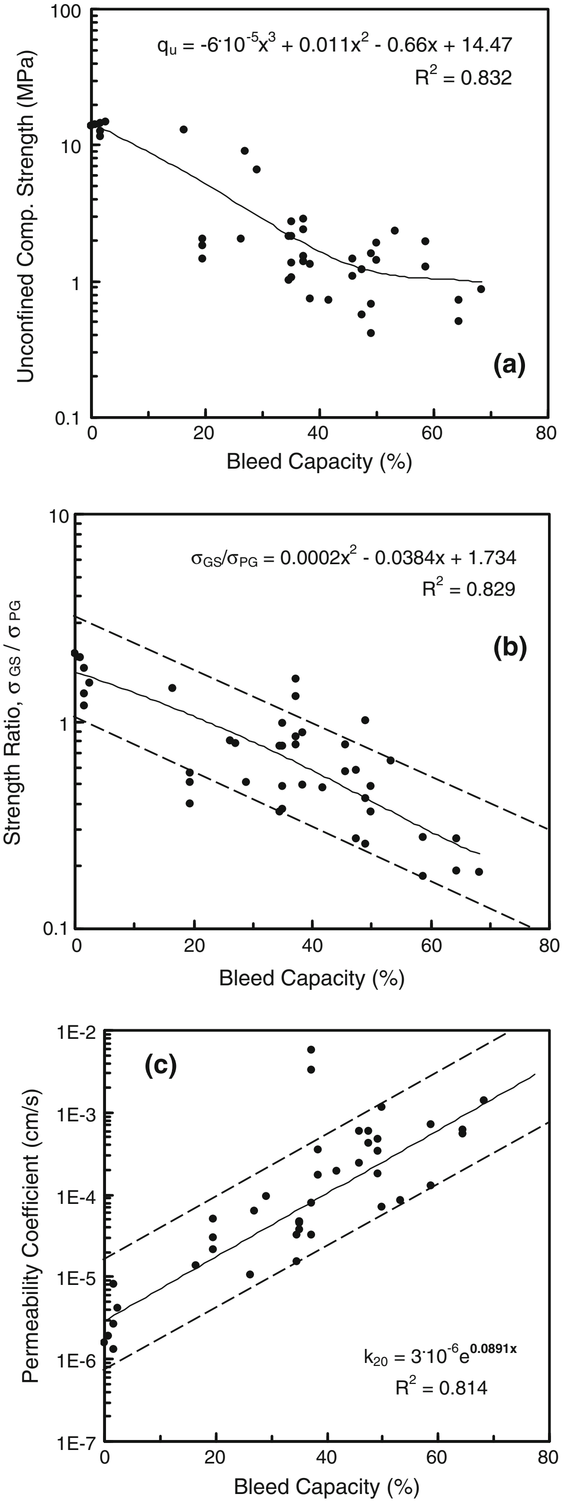


Fig. 7 Effect of suspension bleed capacity on **a** the unconfined compression strength, **b** the strength ratio and, **c** the permeability coefficient of cement grouted sands

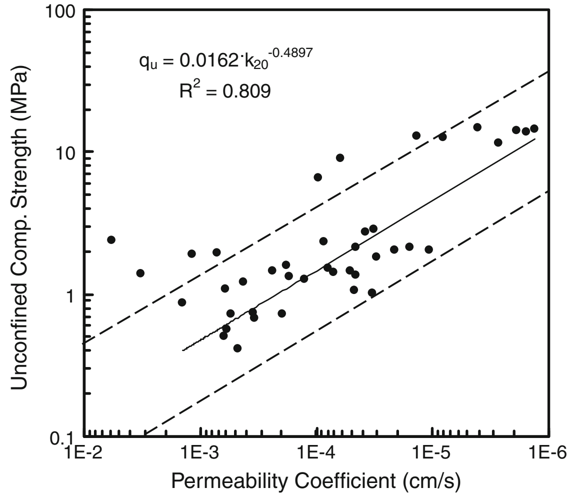


Fig. 8 Correlation of the unconfined compression strength with the permeability coefficient of cement grouted sands

7.1×10^{-5} and 1.2×10^{-4} cm/s for the suspension without and with superplasticizer, respectively. It is pointed out that the bleed capacity values of the two ordinary cement suspensions are similar (50 and 47 %, respectively). Thus, this strength and permeability increase is attributed to the undesirable deterioration of bleeding mechanism caused by the use of superplasticizer in the ordinary cement suspension, resulting in the production of non-homogeneous cement sediment consisting of thick and thin and/or strong and weak layers.

A review of the available literature indicates that the unconfined compression strength of grouted sand increases and the permeability coefficient of grouted sand decreases with increasing curing time up to 28 days (Krizek and Helal 1992) or when comparing the results obtained after curing for 7 and 48 days (Schwarz and Krizek 1994). In the research reported herein, it was decided to investigate the effect on the grouted sand properties of curing times higher than 28 days, because the effect of curing times up to 28 days is considered adequately documented by other researchers (e.g. Krizek and Helal 1992; Vipulanandan and Shenoy 1992; Mollamahmutoglu and Yilmaz 2011). As a result, the strength and permeability values obtained after grouting of sands with microfine cement suspensions of W/C = 2 and curing of grouted sands for 28 and 90 days, are compared in Table 5. The strength increase for the period from 28 to 90 days is low, since it ranges from 0 to 11 %, and is consistent with the observation that the rate of increase of unconfined compression strength decreases drastically after the first 14 days (Vipulanandan and Shenoy 1992) or 28 days (Mollamahmutoglu and Yilmaz 2011) of curing. The values of permeability reduction are also considered as low, although they are generally higher than those of strength increase (Table 5). Therefore, the increase of curing time from 28 to 90 days has a positive but minor effect on the permeability and strength of microfine cement grouted sands. Another interesting finding is that both strength and permeability of sand grouted with CEM I suspension remained unaltered after the first 28 days of curing, possibly due to the higher hydration rates of pure Portland cements in comparison with cements containing pozzolanic materials.

6 Sand Characteristics

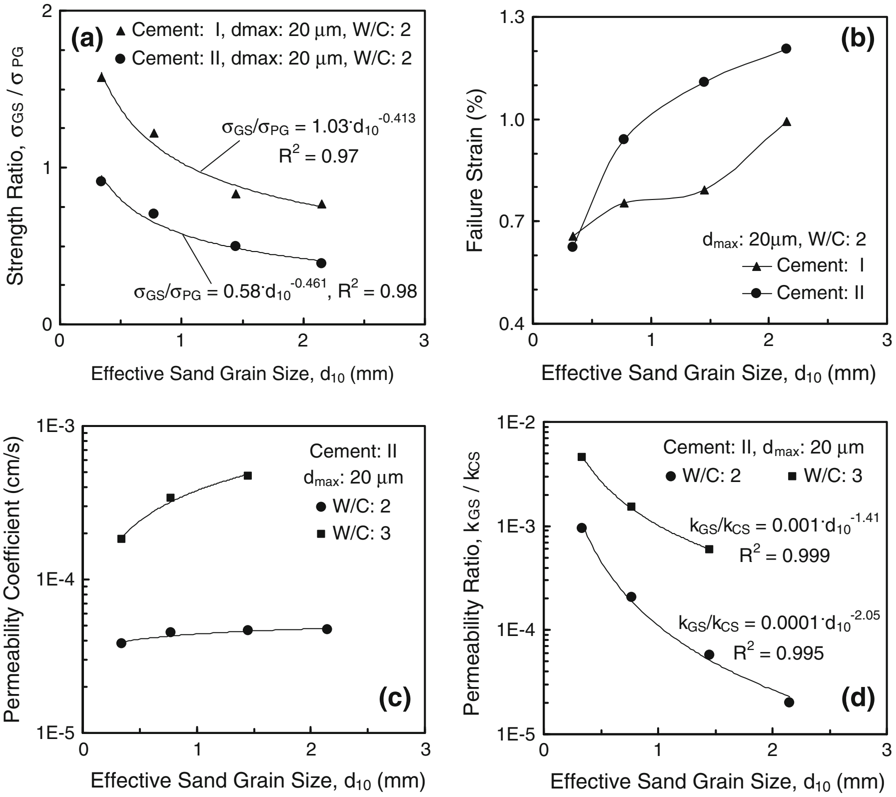
As explained formerly, the sand fractions utilized in this investigation are of the same mineralogy, have the same grain shape, present similar, low uniformity coefficients and differ only in grain size (Table 2). Accordingly, they were injected with microfine cement suspensions and the results obtained, are presented in Fig. 9 with respect to the effective sand grain size, d_{10}. As shown in Fig. 9a, the unconfined compression strength of grouted sand increases considerably with decreasing effective sand grain size. This effect is confirmed by several other research efforts (e.g. Zebovitz et al. 1989; Matsui et al. 1996; Dupla et al. 2004; Dano et al. 2004; Schwarz and Krizek 2006) and is attributed to the increased number of grain-to-grain contact points in a finer soil and, as a result, to the increased number of points available for cementation (Zebovitz et al. 1989). As demonstrated in Fig. 9b, the axial strain at failure (peak axial stress) of grouted sand specimens in unconfined compression tests decreases with decreasing sand grain size. This is the most consistent relationship found between failure strain and any of the factors examined in the present investigation. Although the permeability coefficient of grouted sand decreases with decreasing sand grain size in agreement with the results of other researchers (e.g. Zebovitz et al. 1989; Dano et al. 2004; Schwarz and Krizek 2006), the observed differences are considered as low since they generally do not exceed half an order of magnitude (Fig. 9c). Due to the larger differences between the permeability coefficients of clean sands (Table 2) in comparison with the ones between grouted sands (Fig. 9c), the permeability ratio (ratio of the permeability coefficient of grouted sand to the permeability coefficient of clean sand), k_{GS}/k_{CS}, decreases with increasing grain size of the sand (Fig. 9d) indicating a higher permeability improvement (reduction) as the grain size of sand increases.

As also demonstrated in Fig. 9a, d respectively, the strength ratio (ratio of the 28-day unconfined compression strengths of grouted sand and pure grout used in the injections), σ_{GS}/σ_{PG}, and the permeability ratio, k_{GS}/k_{CS}, are correlated exceptionally (values of R^2 ranging from 0.97 to 0.999) with the effective grain size of uniform sands. The fact that distinct curves and equations are obtained for each different suspension, reveals that these correlations also depend on the characteristics of the suspension used in the injections. The equations resulting from the correlation of strength ratio with the effective sand grain size d_{10} (Fig. 9a), are of the same form with the one developed by Ozgurel and Vipulanandan (2005) for acrylamide grouted sands. It must be mentioned that other characteristic grain sizes of sands, such as d_{20}, d_{50} and d_{90}, were also tested but the effective grain size, d_{10}, showed the best correlation with strength ratio in agreement with Ozgurel and Vipulanandan (2005).

Table 5 Strength and permeability values of grouted sands after curing for 28 and 90 days

Cement		Sand	Unconfined compression strength (MPa)			Permeability coefficient (cm/s)		
Type	d_{max} (μm)		28 days	90 days	Increase (%)	28 days	90 days	Decrease (%)
I	20	14–25	2.22	2.22	0.0	5.7×10^{-3}	5.7×10^{-3}	0.0
II/B-M	20	5–10	1.07	1.06	0.0	4.7×10^{-5}	3.8×10^{-5}	19.2
II/B-M	20	10–14	1.36	1.51	11.0	4.6×10^{-5}	3.5×10^{-5}	23.9
II/B-M	20	14–25	1.93	2.11	9.3	4.5×10^{-5}	3.2×10^{-5}	28.9
II/B-M	10	10–14	1.36	1.46	7.4	5.1×10^{-5}	3.9×10^{-5}	23.5

Fig. 9 Effect of sand grain size on **a** the strength ratio, **b** the failure strain, **c** the permeability coefficient and, **d** the permeability ratio of microfine cement grouted sands



In an attempt to examine sand gradation apart from sand grain size and to scrutinize the effect of it on the improvement of sand properties because of microfine cement grouting, the eight composite sands (Table 3) were injected, in dense and dry condition, with II/B-M cement suspension of $d_{max} = 10$ μm and W/C = 2. With the exception of 5–100 (1) sand, the permeability coefficients of all the other grouted 5–100 sands range from 1.8×10^{-5} to 2.1×10^{-5} cm/s and are slightly lower than the permeability coefficients of grouted 5–50 sands, ranging from 2.8×10^{-5} to 3.7×10^{-5} cm/s. In view of the fact that these differences are minor, it can be concluded that the effect of sand gradation on grouted sand permeability is not significant. The permeability coefficient of grouted 5–100 (1) sand is equal to 2.4×10^{-4} cm/s or is by one order of magnitude higher than those of the other 5–100 sands. This high value of permeability coefficient appears to be affected by the intense filtration that occurred during the injection of 5–100 (1) sand, leading to uneven distribution of grout solids with distance from the injection point. The unconfined compression strength values of grouted 5–100 sands range from 1.88 to 4.26 MPa and are generally higher than the unconfined compression strength values of grouted 5–50 sands, ranging from 0.88 to 2.92 MPa. The maximum value of 4.26 MPa, obtained from the 5–100 (1) sand, is attributed to the aforesaid influence of filtration and/or to the increase of suspension compression resulting from the increase of injection pressure (>700 kPa). In order to quantify the effect of sand gradation, the properties of grouted, composite sands were associated with various clean sand characteristics, such as effective grain size d_{10}, uniformity coefficient, void ratio and permeability coefficient. It was found that the first three parameters cannot express successfully the impact of sand gradation on grouted sand properties. On the contrary, the unconfined compression strength of grouted sands and the permeability ratio decrease as the permeability coefficient of clean sand increases and these relations can be expressed satisfactorily by the equations presented in Fig. 10. As shown in Fig. 10, the sand fractions grouted with the same suspension were also used to obtain the proposed correlations, which appear to be suitable for uniform sands as well. In conclusion, the sand gradation affects indirectly the strength and the permeability improvement due to microfine cement grouting, because it causes alterations in the sand voids and this end result is reflected by the permeability coefficient of clean sand, a property also connected to the size and distribution of sand voids.

The influence of sand relative density on the effectiveness of microfine cement suspension grouting was investigated by injecting the same suspension (cement: II/B-M, $d_{max} = 10$ μm and W/C = 2) into initially dry 25–50 sand columns in dense ($D_r = 98$ %) or loose ($D_r = 42$ %) condition. The reduction of sand relative density has a negligible effect on the grouting effectiveness since the obtained values of unconfined compression strength are equal to 2.04 and 2.10 MPa and those of permeability coefficient are equal to 2.1×10^{-5} and 2.6×10^{-5} cm/s, for grouted, dense and loose sand, respectively. As reported in the available literature (Akbulut and Saglamer 2002; Dano et al. 2004), the increase of the relative density of sand leads to small differentiations (increases or decreases) of the unconfined compression strength of grouted sand. These findings are in accordance with the results of present research, not only for unconfined compression strength but also for permeability coefficient of grouted sand.

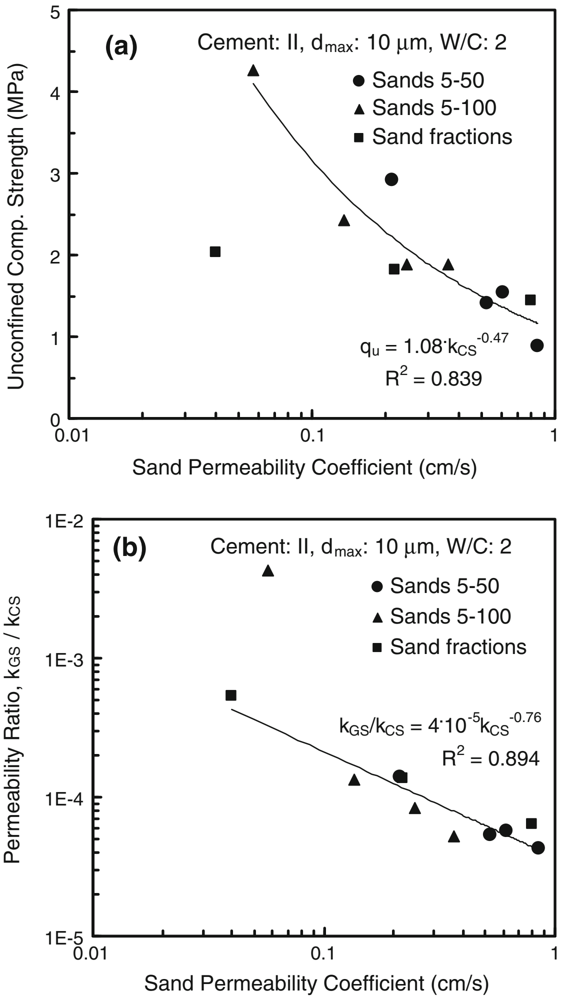


Fig. 10 Correlation of **a** the unconfined compression strength and, **b** the permeability ratio of microfine cement grouted sands to the permeability coefficient of clean sands

By grouting initially dry or saturated 25–50 sand columns, both in dense condition, with cement II/B-M suspension of $d_{max} = 10$ μm and W/C = 2, it was possible to study the effect of degree of saturation of sand prior to grouting, on the microfine cement grouted sand properties. By comparing the permeability coefficient values of 2.1×10^{-5} and 1.2×10^{-5} cm/s, obtained for initially dry and saturated, grouted sands, respectively, it can be stated that the degree of saturation of sand prior to grouting has an insignificant effect on grouted sand permeability. On the contrary, the unconfined compression strength of initially saturated, grouted sand is equal to 1.34 MPa or by 34 % lower than the strength of initially dry grouted sand, which is equal to 2.04 MPa. The observed increase of unconfined compression strength in initially dry, grouted sand is verified by the results of Schwarz and Krizek (2006) and can possibly be attributed to (a) the suspension compression as a result of the high injection pressure (>700 kPa) required for grouting dry sand in comparison with the pressure of 35 kPa which was sufficient for grouting saturated sand and/or, (b) the water entrapment in the voids of saturated sand during grouting (O'Connor et al. 1978) leading to incomplete filling of the voids with grout and/or, (c) the absorption of a quantity of suspension water from the dry sand grains (Perret et al. 1997), leading to a decrease of suspension W/C ratio during the injection into initially dry sand. The last justification is supported by measurements of suspension W/C ratio at the outflow from the sand columns, performed during the present research. More specifically, an initial suspension W/C ratio equal to 2 remained unchanged during grouting the initially saturated sand, while it attained lower values, ranging from 1.75 to 1.94, after injection into initially dry sands.

7 Distance from Injection Point

One of the main reasons for grouting sand columns with a length equal to 1,340 mm in this research effort was the investigation of the effect of the distance from injection point on the properties of grouted sands. This was accomplished by cutting every grouted sand column after the curing period and by conducting unconfined compression and permeability tests on the resulting specimens, which had different distances from the injection point. In this way, it was feasible to express the unconfined compression strength and the permeability coefficient of grouted sands as functions of the distance of tested specimens from the injection point and typical results are presented in Fig. 11. It can be observed that the effect of this parameter is variable and three different effect types can be distinguished. More specifically, type A is characterized by strength increase and permeability decrease as the distance from injection point increases. It was noticed in a considerable number of cases (29) in which the injection pressure was relatively low (≤140 kPa) and can possibly be attributed to the transfer of higher amount of grout solids at higher distance from the injection point by the flowing grout during the injection process and/or by the pressure equalization in the grouting column immediately after the end of the injection process. Type B corresponds to cases where the injection pressure remained at very low levels (<50 kPa) and the grouted sand strength and permeability are constant irrespective of the distance from injection point. Type B could be classified as a specific case of type A since, as shown in Fig. 11a, the grouted sand strength generally increases with increasing distance from the injection point, but these increases are so low that are considered as negligible. Type C is related to columns in which the grouted sand strength decreases and the grouted sand permeability increases as the distance from injection point increases. It was observed in cases where one or both materials (sand and/or cement) were well-graded and the injection pressure reached high values (>600 kPa). Under these conditions, the appearance of the filtration phenomenon, leading to the more efficient withholding of grout solids in the sand voids with decreasing distance from the injection point, is the possible explanation of the observed behavior. The ordinary cements used in this investigation, are better-graded than the microfine cements due to the higher differences observed between the characteristic grain sizes d_{95} of ordinary and microfine cements in comparison with the lower differences between the characteristic grain sizes d_{10} of the same cements (Table 1) and, therefore, they are more inclined to filtration than the microfine cements. Type C also includes columns grouted with high pressures (>500 kPa) and exhibiting significantly higher strength and lower permeability near the injection point and, thereafter, relatively invariable strength and permeability values. This behavior can also be attributed to intense filtration close to the injection point.

Summarizing the abovementioned findings, it can be stated that the strength and permeability of grouted sands can increase, decrease or remain constant with distance from the injection point depending on the size relation between the sand voids and the cement grains, the gradation of sand and/or cement and the grouting pressure. The filtration phenomenon was found to take place only under specific conditions. A behavior equivalent to that of type C is regularly reported in the literature (Zebovitz et al. 1989; Santagata et al. 1997; Dupla et al. 2004), often emanating from injections conducted either in well-graded sands or with ordinary cement suspensions (Dupla et al. 2004). It is also reported that the grouted sand strength and permeability are not affected by the distance from injection point, in cases where the size relation between the sand voids and the cement grains favors the easy penetration of suspension into the sand (Zebovitz et al. 1989; Santagata and Collepardi 1998; Dupla et al. 2004). This behavior is in good agreement with the one classified as type B in the present investigation. Finally, there are cases in which the minimum permeability values were attained at distances from the injection point equal to 56 or 86 cm and the maximum unconfined compression strength values were attained at distances from the injection point equal to 51 cm (Zebovitz et al. 1989). This behavior, which is also confirmed by the findings of Schwarz and Chirumalla (2007), appears to be similar to the type A effect, mentioned in the foregoing paragraph.

8 Cement Content of Grouted Sands

For the verification of the effect of sand grain size and distance from the injection point on the strength and the permeability of grouted sands, duplicate injection tests

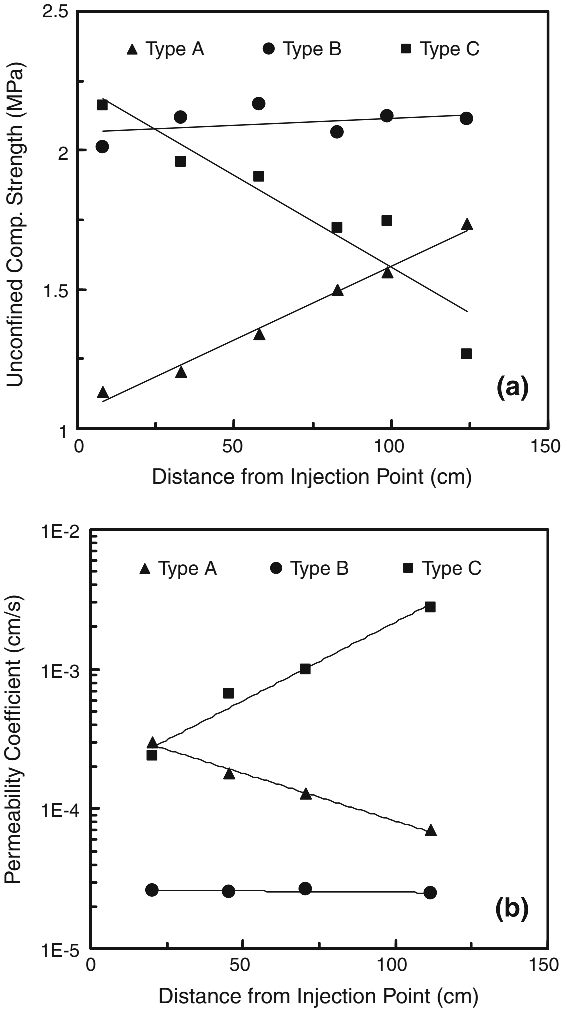


Fig. 11 Typical variations of **a** unconfined compression strength and, **b** permeability coefficient of cement grouted sands with distance from the injection point

were conducted on dense and dry 5–10, 10–14, 14–25 and 25–50 sands with cement II/B-M suspension of $d_{max} = 20$ μm and W/C = 2, in order to determine the cement content of sands after grouting. The applied procedure was based on the methodology described by Schwarz and Krizek (1994) and also used by Schwarz and Chirumalla (2007), with the necessary adjustments to the equipment used in the present research. More specifically, the grouting columns had six cyclical openings positioned in a row, at distances from the injection point equal to 40, 140, 340, 540, 830 and 1,230 mm, respectively, which remained closed throughout the preparation and injection process. During the preparation stage (placement and compaction of sand in the grouting column), screens of suitable aperture were placed in the grouting column, at levels equivalent to the lower edges of the abovementioned openings, to facilitate the division of the sand column in parts without obstructing the grout flow. Following the preparation stage, the sand column was grouted with the usual procedure and, after a period of 5 min needed for pressure equalization, the plugs were removed from the openings in turn, starting from the one at the top of the column. Once a plug was removed, the quantity of grout, corresponded to the part of the column above this particular opening and was not bound by the sand, was collected. Subsequent to the collection of the grout from all openings, the column was put in horizontal position, the top cap was removed and each grouted sand part between two successive screens was extracted from the column and gathered in separate container. Then, the grout quantities collected from the openings were added to the equivalent grouted sand parts and the total weight, W_t, of each grouted sand part was determined. The parts of the column below the first and above the last openings (distances from the injection point equal to 40 and 1,230 mm, respectively) were not included in the determinations because they would be affected by the 50 mm thick gravel layers (filters) that were placed at the ends of every grouting column.

Consequently, the grouted sand column was divided in five parts, bordered by the six openings, with lengths equal to 100, 200, 200, 290 and 400 mm, respectively. The lengths of the parts increase with increasing distance from the injection point with the aim of obtaining more measurements near the injection point where the filtration is more intense. The next step was the determination of the weights of the grouted sand constituents (sand and cement) in each part. At first, the cement grains were washed off the grouted sand and the resultant amount of water–cement mixture was kept in a container and was weighed. The dry weight, W_s, of the clean sand, resulting from this process, was then measured after oven-drying. At the same time, the three samples taken from the homogeneous, due to agitation, water–cement mixture, were weighed and oven-dried for 48 h at 105 °C. Subsequently, the dry weight of the cement, W_c, was determined by weighing the three dry samples and corresponding these weights to the total weight of water–cement mixture. Therefore, the cement content of grouted sand, defined as the percentage of the cement weight to the sand weight,

W_c/W_s, was computed for each part of the grouting column. In addition to the determination of the cement content of sands after grouting, these duplicate injection tests also attested the repeatability of the procedure used in the current research for the preparation and grouting of sand columns, by verifying the sand relative density values, the grout penetration lengths and the injection pressure values attained in the initial grouted sand columns, utilized for strength and permeability determination.

The cement contents of the grouted sands determined with the abovementioned procedure are presented in Fig. 12, in relation to the distance of the mid-height of each part of the grouting columns from the injection point. The cement content values, ranging from 9.5 to 13.2 %, are in reasonable agreement with the values (7.6 to 11.1 %) reported by Schwarz and Chirumalla (2007). This observation supports the trustworthiness of the procedure used for obtaining the cement contents of grouted sands. In all the cases studied (Fig. 12), the cement content increases with increasing distance from the injection point, indicating that the justification of the observed strength increase and permeability decrease of the grouted sands with distance from the injection point, classified previously as type A effect, is valid. As also shown in Fig. 12, the cement content of grouted 5–10, 10–14 and 14–25 sands increases with decreasing sand grain size and the cement content of grouted 25–50 sand is not higher than this of grouted 14–25 sand. Therefore, the considerable increase of the unconfined compression strength of these four grouted sands with decreasing sand grain size (Fig. 9a), can be attributed, in agreement with Schwarz and Krizek (1994), not only to the increase of the cement content but to the combined effect of it with other factors leading to better cementation, such as the increased number of grain-to-grain contact points in a finer soil. The fact that the observed differences in cement content appear to have an insignificant effect on the permeability coefficient of these four grouted sands (Fig. 9c), is consistent with the view of Schwarz and Chirumalla (2007) that the increase of cement content does not always lead to strength increase and permeability decrease of the grouted sands.

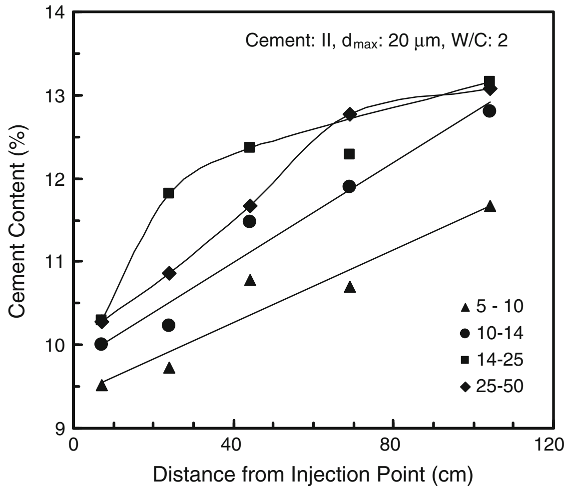


Fig. 12 Cement content of microfine cement grouted sands

9 Conclusions

Based on the results obtained and the observations made during this experimental investigation and within the limitations of the range of parameters investigated, the following conclusions can be advanced:

1. The unconfined compression strength of grouted sands is affected by sand gradation and increases with decreasing sand grain size, suspension W/C ratio and suspension bleed capacity, when CEM I (pure Portland cement) suspensions are used and when the sand is dry prior to grouting. The effect of cement fineness on unconfined compression strength is controlled by the W/C ratio of the suspensions used in the injections.
2. The permeability coefficient of grouted sands decreases with increasing cement fineness, with decreasing suspension W/C ratio and bleed capacity and when CEM IV/B suspensions are used. Although the permeability coefficient of grouted sands is not substantially affected by the sand characteristics investigated, the improvement of permeability increases with increasing grain size and permeability coefficient of the clean sand.
3. The use of superplasticizer, the relative density of sand and the increase of curing time from 28 to 90 days have minor or negligible effect on the strength and permeability of microfine cement grouted sands.
4. Good correlations were found between the grouted sand properties and parameters pertinent to the suspension (W/C ratio and bleed capacity) and the sand (effective grain size and permeability

coefficient), that affect drastically the effectiveness of cement grouting.

5. The unconfined compression strength of grouted sand is greater than the unconfined compression strength of pure grout, when cement grouts with bleed capacity lower than 20 % are used in the injections.
6. The strength and permeability of grouted sands can increase, decrease or remain constant with distance from the injection point depending on the size relation between the sand voids and the cement grains, the gradation of sand and/or cement and the grouting pressure. The strength increase and permeability decrease with increasing distance from the injection point can be attributed to the observed increase of the cement content of grouted sands.
7. Grouting with microfine cements produced by pulverizing ordinary cements, reduced the permeability coefficient of clean sands by up to 5 orders of magnitude. The unconfined compression strength of microfine cement grouted sands may have values up to 14.9 MPa. The effectiveness of the microfine cement suspensions used in this investigation is comparable to that achieved by grouting with other microfine cements.

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