Experimental investigation of microfine cement suspensions injectability in sandy soils

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Abstract: - A laboratory investigation was conducted in order to evaluate the properties and the groutability of microfine cements. Four gradations from CEM II/B-M type of cement were used having nominal maximum grain sizes of 100 μm, 40 μm, 20 μm and 10 μm. The properties of suspensions, with water to cement ratios of 1:1, 2:1 and 3:1 by weight, were determined in terms of viscosity, bleeding, setting times and unconfined compression strength. Injectability was evaluated by conducting one-dimensional injections into five different, clean sands using two specially constructed devices. Groutability of cement suspensions increases with increasing cement fineness and water to cement ratio. Microfine cement suspensions with water to cement ratios of 2:1 and 3:1 can penetrate into medium-to-fine sands. Groutability predictions by conventional criteria are not always confirmed by laboratory injections.

Key-Words: - Permeation grouting, cement suspensions, sands, laboratory investigation, groutability ratios

1 Introduction

The safe construction and operation of many structures frequently requires improvement of the mechanical properties and behavior of soils. The design related on the shear behavior of a soil material is of particular interest because it has a direct impact on practical problems of bearing capacity [1], stability of slopes and embankments [2, 3, 4, 5] as well as permanent seismic movements of slopes [6, 7, 8]. Improving soil properties can be achieved by permeation grouting using either suspensions or chemical solutions. The former have lower cost and are harmless to the environment but cannot be injected into soils with gradations finer than coarse sands. The latter can be injected in fine sands or coarse silts but are more expensive and, some of them pose a health and environmental hazard. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradations. As a result, a number of fine-grained cements, called microfine or ultrafine cements, has been developed and manufactured. The behavior of microfine cements in permeation grouting is the objective of many ongoing research efforts. 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 four different gradations, were tested. It is emphasized that the cements tested are new materials, covering the range from ordinary to microfine cements, for which the anticipated performance should be documented in terms of groutability and effectiveness. The groutability of a suspension grout can be evaluated in terms of two conditions: (a) the ability of the grout to enter into the voids of a given soil, termed ‘‘injectability’’, and (b) the permeation distance that can be achieved under a predetermined maximum injection pressure, termed ‘‘penetrability’’. While experimental investigation and modeling of penetrability was presented by Markou et al. (2015) [9], injectability of these new cement grouts is the objective of the study reported herein. Accordingly, this presentation includes: (a) quantification of injectability of suspensions prepared with these coarse and fine-grained cements in a wide range of sand gradations, (b) investigation of the effect of cement type and fineness, suspension water to cement ratio and apparent viscosity, and sand grain size and gradation on the injectability of these cement grouts and (c) documentation of the performance of the available groutability criteria.

2 Background

The design of structural grouting projects is based, among other factors, on the groutability of suspensions, since this parameter controls the degree of soil improvement as well as the project cost. Therefore, the quantification of groutability of ordinary and/or microfine cement suspensions and the investigation of the factors affecting it have been the objectives of numerous research efforts, mostly based on the results obtained from one-dimensional laboratory injection tests of cement grouts into sand columns of various lengths [10, 11, 12, 13, 14, 15, 16]. For the same purpose, large scale injection tests [17] and multi-dimensional injections, in the laboratory [18, 19] or in the field [20], were also conducted. As a result, available information indicates conclusively that the suspension groutability is improved when: (a) the cement grain sizes decrease [17, 10, 12, 20, 14, 21] or the cement specific surface increases [22, 23] or the cement grain size distribution is improved [22, 24], (b) slag microfine cements are preferred compared to pure Portland microfine cements [25, 26], (c) dispersing agents [17, 12] or superplasticizers [23, 13, 27, 14, 18, 28, 29] are used, (d) the suspension water to cement (W/C) ratio is increased [30, 31, 32, 18, 14, 15] or an optimum W/C ratio is selected [23], (e) mixers with high dispersing action and methods of grain dispersion with ultrasonic vibrations are used [22, 10, 33], and (f) the rheological properties of the suspension are improved, its stability under pressure is increased and its yield value is decreased [11]. Apart from grain size, the soil characteristics which have some influence on the suspension groutability are: (a) density [34, 18], (b) the percentage of fine grains [34, 10] and (c) the grain size distribution [10, 35]. Despite the valuable results and conclusions of all these research efforts, the experimental documentation and parametric study of cement suspension groutability is imperative for every new product developed for permeation grouting. Furthermore, various models of suspension flow in a porous medium were developed in order to simulate the process of cement grouting in sands [36, 37]. In all these models, the process of grout solids filtration in the sand voids was taken into consideration. Also, the filtration process is regarded as one of the three mechanisms resulting in stoppage of the penetration of cementitious grouts [16] and in some cases it was studied experimentally by performing one-dimensional injection tests in sand columns [38] or by using the ‘‘filtration cell’’, a specially developed setup for injecting thin samples of sand put under stress [29]. Accordingly, the enrichment of the existing database with additional laboratory investigation results on this phenomenon, which is crucial to the performance of grouting, is very helpful for a better understanding of the grouting process and for verification of results from prediction models. The trustworthy prediction of the groutability of cement suspensions can lead to the proper selection - design of grouting materials as well as to the rational determination of the distance and sequence of grouting boreholes, minimizing, in this manner, the uncertainties in the design and execution of grouting operations. The most common approach to predicting the groutability of cement-based suspensions in soil formations is the utilization of the ‘‘groutability ratios’’, N_1 and N_2 [39, 40]) Comparison of the criteria based on the N_1 and N_2 ratios [39, 40] indicates that the limiting values for ‘‘positive grouting’’ set by the first criterion [39], decrease significantly in the other criteria. The inadequacy of groutability criteria documented in the available literature [10, 12, 18]) is attributed to the fact that all abovementioned N_1 and N_2 ratios are based solely on characteristic grain sizes of grout and soil and do not take into consideration factors, such as W/C ratio and viscosity, which have an effect on suspension groutability [41]. Thus, a criterion based on more composite models was developed [18] using grout W/C ratio, soil relative density, D_r, finer content, FC, and injection pressure, P, in combination with a ratio of characteristic grain sizes of soil and grout. The effectiveness of existing groutability criteria was recently documented by comparing their estimates with the published experimental results of 489 injection tests collected for this purpose [42].

3 Materials and Procedures

For the purposes of this investigation, a cement of type CEM II/B-M, according to EN 197-1, was used. The ordinary cement (designated as F0) was pulverized in order to produce three additional cements with nominal maximum grain sizes of 40 μm, 20 μm and 10 μm, which are designated as F1, F2 and F3, respectively. The grain size distributions of all cements are shown in Fig. 1. All suspensions were prepared using potable water since it is considered appropriate for preparing cement–based grouts. A dosage of superplasticizer equal to 1.4% by weight of dry cement was added to F1, F2 and F3 cement suspensions for viscosity reduction. The water/cement (W/C) ratios of all suspensions used, was equal to 1:1, 2:1 and 3:1 by weight. The properties of suspensions were evaluated in terms of bleeding capacity, viscosity, setting times and strength. The values of suspension properties presented in Table 1 indicate that fine (F1) and microfine (F2 and F3) cement suspensions enhanced with superplasticizer can be used in permeation grouting for soil improvement. The grouted soils were clean, uniform sands with angular grains. Five different sand gradations were used with grain sizes limited between sieve sizes (ASTM E11) Nos. 5 and

10, 10 and14, 14 and 25, 25 and 50, and 50 and 100, and designated as S1, S2, S3, S4 and S5, respectively. The sands were grouted in dense condition (mean value of relative density, Dr, 98±1%) and were dry prior to grouting. The angles of internal friction, φ, for all sands range from 44° to 45°, as obtained from UU triaxial compression tests in dense, dry specimens.

3.1 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 (CEN 2000a)) 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 (nominal maximum grain size, d_{max} = 100 μm) was pulverized by performing dry grinding in a special laboratory mill, to produce additional cements with nominal maximum grain sizes (d_{max}) of 40μm, 20 μm and 10 μm. The grain size distributions of all cements are shown in Fig. 1. Characteristic grain sizes and Blaine specific surface values for all cements are presented in Table 1.

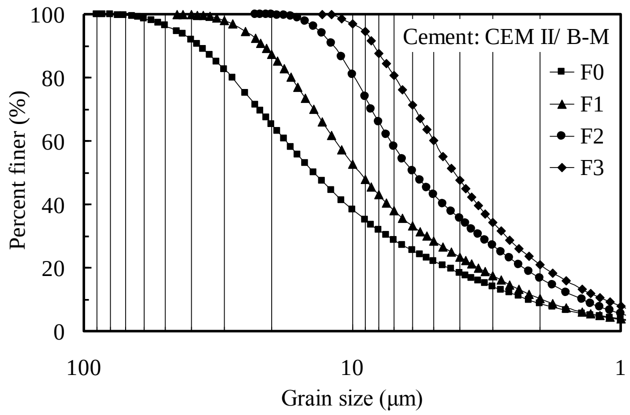


Fig. 1. Grain size curves of cements

Table 1 Gradations of cements

Grain sizes[a] Specific surface	Cement type CEM I				CEM II/B-M				CEM IV/B			
d_{max}[b] (μm)	100	40	20	10	100	40	20	10	100	40	20	10
d_{95} (μm)	57.0	22.5	11.5	8.2	45.5	25.8	13.6	9.1	48.0	26.0	12.8	9.8
d_{90} (μm)	45.0	19.0	9.7	6.8	37.0	21.5	11.8	8.3	39.5	21.2	10.7	8.5
d_{85} (μm)	39.0	16.6	8.5	6.0	32.0	19.0	10.7	7.6	33.0	18.5	9.2	7.8
d_{50} (μm)	16.6	8.6	4.2	3.2	14.0	9.4	5.8	4.2	14.2	9.3	4.4	3.9
d_{10} (μm)	3.0	2.0	1.2	1.0	2.2	2.0	1.4	1.1	3.0	2.2	1.3	1.2
Blaine (m^2/kg)	384	529	710	920	466	591	735	942	452	582	715	923

[a] d_{95}, d_{90}, d_{85}, d_{50}, and d_{10} correspond to the particle diameter at which 95%, 90%, 85%, 50%, and 10% of the weight of the specimen is finer, respectively.

[b] Nominal maximum cement grain size.

In terms of gradation, all cements with nominal d_{max} = 10 μm can be considered as "microfine" because they satisfy the requirements of standard EN 12715 [43] (d_{95} < 20 μm and specific surface over 800 m^2/kg) as well as definitions adopted by the International Society for Rock Mechanics (ISRM), the American Concrete Institute (ACI) Committee 552, and the Portland Cement Association (PCA) [44]. 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 as it is considered appropriate for preparing cement-based suspension grouts [45, 28]. 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, and low strengths, while suspensions with a W/C < 1 would have prohibitively high viscosity [45, 46, 47]. 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 pulverized cements. This fixed superplasticizer dosage was determined following a laboratory evaluation of the effect of various dosages on the apparent viscosity and rheological characteristics of the pulverized cement suspensions [48]. 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, and unconfined compression strength, 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, and have reasonable setting times for field applications [48]. The properties of suspensions were evaluated in terms of bleeding capacity, viscosity, setting times and strength. The values of suspension properties presented in Table 2 indicate that fine (F1) and microfine (F2 and F3) cement suspensions enhanced with superplasticizer can be used in permeation grouting for soil improvement.

Table 2. Cement suspension properties.

Cement	W/C ratio	Apparent viscosity, cP		Bleeding capacity, %	Setting times, hours		Unconfined compression strength, MPa	
		60 rpm*	3 rpm*		Initial	Final	7 days	28 days
F0	1:1	193	2123	16	9	14	4.4	9.0
	2:1	26	265	50	9	18	2.5	3.9
	3:1	10	23	64	10	37	1.4	2.7
F1	1:1	7	14	29	7	10	10.3	12.7
	2:1	2	2	47	7	11	1.9	3.3
	3:1	1.5	2	67	8	12	1.0	1.9
F2	1:1	30	416	2	5	8	6.9	10.6
	2:1	8	40	35	7	12	2.3	2.8
	3:1	2	4	49	8	19	1.1	1.6
F3	1:1	111	1885	2	4	6	8.3	9.7
	2:1	17	226	19	5	8	3.2	3.6
	3:1	3	15	38	6	8	1.3	1.5

* Viscometer rotation speed, Viscosity values obtained at t = 0 min

3.2 Sands

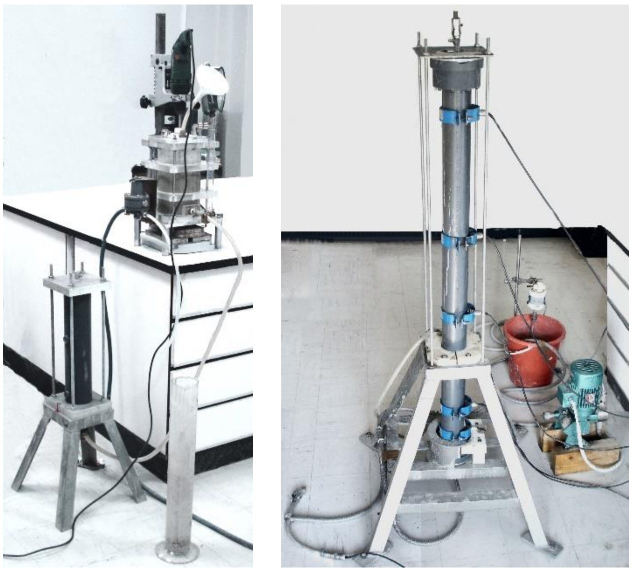
A limestone sand with angular grains was used for the preparation of three types of soils, utilized for injectability evaluation. With appropriate treatment (washing and sieving), six clean, uniform sand fractions (type I sands) with grain sizes limited between American Society for Testing and Materials [49] sieve size Nos. 5 and 10, 10 and 14, 14 and 25, 25 and 50, 50 and 100, and 100 and 200, were produced. In terms of grain size, 5-10 sand is coarse, 10-14 and 14-25 sands are medium, 25-50 sand is medium-to-fine and 50-100 and 100-200 sands are fine-grained, according to ASTM (2007) standard D422 [50]. The values of other properties of sands are presented in Table 3. The groutability of suspensions was evaluated by performing injections into sand columns of a diameter equal to 7.5 cm and a length equal to 36.5 cm. The special device (Fig. 2a) consisting of a pressurized feed tank with a stirring shaft, an air pressure regulator and a line to the PVC grouting column, was used. 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 200 kPa. The special apparatus shown in Fig. 2b was 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 grouted sand.

The grouting column was made of PVC tube with an internal diameter of 7.5 cm and a height of 144 cm. Injection was stopped when either the volume

Table 3 Gradation characteristics of sand grain size fractions

Sand fraction	Specific gravity	Grain size limits (mm)	Characteristic grain sizes (mm)			Uniformity coefficients	
			d_{15}	d_{10}	$d_{2.5}$	C_u	$C_{u,25}$
5-10	2.71	4.00 – 2.00	2.25	2.15	2.04	1.40	1.10
10-14	2.72	2.00 – 1.40	1.48	1.45	1.41	1.19	1.05
14-25	2.72	1.40 – 0.71	0.80	0.77	0.72	1.43	1.11
25-50	2.70	0.71 – 0.30	0.36	0.34	0.31	1.56	1.16
50-100	2.72	0.30 – 0.15	0.166	0.160	0.152	1.43	1.09
100-200	2.72	0.15 – 0.074	0.082	0.079	0.075	1.45	1.09

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 curing for 28 days, the grouted columns were cut in alternating lengths of 16 cm and 9 cm. The resulting specimens with a length of 16 cm were tested in unconfined compression at an axial strain rate equal to 0.05 %/min. The specimens with a length of 9 cm were utilized for constant head permeability testing under water pressures ranging from 10 kPa to 200 kPa, using a specially constructed apparatus which allowed for testing of the grouted specimens in the PVC tube.



(a) (b)

Fig. 2. Laboratory equipment for (a) injectability and (b) penetrability evaluation of suspensions

4 Experimental results

4.1 Injectability

For the purposes of the experimental investigation reported herein, injectability was evaluated by conducting injection tests with the apparatus shown in Figure 2a. Groutability was characterized as "satisfactory" when the predetermined quantity of grout (two void volumes of the sand column) could be injected, as "moderate" when the volume of injected grout was approximately equal to one void volume of the sand column, and as "impossible" when the quantity of the injected grout was very small. From the results of the injection tests presented in Table 4, it can be observed that groutability was "satisfactory" in S1 and S2 (Nos. 5-10 and 10-14) sands for all combinations of suspension composition. Groutability in S3 (Nos. 14-25) sand was "moderate" or "impossible" for F0 (ordinary) cement suspensions and "satisfactory" for the finer cement suspensions. The S4 (Nos. 25-50) sand was grouted "satisfactorily" only with microfine cement F2 suspensions having W/C ratio equal to 3:1 and microfine cement F3 suspensions having W/C ratios of 2:1 and 3:1. Groutability of all suspensions with W/C ratio equal to 1:1 was "impossible" in S4 sand. Penetration in S5 (Nos. 50-100) sand was negligible for any cement suspension used. Accordingly, it can be stated that the increase of cement fineness and/or W/C ratio significantly improves the groutability of cement suspensions. On a quantitative basis, microfine cement suspensions with W/C ratios of 2:1 and 3:1 can be injected in medium to fine sands.

4.2 Penetrability

The term "penetrability" describes the maximum length from the injection site that a particular suspension can penetrate a specific sandy soil under a specified maximum injection pressure. According to the results of the injections performed to determine the injectability, in the second stage, an attempt was made to more accurately determine the maximum penetration length of the suspensions into the soil columns with the help of the laboratory device shown in Fig. 2b. Table 5 summarizes the results obtained from these injections. In order to have some escalation in terms of ease or difficulty of compressing the suspensions, the following penetration characterizations were adopted. In particular, the penetration of the suspension is characterized as "optimal" when the entire amount of suspension penetrates (volume of compressed suspension equal to twice the volume of sand voids

Table 4. Injectability - Experimental results.

Cement	Sand	W/C ratio	Injection result *
F0	S1	1:1–3:1	S
	S2	1:1–3:1	S
	S3	1:1	I
		2:1	M
		3:1	M
	S4	1:1–3:1	I
	S5	1:1–3:1	I
F1	S1	1:1–3:1	S
	S2	1:1–3:1	S
	S3	1:1–3:1	S
	S4	1:1	I
		2:1	I
		3:1	I
	S5	1:1–3:1	I
F2	S1	1:1–3:1	S
	S2	1:1–3:1	S
	S3	1:1–3:1	S
	S4	1:1	I
		2:1	M
		3:1	S
	S5	1:1–3:1	I
F3	S1	1:1–3:1	S
	S2	1:1–3:1	S
	S3	1:1–3:1	S
	S4	1:1	I
		2:1	S
		3:1	S
	S5	1:1–3:1	I

* S: satisfactory, M: moderate, I: impossible

in the column) with low injection pressure, as "satisfactory" when penetrating all or almost all amount of suspension with increasing injection pressure, as "marginal" when the column is grouted to a length of more than 60 cm with a maximum pressure of 700 kPa and as "small" when the column is impregnated to a length of less than 60 cm with a maximum impregnation pressure of 700 kPa. From the experimental results of the injections presented in Table 5, it appears that the suspensions of all cements (common and microfine) easily penetrate the sands 5-10 and 10-14. The suspensions based on fine-grained cements F2 and F3 showed optimal penetration into the soil columns of sand 14-25, while the satisfactory penetration of the suspensions of common cement F0 with W/C ratios of 1:1 and 2:1 in the specific sand, was accompanied by increase of injection pressure. The suspensions of common cement F0 show impossibility of compression in sand columns 25-50, while satisfactory penetration in the specific sand, present the suspensions of only fine-grained cements (F2 and F3) with W/C ratios equal to 2:1 and 3:1.

Table 5. Penetrability of Suspensions – Experimental Results

Cement	Sand	W/C Ratio	Result*	PL$ (cm)
F0	S1	1:1-3:1	B	>134
	S2	1:1-3:1	B	>134
	S3	1:1	I	>134
		2:1	I	>134
		3:1	B	>134
	S4	3:1	M	16.2
	S5	1:1-3:1	M	-
F2	S1	1:1-3:1	B	>134
	S2	1:1-3:1	B	>134
	S3	1:1-3:1	B	>134
	S4	1:1	M	10.7
		2:1	I	>134
		3:1	B	>134
	S5	3:1	M	13.4
F3	S1	1:1-3:1	B	>134
	S2	1:1-3:1	B	>134
	S3	1:1-3:1	B	>134
	S4	1:1	O	92.7
		2:1	O	83.0
		3:1	I	>134
	S5	3:1	M	22.8

* B: Optimal, I: Satisfactory, O: Marginal, M: Small
$ PL: Penetration Length

The better behavior of these F2 cement suspensions compared to those of the finer F3 cement is attributed to the lower viscosity values of the former compared to the latter. Also, the sand 25-50 was grouted with a length of about 90 cm from the suspension of the finest available cement F3 with W/C ratio equal to 1:1. The penetration of all the examined suspensions in soil sand columns 50-100 is significantly reduced as the penetration lengths determined range from 13 cm to 23 cm (Table 5). The above observation leads to the conclusion that the sand 50-100 is the upper penetration limit of the suspensions of fine-grained cements. This finding is also consistent with the results concerning the suspensions injectability (Table 4).

4.3 Results Evaluation

Summarizing the results (Tables 4 and 5) concerning the scaling of the injectability and penetrability of cement suspensions into uniform sands, it appears, as expected, that the reduction in the grain size of the soil formation leads to an increase in the degree of difficulty of penetration sand columns. This is due to the fact that the reduction of the grain size of the soil formation also regulates the size of its voids. The reduction of the size of the gaps, consequently, differentiates their geometric correlation with the size of the cement grains of the suspension, as a result of which additional obstacles are placed in the flow through the soil formation. Increasing the water-to-cement ratio also contributes substantially to improving the injectability and increasing the penetration length of the suspensions. In addition, the increase in the fineness of the cement has a positive effect on the injectability and penetrability of the suspensions, thus highlighting the usefulness of the fine-grained cements and the effort to develop new materials. Increasing the injection pressure improves the injection effect only in marginal cases in terms of the geometric relationship between cement grain sizes and sand voids. In contrast, in cases where this relationship does not allow penetration of the suspension, increasing the impregnation pressure does not affect the outcome of the injection. In conclusion, it is found that the suspensions of the fine-grained cements used (F2 and F3) with water to cement ratios of 2:1 and 3:1 by weight can penetrate to a sufficient length into formations with medium to fine-grained sand.

5 Efficiency of "groutability criteria"

Groutability prediction of cement suspensions can lead to the proper design of grouting materials as well as to the rational determination of the distance and sequence of grouting boreholes, minimizing, in this manner, the uncertainties in the design and execution of grouting operations. A preliminary evaluation of groutability can be made using available criteria, such as the "groutability ratios" [39, 51] which are defined as $N_1=(D_{15})$soil:(D_{85})grout and $N_2=(D_{10})$soil:(D_{95})grout. D_{10}, D_{15}, D_{85}, and D_{95} are characteristic grain sizes of soil and grout. Grouting is considered possible for $N_1>25$ or $N_2>11$ and not possible for $N_1<11$ or $N_2<6$. $N_1>20$ is considered the minimum condition necessary for penetration and, if $N_1\geq50$, satisfactory permeation should be achieved. The characteristic grain sizes d_{10}, and d_{15} of soil correspond to the grain diameter at which 10% and 15% of the weight of the specimen is finer, respectively. Likewise, the characteristic grain sizes d_{85}, d_{90} and d_{95} of grout correspond to the particle diameter at which 85%, 90% and 95% of the weight of the specimen is finer, respectively. The conditions that must be satisfied for considering grouting as possible or not possible in accordance with each groutability criterion, are also given in Table 6. Groutability can also be estimated using the empirical formula presented by Akbulut & Saglamer (2002) [18] (Table 6) where N is groutability (if N>28 soil can be grouted sufficiently by cement-based grouts), d_{10} and d_{90} are characteristic grain sizes of soil and grout, w/c is water to cement ratio of grout, FC is the finer content of soil passing through a 0.6 mm sieve, P is the grouting pressure, D_r is relative density of soil and k_1, k_2 are constants. Values of N_1 and N_2 for the materials used in this investigation are presented in Table 7. Although the values used, were not always between the limits given by Akbulut & Saglamer (2002), groutability was computed by applying the empirical formula for the injection tests conducted in this investigation and the results obtained, are shown in Table 7.

Table 6 Criteria for the estimation of soil groutability

Reference	Equation(s)		Grouting possible	Grouting not possible
Mitchell (1981)	$N_1=\frac{(d_{15})_{soil}}{(d_{85})_{grout}}$	$N_2=\frac{(d_{10})_{soil}}{(d_{95})_{grout}}$	$N_1>25$ $N_2>11$	$N_1<11$ $N_2<6$
Krizek, Liao and Borden (1992)	$N_1=\frac{(d_{15})_{soil}}{(d_{85})_{grout}}$	$N_2=\frac{(d_{10})_{soil}}{(d_{95})_{grout}}$	$N_1>15$ and $N_2>8$	---------
Akbulut and Saglamer (2002)	$N_3=\frac{(d_{10})_{soil}}{(d_{90})_{grout}}+0.5\frac{W/C}{FC}+0.01\frac{P}{D_r}$ [a]		$N_3>28$	$N_3<28$

[a] It gives reasonable values when: 0% < FC < 6%, 0.8 < W/C < 2 and 50 kPa < P < 200 kPa.

Table 7 Groutability predictions and experimental results.

Cement	Sand	N_1	N_2	W/C ratio	N	Injection result *
F0	S1	70	47	1:1–3:1	58	S
	S2	46	32	1:1–3:1	39	S
	S3	25	17	1:1	23	I
				2:1	23	M
				3:1	23	M
	S4	11	7	1:1–3:1	12	I
	S5	5	3	1:1–3:1	7	I
F1	S1	119	85	1:1–3:1	101	S
	S2	78	57	1:1–3:1	68	S
	S3	42	30	1:1–3:1	36	S
	S4	19	13	1:1	19	I
				2:1	19	I
				3:1	20	I
	S5	9	6	1:1–3:1	10	I
F2	S1	210	161	1:1–3:1	183	S
	S2	138	108	1:1–3:1	123	S
	S3	75	58	1:1–3:1	66	S
	S4	34	25	1:1	32	I
				2:1	32	M
				3:1	31	S
	S5	15	12	1:1–3:1	16	I
F3	S1	297	236	1:1–3:1	260	S
	S2	195	159	1:1–3:1	175	S
	S3	106	85	1:1–3:1	93	S
	S4	47	37	1:1	44	I
				2:1	43	S
				3:1	43	S
	S5	22	18	1:1–3:1	23	I

* S: satisfactory, M: moderate, I: impossible

According to the values of the ratio N_1 (Table 7) and the relevant criteria, it appears that the sands S1 and S2 can be satisfactorily injected with the suspensions of all the examined cements. In S3 sand, injection with suspensions of cements F0 and F1 is feasible while a satisfactory penetration length can be achieved with suspensions of cements F2 and F3. In S4 sand, injection is not feasible with F0 and F1 cement suspensions, it is feasible with F2 cement suspensions and satisfactory penetration length can probably be achieved with F3 cement suspensions. Finally, the injection with the suspensions of all the examined cements in the S5 sand is not possible or impracticable. The criteria based on the N_2 ratio provide even more optimistic predictions which deviate significantly from the experimental ones. In terms of the empirical formula proposed by Akbulut et al. (2002) [18], if the water to cement ratio is less than 0.8:1, satisfactory soil groutability is not possible, even if the injection pressure increases above 200 kPa. Conversely, in cases where the W/C ratio of the suspension is greater than 2:1, the value of N may be greater than 28 (satisfactory injection), but the suspension is filtered (hence not sufficient penetration) especially in cases where the injection pressure has increased significantly. Also, even if the injection pressure and the water-to-cement ratio of a suspension increase, it does not appear that this will penetrate the soil if the percentage of fine components is greater than 6%. Despite the limitations regarding the application of this empirical relationship, an attempt was made to evaluate its reliability in comparison with the findings resulting from the injections carried out in the present study. It can be observed that, predictions of groutability using the empirical formula proposed by Akbulut et al. (2002) [18] are "closer" to the experimental results than the predictions based on groutability ratios, due to the fact that a larger number of factors affecting groutability is taken into consideration in this formula [52].

6 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 use of microfine cements, produced by grinding of common cements, improves the penetrability of cement suspensions rendering them effective for grouting of medium-to-fine sands.
2) Cement suspension penetrability is also improved by increasing W/C ratio, decreasing viscosity, reducing sand relative density or saturating the sand prior to grouting and is affected by sand gradation.
3) Predictions of injectability based on most of the available groutability criteria, are rather optimistic and are often not confirmed experimentally. This prediction inefficiency can be attributed to the fact that the effect of significant factors, such as W/C ratio, viscosity and composition of the finer portion of the sand gradation, is not considered adequately. The implementation limitations and the material differences are also responsible for the reduced prediction efficiency of groutability criteria.

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Contributions

D. Christodoulou had the idea of writing this article. In fact, together with I. Markou, organized the research along with the methodology of the paper and actively participated in both the translation and the submission of the text. He, also,

contributed to the execution of the experiments and to the writing of literature review.
I. Markou had the original idea of dealing with this subject and succeeded in financing the research. He also organized the research effort and carried out the literature review.
A. Droudakis contributed to the execution of the experimental tests and to the writing of literature review.

It should be noted, however, that all the authors reviewed the paper and came to the interesting conclusions of the above work.

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