

Injectability of Microfine Cement Grouts into Limestone Sands with Different Gradations: Experimental Investigation and Prediction

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Abstract One-dimensional injection tests were conducted on dry and dense sand columns with a height of 36.5 cm for the injectability evaluation of cement grouts. Three ordinary cement types were pulverized to obtain fine-grained cements having nominal maximum grain sizes of 40, 20 and 10 μm . Suspensions of these cements with water to cement (W/C) ratios of 1, 2 and 3, by weight, were injected into 54 clean, limestone sands with different gradations. Pulverization of the ordinary cements to produce microfine cements extends the range of groutable sands to “medium-to-fine”. Suspension injectability is improved by increasing cement fineness and suspension W/C ratio or by decreasing apparent viscosity and is controlled by the synthesis of the finer portion

($d \leq d_{25}$) of the sand gradation. The outcome of the 131 injectability tests conducted is successfully predicted by available groutability criteria at a rate ranging between 51 and 69%. The “new groutability and filtration criteria” proposed in this study, are adapted to the finer 25% of the sand gradation, have successful predictions for 79% of the cases (10–28% higher than those of the existing groutability criteria) and predict successfully the appearance of filtration in 83% of the available cases. The model developed by performing Binary Logistic Regression analyses of the injection test results is considered appropriate for the prediction of injectability of cement grouts in sands because it exhibits a coefficient of multiple determination equal to 0.84 and provides a rate of successful predictions equal to 78% of the available experimental results.

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1 Introduction

Improvement of the mechanical properties and behavior of soils by permeation grouting, using either suspensions or chemical solutions, is frequently required in order to assure the safe construction and operation of many structures. Suspensions have lower

cost and are harmless to the environment but cannot 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. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradations and, as a result, a number of “microfine” or “ultrafine” cements has been developed and marketed in the last decades. A variety of projects in which different microfine cement grouts were utilized, is reported by Henn and Soule (2010). The already costly to produce microfine cements are supplied from a limited number of locations throughout the world and their final cost is affected by shipping charges and currency exchange rates. As a result, the price of microfine cements in the U.S.A. is roughly 10 times higher than that of ordinary Portland cement (Henn and Soule 2010). The increase of availability by developing new, cost-effective materials of this type would be a solution to this problem.

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), 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, (c) evaluation of filtration of grout solids in the sand

voids during the injection process, (d) documentation of the performance of the available groutability criteria, and (e) development of efficient and practical tools, suitable for injectability prediction of cement grouts in relation to parameters pertinent to the suspension and the sand. The 131 one-dimensional injection tests on limestone sand columns required for the present investigation were conducted using a specially constructed grouting apparatus. Binary Logistic Regression analyses of the obtained experimental results were performed for the development of a model suitable for injectability prediction of cement grouts.

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 (e.g. Zebovitz et al. 1989; De Paoli et al. 1992a, b; Sano et al. 1996; Santagata and Collepari 1998; Warner 2003; Schwarz and Krizek 2006; Axelsson et al. 2009; Mollamahmutoglu and Yilmaz 2011). For the same purpose, large scale injection tests (Legendre et al. 1987) and multi-dimensional injections, in the laboratory (Akbulut and Saglamer 2002; Mittag and Savvidis 2003) or in the field (Tamura et al. 1994), were also conducted. As a result, available information indicates conclusively that the suspension groutability is improved when: (a) the cement grain sizes decrease (Legendre et al. 1987; Zebovitz et al. 1989; De Paoli et al. 1992b; Tamura et al. 1994; Santagata and Collepari 1998; Mollamahmutoglu 2003) or the cement specific surface increases (Paillere et al. 1989; Ziming et al. 1990) or the cement grain size distribution is improved (Paillere et al. 1989; Eklund and Stille 2008), (b) slag microfine cements are preferred compared to pure Portland microfine cements (Warner 2003; Henn and Davenport 2005), (c) dispersing agents (Legendre et al. 1987; De Paoli et al. 1992b; Draganovic and Stille 2011) or

superplasticizers (Ziming et al. 1990; Sano et al. 1996; Bremen 1997; Santagata and Collepardi 1998; Akbulut and Saglamer 2002; Eriksson et al. 2004; Saada et al. 2006; Mollamahmutoglu and Yilmaz 2011) are used, (d) the suspension water to cement (W/C) ratio is increased (Arenzana et al. 1989; Perret et al. 1997; Eriksson et al. 2000; Akbulut and Saglamer 2002; Santagata and Santagata 2003; Schwarz and Krizek 2006) or an optimum W/C ratio is selected (Ziming et al. 1990), (e) mixers with high dispersing action and methods of grain dispersion with ultrasonic vibrations are used (Paillere et al. 1989; Zebovitz et al. 1989; Toumbakari et al. 1999), and (f) the rheological properties of the suspension are improved, its stability under pressure is increased and its yield value is decreased (De Paoli et al. 1992a). Apart from grain size, the soil characteristics which have some influence on the suspension groutability are: (a) density (Karol 1985; Akbulut and Saglamer 2002), (b) the percentage of fine grains (Karol 1985; Zebovitz et al. 1989), and (c) the grain size distribution (Zebovitz et al. 1989; Santagata and Santagata 2003; Jorne et al. 2015). 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 (e.g. Bouchelaghem et al. 2001; Maghous et al. 2007; Chupin et al. 2009; Kim et al. 2009; Kim and Whittle 2009). 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 (Axelsson et al. 2009) and in some cases it was studied experimentally by performing one-dimensional injection tests in sand columns (Chupin et al. 2008) or by using the “filtration cell”, a specially developed setup for injecting thin samples of sand put under stress (Saada et al. 2006). 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 criteria, mainly for simplicity reasons. The known groutability criteria are shown in Table 1 starting with those based on the original “groutability ratios”, N_1 and N_2 (Mitchell 1981; Krizek et al. 1992; Huang et al. 2007, 2013) and those introducing other similar ratios (Incecik and Ceren 1995; Axelsson et al. 2009; Miltiadou-Fezans and Tassios 2013). The characteristic soil grain sizes d_{10} , d_{15} , and d_{50} correspond to the grain diameter at which 10, 15, and 50% of the weight of the specimen is finer, respectively. Likewise, the characteristic grout grain sizes d_{85} , d_{90} , d_{95} , and d_{99} correspond to the particle diameter at which 85, 90, 95, and 99% of the weight of the specimen is finer, respectively. W_{nom} is a nominal lower value of the apertures of fissures or interfaces to be injected (Miltiadou-Fezans and Tassios 2013). 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 1. Comparison of the four criteria based on the N_1 and N_2 ratios (Mitchell 1981; Krizek et al. 1992; Huang et al. 2007, 2013) indicates that the limiting values for “positive grouting” set by the first criterion (Mitchell 1981), decrease significantly in the other criteria (N_1 decreases from 25 to 15, 9 and 3.125 while N_2 decreases from 11 to 8, 4 and 1.5). This decrease seems reasonable for the two criteria proposed by Huang et al. (2007, 2013) because they were developed for sandy silt soils grouted with microfine cement suspensions. The prediction inefficiency of some groutability criteria documented in the available literature (i.e. Zebovitz et al. 1989; De Paoli et al. 1992b; Akbulut and Saglamer 2002) 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. Thus, as shown in Table 1, a number of criteria based on more composite models were developed (Akbulut and Saglamer 2002; Yoon and El Mohtar 2013; Huang et al. 2013) using grout W/C ratio or relative viscosity (ratio of the apparent viscosity of grout to that of water), μ_r , soil relative density, D_r , and/or finer content, FC, and, some of them, injection pressure, P , in combination with a ratio of

Table 1 Available 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 $N_2 > 8$	–
Huang, Fan and Yang (2007)	$N_1 = \frac{(d_{15})_{soil}}{(d_{85})_{grout}}$ $N_2 = \frac{(d_{10})_{soil}}{(d_{95})_{grout}}$	$N_1 > 9$ or $N_2 > 4$	–
Huang, Fan, Liao and Lien (2013)	$N_1 = \frac{(d_{15})_{soil}}{(d_{85})_{grout}}$ $N_2 = \frac{(d_{10})_{soil}}{(d_{95})_{grout}}$	$N_1 > 3.125$ and $N_2 > 1.5$	$N_1 < 3.125$ or $N_2 < 1.5$
Incecik and Ceren (1995)	$N_3 = \frac{(d_{10})_{soil}}{(d_{90})_{grout}}$	$N_3 > 10$	–
Axelsson, Gustafson and Fransson (2009)	$N_4 = \frac{b_{fc}}{(d_{95})_{grout}} = \frac{0.15 \cdot (d_{50})_{soil}}{(d_{95})_{grout}}$	$N_4 > 5$ Filtration for $3 < N_4 < 5$	$N_4 \leq 3$
Miltiadou-Fezans and Tassios (2013)	$N_5 = \frac{W_{nom}}{(d_{85})_{grout}} \approx \frac{0.15 \cdot (d_{15})_{soil}}{(d_{85})_{grout}}$ $N_6 = \frac{W_{nom}}{(d_{99})_{grout}} \approx \frac{0.15 \cdot (d_{15})_{soil}}{(d_{99})_{grout}}$	$N_5 > 5$ and $N_6 > 2$	–
Akbulut and Saglamer (2002)	$N_7 = \frac{(d_{10})_{soil}}{(d_{90})_{grout}} + 0.5 \frac{W/C}{FC} + 0.01 \frac{P_a}{D_r}$ ^a	$N_7 > 28$	$N_7 < 28$
Yoon and El Mohtar (2013)	$N_8 = \frac{(d_{10})_{soil}}{(d_{95})_{grout}} + 1900 \frac{(P/1 \text{ atm})^{0.2}}{(\mu)^{1.4}} + \left(\frac{D_r}{100}\right)^{8.5} - EXP(9.3 * \frac{FC}{100})$ ^b	$N_8 > 11$	$N_8 < 9$
Huang, Fan, Liao and Lien (2013)	$N_9 = \frac{(d_{15})_{soil}}{(d_{85})_{grout}} + 56.5 \frac{W/C}{FC}$ $N_{10} = \frac{(d_{10})_{soil}}{(d_{95})_{grout}} + 31.125 \frac{W/C}{FC}$	$N_9 > 11.125$ and $N_{10} > 5.5$	$N_9 < 11.125$ or $N_{10} < 5.5$

^aIt gives reasonable values when: $0\% < FC < 6\%$, $0.8 < W/C < 2$ and $50 \text{ kPa} < P < 200 \text{ kPa}$

^bIt gives reasonable values when: $5\% \leq$ bentonite fraction $\leq 12\%$, $0\% \leq$ sodium pyrophosphate $\leq 4\%$, $4.8 < d_{10,soil}/d_{95,grout} < 12.6$, $30\% \leq D_r \leq 80\%$, $0\% \leq FC \leq 15\%$, $k \geq 0.01 \text{ cm/s}$ and $P \leq 140 \text{ kPa}$

characteristic grain sizes of soil and grout. Artificial neural network models (Tekin and Akbas 2011; Liao et al. 2011) as well as an approach integrating the Bayesian framework and the K-nearest neighbor density estimation technique (Cheng and Hoang 2014) were also introduced for groutability prediction. Documentation of the effectiveness of the groutability estimations made by applying existing approaches for a variety of grouts and soils and the development of new, easy-to-use criteria and/or models with increased efficiency will enhance the capability of obtaining accurate groutability predictions.

3 Materials and Procedures

For the purposes of this study, sand columns were injected with suspensions of ordinary and pulverized cements of three different types having W/C ratios of 1, 2 and 3, by weight. Six uniform, clean, limestone sands with different grain sizes were used alone or

mixed in various proportions to obtain 48 additional soils, with different gradations, for grouting.

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, $d_{max} = 100 \mu\text{m}$) was pulverized by performing dry grinding in a special laboratory mill, to produce additional cements with nominal maximum grain sizes (d_{max}) of 40, 20 and 10 μm . Characteristic

grain sizes and Blaine specific surface values for all cements are presented in Table 2. In terms of gradation, all cements with nominal $d_{max} = 10 \mu\text{m}$ can be considered as “microfine” because they satisfy the requirements of standard EN 12715 (CEN 2000b) ($d_{95} < 20 \mu\text{m}$ and specific surface over $800 \text{ m}^2/\text{kg}$) 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) (Henn and Soule 2010). Also, cements with nominal $d_{max} = 20 \mu\text{m}$ 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 (Littlejohn 1982; Eriksson et al. 2004). 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 (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 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 (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, 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 (Pantazopoulos et al. 2012). Presented in Table 3 are the apparent viscosity values of ordinary cement suspensions without superplasticizer and pulverized cement suspensions with superplasticizer, obtained at time $t = 30$ min after preparation and at viscometer rotation speed equal to 60 rpm.

3.2 Sands

A limestone sand with angular grains, having a gradation shown in Fig. 1a, was used for the preparation of three types of soils, utilized for injectability evaluation. With appropriate washing and sieving through a stack of seven sieves with sizes No. 5, 10, 14, 25, 50, 100 and 200 according to ASTM (2009) standard E11, six clean, uniform sand fractions (type I sands) with grain sizes limited between the consecutive sieves employed, were produced. Gradation characteristics of the limestone sand fractions, designated using the aforementioned sieve Nos. and tested with the purpose of evaluating the effect of sand grain size on the injectability of cement grouts, are presented in Table 4. In terms of grain size, 5–10

Table 2 Gradations of cements

	Grain sizes ^a	Cement type											
		CEM I				CEM II/B-M				CEM IV/B			
	Specific surface												
	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

^bNominal maximum cement grain size

Table 3 Apparent viscosity (mPa·s) of cement suspensions

Cement d_{max} (μm)	W/C ratio	Cement type		
		CEM I	CEM II/B-M	CEM IV/B
100	1	86	213	160
	2	16	33	23
	3	9	13	10
40	1	5	16	43
	2	2	2	4
	3	2	2	2
20	1	22	36	51
	2	6	8	4
	3	4	2	3
10	1	164	117	168
	2	9	22	9
	3	6	4	5

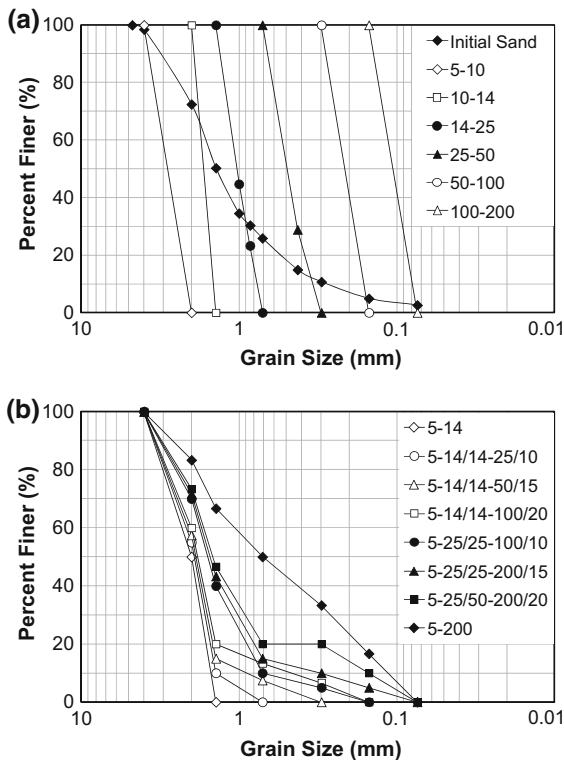


Fig. 1 Grain size distributions of **a** initial limestone sand and sand fractions, and **b** composite limestone sands

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. As shown in Table 4, the

uniformity coefficient, C_u , values of the sand fractions are comparable and low ranging between 1.19 and 1.56. It was also observed that the C_u values were not significantly affected when intermediate sieves were used in the grain size analysis. For example, as shown in Fig. 1a, use of sieve No. 40 between sieves No. 25 and 50 yielded a grain size distribution of the 25–50 sand fraction which was, for practical purposes, similar to a straight line. These observations indicate that the grain size distributions of the uniform sand fractions can be plotted as straight lines, as shown in Fig. 1a. Summarized in Table 5 are the compositions and selected gradation characteristics of all composite limestone sands, prepared with the abovementioned sand fractions. Typical grain size distributions of composite sands, tested with the aim of investigating the effect of sand gradation on the injectability of cement grouts, are presented in Fig. 1b. As all composite sands consist of sand fractions, their grain size distributions were plotted using straight lines as well.

More specifically, type II (composite) sands were produced using a coarser part (basic sand), easily groutable with each cement (5–14 sand for ordinary cement and 5–25 and 14–25 sands for microfine cements), in three alternative total percentages of 90, 85 and 80%. The coarser part was modified with the addition of a finer part in three complementary percentages (10, 15 and 20%, respectively), containing various combinations of sand fractions in equal proportions. Accordingly, the exact proportions of the sand fractions comprising each type II sand are shown in Table 5. The designations of the 42 different type II sands, produced in this manner, consist of three parts. The first part denotes the basic sand (coarser part), the second part denotes the sand fractions comprising the finer part and the last part denotes the total percentage of the finer part. For example, 5–25/50–200/20 sand (Table 5 and Fig. 1b) consists of 5–25 basic sand (containing equal amounts of sand fractions 5–10, 10–14 and 14–25) and the finer part 50–200 (containing equal weight percentages of sand fractions 50–100 and 100–200) in overall percentages of 80 and 20%, respectively. As typically shown in Fig. 1b, the shape of type II sands gradation can be idealized as bilinear with the coarser portion represented by the basic sand and the finer portion resembling a “tail”. Finally, the four type III (composite) sands are designated as 5–50, 5–100, 5–200 and 14–100 and, as shown in Table 5,

Table 4 Gradation characteristics of limestone 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

they were prepared by mixing successive sand fractions in equal proportions in order to produce sands with higher uniformity coefficients, C_u , than type I sands (Table 4) and with smoother gradations compared to type II sands (Fig. 1b). It was established that, of the original limestone sand, 1.5% of the material was retained on the No. 5 sieve and 2.6% of the material passed the No. 200 sieve. This fact, combined with the observation that the original limestone sand was not gap-graded, allows the realistic assumption that the coarsest (No. 5–10 sieves) and the finest (No. 100–200 sieves) sand fractions (as well as the intermediate ones) have grain sizes covering the whole range of sizes between the limiting sieves. Accordingly, it can be safely stated that the lower limiting grain size of any composite sand corresponds to lower sieve size of the finer fraction used and that grain sizes intermediate to the sieve sizes used can be obtained dependably from the gradation curves by simple graphical (interpolation) means.

A penetrability reduction due to the increase of sand compaction degree was observed experimentally for the materials used in the present research (Markou et al. 2015) and has also been reported by other researchers (Akbulut and Saglamer 2002). Therefore, it was decided to grout all sands at a dense condition (mean value of relative density, D_r , $98 \pm 1\%$) in order to obtain results being on the safe side. The dry density of the type I sands tested ranged between 1.53 and 1.65 g/cm³, while the dry density of the type II and III sands tested ranged from 1.70 to 1.94 g/cm³. The difference between the dry densities of sand fractions and composite sands is attributed to their grain size distributions. Also, all sands were dry prior to grouting. The preference to grout dry sands for simplicity reasons was based on European standard

EN 1771 (CEN 2004), which makes provision for the use of granular soils either in dry or in saturated condition during the laboratory injection process.

3.3 Injection Tests

The special apparatus shown in Fig. 2 was constructed and used for injecting sand columns with cement suspensions. It is attuned to standard EN 1771 (CEN 2004) and allows for adequate laboratory simulation of the injection process and for the conduct of more tests due to the saving of materials and time. Equivalent setups have also been used by other researchers (Perret 1997; Santagata and Collepardi 1998; Santagata and Santagata 2003). It consists of a pressurized grout tank with an agitator, an air pressure regulator and a line to the grouting column (reinforced plastic pipe of internal diameter equal to 1 cm). The grouting column was made of a polyvinyl chloride (PVC) tube with a thickness of 0.7 cm to avoid tube deformation with increasing injection pressure, which may lead to the formation of preferred flow channels along the internal surface of the tube. The grouting column had an internal diameter of 7.5 cm and a height of 40.5 cm and was formed by placing at each end a 2 cm thick gravel layer, between two screens of suitable aperture, and filling the remaining length (36.5 cm) with dry and dense sand. The computed sand void ratio is the mean value over the full length of the sand column. Injection was terminated when either the volume of the grout, injected through the bottom end of the column, was equal to two void volumes of the sand in the column or when the injection pressure became equal to 200 kPa with no grout flow. The injection pressure was controlled by adjusting the pressure of the compressed air in the grout tank with the air

Table 5 Composition and gradation characteristics of composite limestone sands

Sand designation	Contained sand fractions (%)						Gradation characteristics				
	5–10	10–14	14–25	25–50	50–100	100–200	d ₁₅ (mm)	d ₁₀ (mm)	d _{2.5} (mm)	C _u	C _{u,25}
5–14 (basic sand)	50.0	50.0	0.0	0.0	0.0	0.0	1.55	1.49	1.42	1.54	1.09
5–14/14–25/10	45.0	45.0	10.0	0.0	0.0	0.0	1.45	1.40	0.84	1.53	1.73
5–14/14–25/15	42.5	42.5	15.0	0.0	0.0	0.0	1.39	1.11	0.79	1.86	1.76
5–14/14–25/20	40.0	40.0	20.0	0.0	0.0	0.0	1.21	1.00	0.74	2.00	1.64
5–14/14–50/10	45.0	45.0	5.0	5.0	0.0	0.0	1.45	1.40	0.45	1.53	3.22
5–14/14–50/15	42.5	42.5	7.5	7.5	0.0	0.0	1.39	0.90	0.39	2.30	3.56
5–14/14–50/20	40.0	40.0	10.0	10.0	0.0	0.0	1.00	0.71	0.37	2.82	2.70
5–14/14–100/10	45.0	45.0	3.3	3.3	3.3	0.0	1.45	1.40	0.24	1.53	6.04
5–14/14–100/15	42.5	42.5	5.0	5.0	5.0	0.0	1.39	0.72	0.21	2.88	6.62
5–14/14–100/20	40.0	40.0	6.7	6.7	6.7	0.0	0.84	0.46	0.19	4.35	4.42
5–14/25–50/10	45.0	45.0	0.0	10.0	0.0	0.0	1.45	0.71	0.37	3.01	3.92
5–14/25–50/15	42.5	42.5	0.0	15.0	0.0	0.0	0.71	0.53	0.34	3.91	2.09
5–14/25–50/20	40.0	40.0	0.0	20.0	0.0	0.0	0.57	0.46	0.33	4.35	1.73
5–14/25–100/10	45.0	45.0	0.0	5.0	5.0	0.0	1.45	0.71	0.21	3.01	6.90
5–14/25–100/15	42.5	42.5	0.0	7.5	7.5	0.0	0.71	0.40	0.18	5.18	3.94
5–14/25–100/20	40.0	40.0	0.0	10.0	10.0	0.0	0.46	0.30	0.17	6.67	2.71
5–25 (basic sand)	33.3	33.3	33.3	0.0	0.0	0.0	0.96	0.87	0.74	2.14	1.30
5–25/25–50/10	30.0	30.0	30.0	10.0	0.0	0.0	0.79	0.71	0.37	2.51	2.14
5–25/25–50/15	28.3	28.3	28.3	15.0	0.0	0.0	0.71	0.53	0.35	3.26	2.03
5–25/25–50/20	26.7	26.7	26.7	20.0	0.0	0.0	0.57	0.46	0.33	3.63	1.73
5–25/25–100/10	30.0	30.0	30.0	5.0	5.0	0.0	0.80	0.71	0.21	2.51	3.81
5–25/25–100/15	28.3	28.3	28.3	7.5	7.5	0.0	0.71	0.40	0.19	4.33	3.74
5–25/25–100/20	26.7	26.7	26.7	10.0	10.0	0.0	0.46	0.30	0.18	5.57	2.56
5–25/25–200/10	30.0	30.0	30.0	3.3	3.3	3.3	0.80	0.71	0.13	2.51	6.15
5–25/25–200/15	28.3	28.3	28.3	5.0	5.0	5.0	0.71	0.31	0.10	5.58	7.10
5–25/25–200/20	26.7	26.7	26.7	6.7	6.7	6.7	0.37	0.21	0.10	7.95	3.70
5–25/50–100/10	30.0	30.0	30.0	0.0	10.0	0.0	0.80	0.30	0.18	5.93	4.44
5–25/50–100/15	28.3	28.3	28.3	0.0	15.0	0.0	0.30	0.24	0.17	7.21	1.76
5–25/50–100/20	26.7	26.7	26.7	0.0	20.0	0.0	0.27	0.21	0.16	7.95	1.69
5–25/50–200/10	30.0	30.0	30.0	0.0	5.0	5.0	0.80	0.30	0.11	5.93	7.27
5–25/50–200/15	28.3	28.3	28.3	0.0	7.5	7.5	0.30	0.19	0.09	9.11	3.33
5–25/50–200/20	26.7	26.7	26.7	0.0	10.0	10.0	0.21	0.15	0.09	11.13	2.33
5–25/100–200/10	30.0	30.0	30.0	0.0	0.0	10.0	0.80	0.15	0.09	11.87	8.89
5–25/100–200/15	28.3	28.3	28.3	0.0	0.0	15.0	0.15	0.12	0.08	14.42	1.88
5–25/100–200/20	26.7	26.7	26.7	0.0	0.0	20.0	0.14	0.11	0.08	15.18	1.75
14–25/25–50/10	0.0	0.0	90.0	10.0	0.0	0.0	0.73	0.71	0.37	1.45	1.97
14–25/25–50/15	0.0	0.0	85.0	15.0	0.0	0.0	0.71	0.53	0.35	1.92	2.03
14–25/25–50/20	0.0	0.0	80.0	20.0	0.0	0.0	0.57	0.46	0.33	2.17	1.73
14–25/25–100/10	0.0	0.0	90.0	5.0	5.0	0.0	0.74	0.71	0.21	1.45	3.52
14–25/25–100/15	0.0	0.0	85.0	7.5	7.5	0.0	0.70	0.40	0.19	2.55	3.68
14–25/25–100/20	0.0	0.0	80.0	10.0	10.0	0.0	0.46	0.30	0.18	3.33	2.56
14–25/25–200/10	0.0	0.0	90.0	3.3	3.3	3.3	0.74	0.71	0.13	1.45	5.69
14–25/25–200/15	0.0	0.0	85.0	5.0	5.0	5.0	0.71	0.30	0.11	3.40	6.45

Table 5 continued

Sand designation	Contained sand fractions (%)						Gradation characteristics				
	5–10	10–14	14–25	25–50	50–100	100–200	d_{15} (mm)	d_{10} (mm)	$d_{2.5}$ (mm)	C_u	$C_{u,25}$
14–25/25–200/20	0.0	0.0	80.0	6.7	6.7	6.7	0.37	0.21	0.10	4.76	3.70
5–50	25.0	25.0	25.0	25.0	0.0	0.0	0.50	0.43	0.33	3.77	1.52
5–100	20.0	20.0	20.0	20.0	20.0	0.0	0.25	0.21	0.16	6.67	1.56
5–200	16.7	16.7	16.7	16.7	16.7	16.7	0.13	0.11	0.08	9.73	1.58
14–100	0.0	0.0	33.3	33.3	33.3	0.0	0.21	0.19	0.16	3.11	1.31

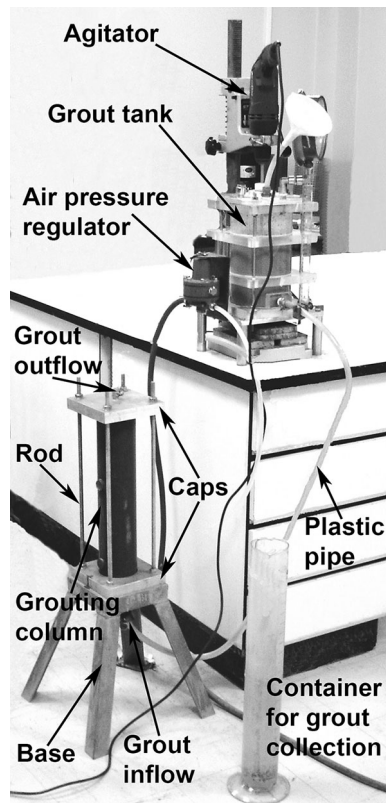


Fig. 2 Experimental setup for injectability evaluation

pressure regulator and by measuring it with a pressure gauge installed on the grout tank. In the cases of limited grout penetration in the sand, the penetration length of the grout was determined by measuring the length of the grouted sand in the column after dismantling it at the end of the injection test.

The investigation of all parameters incorporated in the present research (3 cement types, 4 gradations per cement type, 3 suspension W/C ratios and 54 sand gradations) leads to an excessive number of injection tests. This number was significantly reduced by

applying rational hypotheses and tactically selected succession of tests. For example, the successful injection of a specific cement suspension with $d_{max} = 100 \mu\text{m}$ and/or $W/C = 1$ means that it is not necessary to conduct injections in the same sand with suspensions of higher cement fineness and/or W/C ratios, because they would be successful too. Moreover, the composite sands were grouted only with CEM II/B-M suspensions due to the best overall behavior of them in comparison with the suspensions of the other two cement types (Pantazopoulos et al. 2012). As a result, a total of 131 injection tests (39, 84 and 8 tests in type I, II and III limestone sands, respectively) were performed for the purposes of the current research.

4 Experimental Investigation of Injectability

Presented in Figs. 3, 4, 5, 6 and 7 are the “groutability ratio” values, N_1 , and the ranges of the “groutability ratio”, N_2 , values (Table 1) together with the corresponding experimental results obtained for all grout—sand combinations tested in this investigation. The N_1 and N_2 values were computed using the values of the characteristic grain sizes summarized in Tables 2, 4 and 5 for all cements and limestone sands used in this study. The results of the injection tests were characterized as “satisfactory” when the predetermined quantity of grout (two void volumes of the sand column) was injected with a grouting pressure not exceeding 200 kPa, as “questionable” when either the volume of injected grout was less than the predetermined quantity or grout penetration was less than the length of the sand column (36.5 cm) under the maximum applied pressure (200 kPa), and as “impossible” when grout penetration was very small under the maximum applied pressure of 200 kPa.

Accordingly, the experimental results are presented in Figs. 3, 4, 5, 6 and 7 with white, grey and black data points, respectively. For each sand, the position of the data points in these figures is determined by the values of N_1 and W/C ratios and the shape of the data points is associated with the nominal maximum cement grain size, d_{max} , in Figs. 3 and 4 or with the total percentage of the sand finer part in Figs. 5, 6 and 7. The 131 cases in which, as explained in the previous section, injection tests were conducted, are marked with crosses in Figs. 3, 4, 5, 6 and 7. For different cement types of the same d_{max} injected into a specific sand fraction (Fig. 3), small differences are obtained for the N_1 values which are due to differences in the d_{85} values of the cements (Table 2). As shown in Fig. 3, injectability was “satisfactory” in coarse sand, regardless of the W/C ratio of the suspensions. Injectability in medium sands was, generally, “satisfactory” for cement suspensions with groutability ratios $N_1 > 25$. The medium-to-fine sand was grouted “satisfactorily” with microfine cement suspensions having, generally, W/C = 2 or 3. More specifically, grouting with suspensions having nominal d_{max} of 20 μm and 10 μm was not successful for the cases of suspensions with W/C = 1 which had apparent viscosity values ranging from 22 to 168 mPa·s (Table 3). Conditions were improved when the W/C ratio was increased to 2

yielding apparent viscosity values between 4 and 22 mPa·s and even further improved for suspensions with W/C = 3 (apparent viscosity between 2 and 6 mPa·s). The “satisfactory” injectability of CEM I suspension with $d_{max} = 40 \mu\text{m}$ and W/C = 3 in the medium-to-fine sand can be attributed to the combination of a relatively high N_1 value (22) with increased W/C ratio and low apparent viscosity value (2 mPa·s). This information indicates that the injectability of cement suspensions is controlled not only by the size relation between the sand voids and the cement grains but also by the suspension W/C ratio and viscosity. Penetration in fine sands was negligible for any cement suspension used. The effect of cement type on injectability was not significant. In terms of observed performance, cement types I and II/B-M are rated as about equivalent and slightly superior to cement type IV/B.

As shown in Fig. 4, the basic sands 5–14 and 5–25 are easily groutable by the ordinary and microfine CEM II/B-M suspensions, respectively. However, the modification of the gradation of these sands, with the addition of the finer part, affects considerably the suspension injectability. The experimental results presented in Fig. 5, indicate that the injectability of ordinary CEM II/B-M suspensions in type II sands is reduced as the proportion of the 25–50 and 50–100

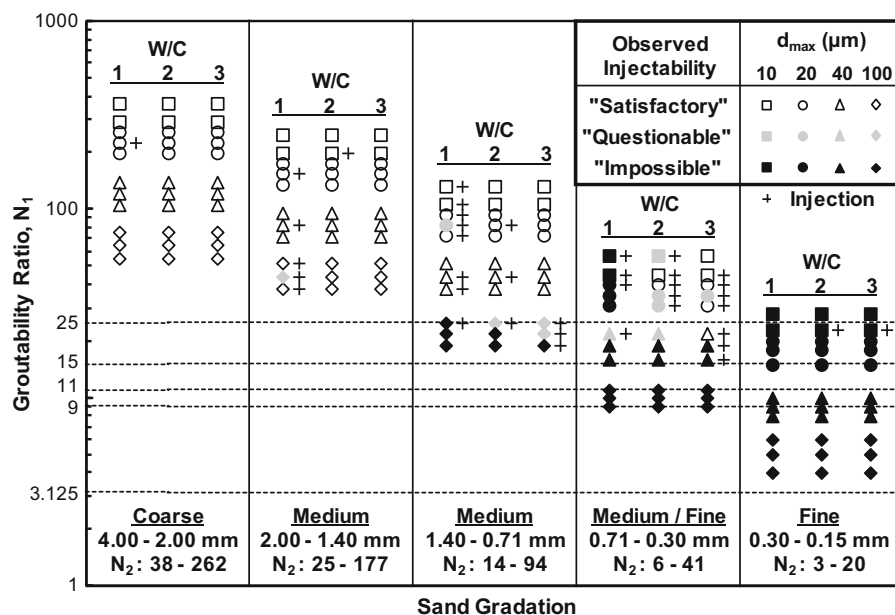


Fig. 3 Comparison of injection test results with the values of N_1 groutability ratio for type I sands and all grout compositions

Fig. 4 Comparison of injection test results with the values of N_1 groutability ratio for basic and type III sands grouted with CEM II/B-M suspensions

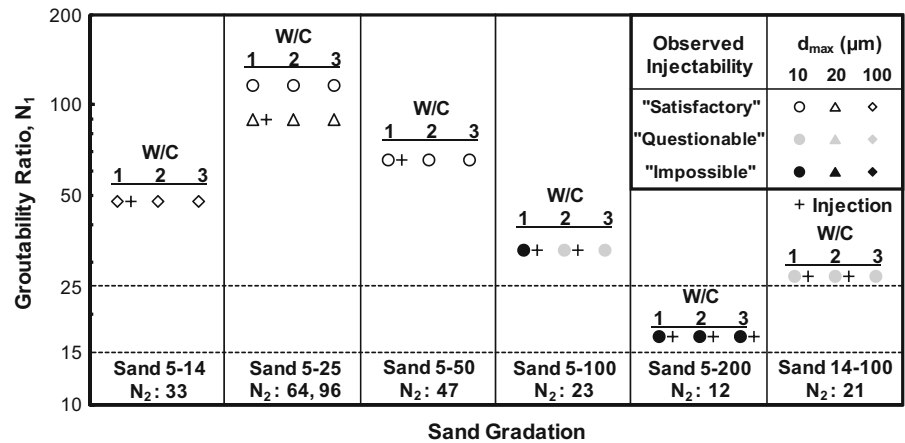
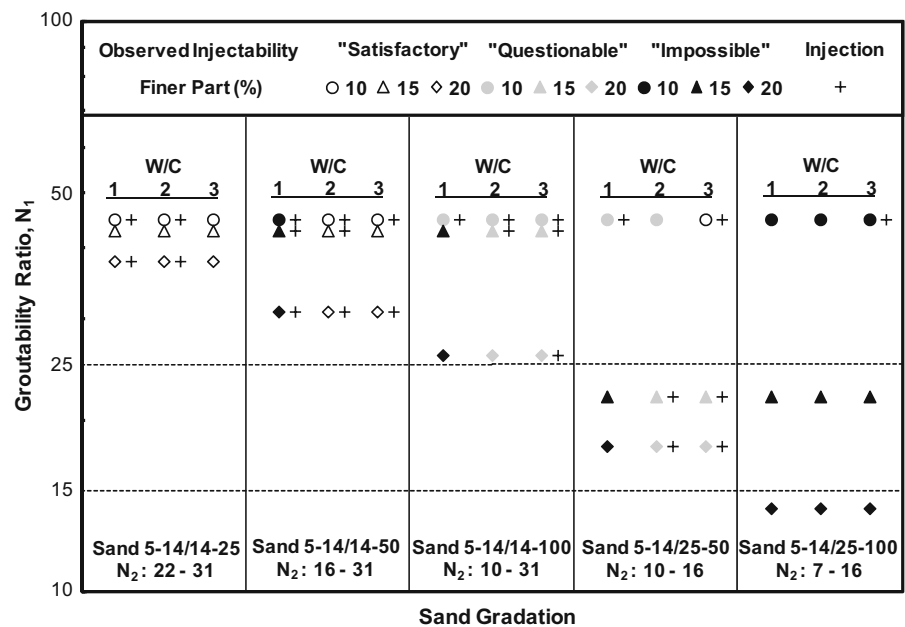


Fig. 5 Comparison of injection test results with the values of N_1 groutability ratio for type II sands (5–14 basic sand) grouted with ordinary CEM II/B-M suspensions



sand fractions increases (Table 5). Similarly, a significant injectability reduction of the microfine CEM II/B-M suspensions, due to the increase of the 50–100 and 100–200 sand fractions (Table 5), is observed in Figs. 4, 6 and 7. The increase of the total percentage of the finer part also leads to injectability limitation on composite sands. For example, the observed injectability deterioration in 5–25/25–200 sands (upper data points in Fig. 6) and in 5–200 sand (Fig. 4), all grouted with CEM II/B-M suspensions of $d_{max} = 10 \mu\text{m}$, is accompanied with values of the total percentage of the finer part (25–200) equal to 10, 15, 20 and 50% (Table 5). Accordingly, the result of the injection process is controlled by the synthesis

(grain sizes and overall percentage) of the finer portion of the sand gradation ($d \leq d_{25}$). This effect is also corroborated by the reasonable agreement of the injection results obtained for sands with identical finer parts and different coarser parts (Figs. 6 (upper data points) and 7), and can be attributed to the variations of the size and distribution of sand voids because of the sand gradation modification. The positive effect of W/C ratio increase or apparent viscosity decrease (Table 3) on the suspension injectability is evident in type II sands as well (Figs. 5, 6, 7). The results obtained by grouting the same type II sands with CEM II/B-M suspensions of $d_{max} = 20 \mu\text{m}$ (lower data points) and $d_{max} = 10 \mu\text{m}$ (upper data points), are

Fig. 6 Comparison of injection test results with the values of N_1 groutability ratio for type II sands (5–25 basic sand) grouted with microfine CEM II/B-M suspensions

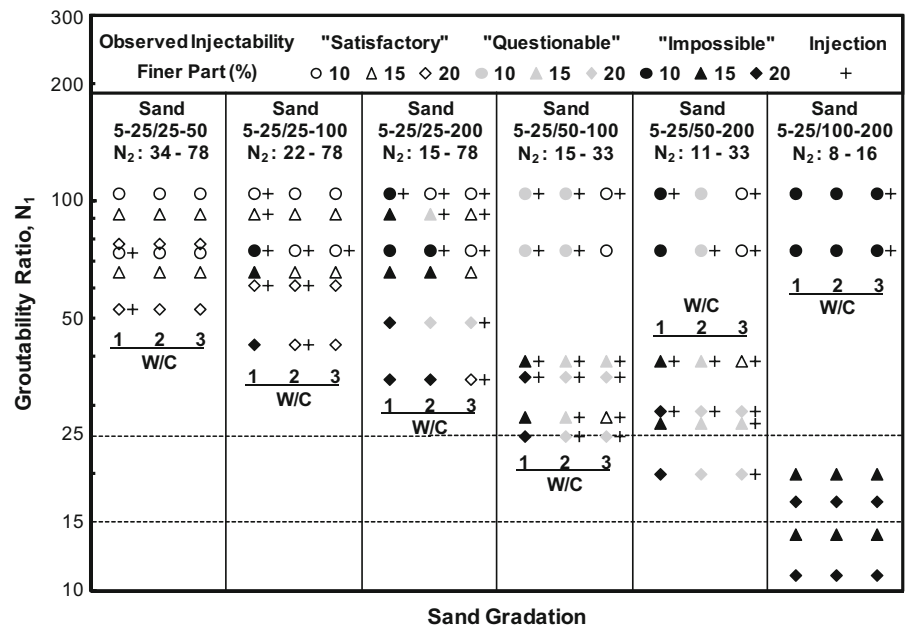
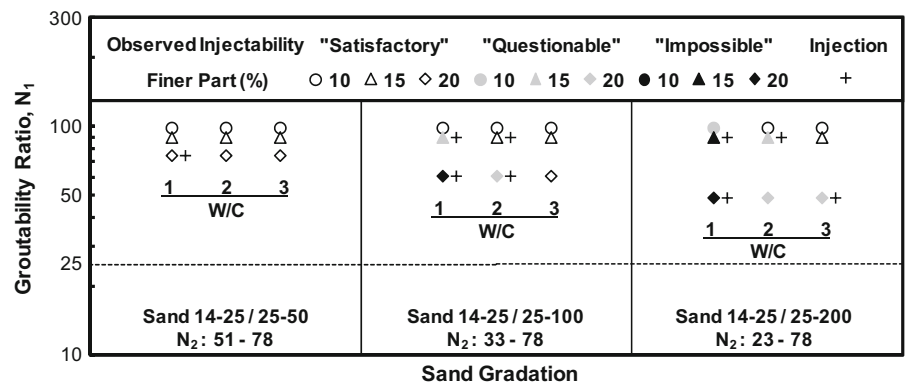


Fig. 7 Comparison of injection test results with the values of N_1 groutability ratio for type II sands (14–25 basic sand) grouted with CEM II/B-M suspensions of $d_{max} = 10 \mu m$



compared in Fig. 6. It can be seen that the performance of the finer cement suspensions ($d_{max} = 10 \mu m$) is equivalent or better than that of the coarser cement suspensions ($d_{max} = 20 \mu m$). This observation possibly indicates that the injectability improvement of microfine cement suspensions due to cement fineness increase, can be negated in some cases by the increased apparent viscosity of CEM II/B-M suspensions with $d_{max} = 10 \mu m$ (Table 3).

5 Efficiency of Existing Groutability Criteria

Apart from the groutability ratio values, N_1 , the limits associated with the relevant groutability criteria of

Table 1 (Mitchell 1981; Krizek et al. 1992; Huang et al. 2007, 2013) are plotted in Figs. 3, 4, 5, 6 and 7. It can be observed that the less optimistic N_1 criterion (Mitchell 1981) is more consistent with the experimental results than the other three N_1 criteria. From the ranges of the groutability ratio, N_2 , values included in Figs. 3, 4, 5, 6 and 7, it is confirmed that the first N_2 criterion (Mitchell 1981) is also more consistent with the experimental results, as grouting is considered possible for the vast majority or almost the entirety of the investigated cases according to the N_2 criteria used by Krizek et al. (1992) and proposed by Huang et al. (2007; 2013), respectively. However, predictions based on the $N_2 > 11$ criterion (Mitchell 1981) are less conservative than those obtained by applying the

$N_1 > 25$ criterion (Mitchell 1981). For example, grouting is considered possible and questionable according to the $N_2 > 11$ and $N_1 > 25$ criteria, respectively, for all cement suspensions of $d_{\max} = 100 \mu\text{m}$ in 14–25 (medium) sand (Fig. 3) and for CEM II/B-M suspensions of $d_{\max} = 10 \mu\text{m}$ in 5–200 sand (Fig. 4). On the other hand, it is observed that, for a number of cases, the $N_1 > 25$ criterion yields rather optimistic predictions which are not always confirmed experimentally. More specifically, the agreement of positive groutability predictions with the experimental results is improved as the suspension W/C ratio increases (or, according to Table 3, as the suspension apparent viscosity decreases) in 25–50 (medium/fine) sand grouted with cement suspensions of d_{\max} equal to 20 μm and 10 μm (Fig. 3), in 5–14/14–50 sands grouted with ordinary CEM II/B-M suspensions (Fig. 5), as well as in 5–25/25–200 and 14–25/25–200 sands grouted with microfine CEM II/B-M suspensions (Figs. 6 and 7). As also shown in Figs. 5, 6 and 7, the significant effect of the finer portion of sand gradation ($d \leq d_{25}$) on the injectability is not fully reflected on the predictions of the $N_1 > 25$ criterion, which are positive for the majority of type II sands. For type II sands consisting of the same basic sand, the values of the N_1 ratio remain constant regardless of the composition of the finer part, are either invariable or variable depending on the finer part composition and change for all finer part compositions, when the percentage of the finer part is equal to 10, 15 and 20%, respectively. These observations indicate that, apart from W/C ratio or viscosity, the N_1 groutability ratio also does not adequately incorporate the effect of the composition of the finer portion of the sand gradation, leading to prediction inefficiency of the pertinent groutability criteria.

Implementation of the groutability criteria proposed by Akbulut and Saglamer (2002) and Yoon and El Mohtar (2013) requires use of the injection pressure (Table 1) and, hence, is feasible for all of the 131 injection tests conducted during this study. For comparison purposes, the efficiency of all the other groutability criteria presented in Table 1 was also evaluated on the basis of these 131 injection tests. The predictions of the available criteria were compared with the 131 laboratory measurements of injectability and the agreement between them indicated successful predictions. The numbers and the percentages of the successful groutability predictions are summarized in

Table 6 for each sand type and in total. The variable FC employed in the composite models of Yoon and El Mohtar (2013) and Huang et al. (2013) is defined as the percentage of soil having particle sizes lower than 0.074 mm and is equal to zero for all sands tested in the present research. Thus, the groutability criteria based on the equations N_9 and N_{10} (Table 1) were not evaluated because the denominator of the second fraction (FC) was always equal to zero. As also shown in Table 1, the criteria based on the N_1 and N_2 ratios were examined either separately (Mitchell 1981; Huang et al. 2007) or in combination (Krizek et al. 1992; Huang et al. 2013) and the results are presented accordingly in Table 6. As a result of the observations presented above, the first criteria based on the N_1 and N_2 ratios (Mitchell 1981) either suggest positive possibility for grouting or cannot provide groutability predictions ($11 < N_1 < 25$ or $6 < N_2 < 11$) in the 19 (14.5%) and 4 (3%) of the 131 cases, respectively. Accordingly, the performance of the N_1 criterion is slightly reduced as compared to the performance of the N_2 criterion, which is the same as the ones of other criteria for the reason mentioned below.

The identical performance of most criteria in all sands (Krizek et al. 1992; Incecik and Ceren 1995; Huang et al. 2007, 2013; Yoon and El Mohtar 2013) or in type II and III sands (Axelsson et al. 2009) is attributed to the fact that they are optimistic and provide positive predictions for grouting in all cases. Consequently, their predictions are in agreement with all successful injection tests and in disagreement with the unsuccessful injection tests. This fictitious performance is possibly justifiable for certain criteria developed for sandy silt soils (Huang et al. 2007; 2013) or sodium pyrophosphate modified bentonite suspensions (Yoon and El Mohtar 2013), materials that are different from those used in the present study. In the criterion of Axelsson et al. (2009), the “fictitious aperture”, b_{fic} , is equal to $0.15 \cdot (d_{50})_{\text{soil}}$ (Table 1) for rather narrow sand grain size distributions. The gradations of uniform type I sands are narrow but, as typically shown in Fig. 1b, the gradations of type II and III sands are not narrow. This observation gives a possible explanation for the optimistic predictions of this criterion in type II and III sands. The same criterion predicted the appearance of filtration ($3 < N_4 < 5$), an issue that is discussed in one of the subsequent sections, in 11 (28%) of the 39 tests with type I sands and, for this reason, it presents relatively

Table 6 Performance of soil groutability criteria

Groutability criteria		Sand type			Overall performance
		I	II	III	
Mitchell (1981)	N ₁	21/39 (54%)	53/84 (63%)	3/8 (38%)	77/131 (59%)
	N ₂	23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
Krizek et al. (1992)		23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
Huang et al. (2007)	N ₁	23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
	N ₂	23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
Huang et al. (2013)		23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
Incecik and Ceren (1995)		23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
Axelsson et al. (2009)		20/39 (51%)	55/84 (66%)	3/8 (38%)	78/131 (60%)
Miltiadou-Fezans and Tassios (2013)		30/39 (77%)	54/84 (64%)	6/8 (75%)	90/131 (69%)
Akbulut and Saglamer (2002)		11/39 (28%)	50/84 (60%)	6/8 (75%)	67/131 (51%)
Yoon and El Mohtar (2013)		23/39 (59%)	55/84 (66%)	3/8 (38%)	81/131 (62%)
Present study (criteria based on N _f)		28/39 (72%)	70/84 (83%)	6/8 (75%)	104/131 (79%)

reduced performance. The parameter FC in the composite model of Akbulut and Saglamer (2002), is the finer content of soil passing through a 0.6-mm sieve and attains values equal to zero for 5–10, 10–14 and 14–25 sands (Table 4) as well as for 5–14, 5–25 and all 5–14/14–25 sands (Table 5). Therefore, the criterion of Akbulut and Saglamer (2002) is inapplicable to 21 (54%) of the 39 tests with type I sands and to 6 (7%) of the 84 tests with type II sands, because the denominator of the second fraction (FC) is equal to zero. This is the reason for the particularly low and decreased performance of this criterion in type I and II sands, respectively. By excluding the cases in which the criterion cannot be applied, the percentages of successful predictions in type I and II sands reach 61% and 64%, respectively, and become comparable to those of the majority of the other criteria, even though the values of suspension W/C ratio are often higher and the values of sand FC are in most cases much greater than the corresponding limits of 2 and 6% (Table 1) below which the criterion provides reasonable predictions (Akbulut and Saglamer 2002). Finally, the criteria proposed by Miltiadou-Fezans and Tassios (2013) demonstrate the best efficiency as they were applied without limitations in all cases, they provide positive and negative groutability predictions for the materials used in this study and they achieve the largest percentages of successful predictions in type I sands (77%) and in type III sands (75%) together with the criterion of Akbulut and Saglamer (2002).

They also have a reduced, but comparable to the other criteria, percentage of successful predictions in type II sands. As a result, they exhibit the best overall performance reaching a percentage of successful predictions almost equal to 70%. It was also noticed that the criterion based on the N₅ ratio (Table 1) was more decisive for negative groutability predictions, since values $N_5 < 5$ were obtained more often than values $N_6 < 2$ and that, as in all criteria of this type, an amount of unsuccessful predictions is due to the fact that the effect of suspension W/C ratio or viscosity on the injectability is not taken into account by these criteria.

6 New Groutability Criteria

From the results presented in the previous sections it is evident that the sizes and percentages of the finer sand grains ($d \leq d_{25}$) determine the size and distribution of the sand voids and, as a result, they affect substantially the outcome of the injection process. For this reason, the prediction inefficiency of the available groutability criteria (Table 6) can also be attributed to the fact that they are based on the characteristic grain sizes d_{10} , d_{15} and d_{50} of soil (Table 1), which appear to be too high to be considerably affected by the composition of the finer part of sand gradation. Consequently, new groutability criteria are proposed in this investigation based on a “modified uniformity coefficient”, defined

as $C_{u,25} = d_{15} : d_{2.5}$, as well as a “modified groutability ratio”, defined as $N_f = (d_{2.5})_{\text{soil}} : (d_{85})_{\text{grout}}$, where $d_{2.5}$ is the sand grain size at which 2.5% of the weight of the specimen is finer and, d_{15} and d_{85} are the characteristic grain sizes of the sand and the cement, respectively, used in the N_1 groutability ratio (Table 1). These modified parameters were chosen to correspond to the finer 25% of the sand gradation. As explained in the previous section on the sands used for this investigation, the grain sizes corresponding to any selected % passing, including d_{15} and $d_{2.5}$, of the sands used can be approximated with confidence. From the values of “modified uniformity coefficient”, $C_{u,25}$, presented in Tables 4 and 5, it can be seen that the sands used in this investigation, can be divided in two groups. Type I, basic (5–14 and 5–25) and type III sands, all having $C_{u,25}$ values lower than 1.60, are included in the first group whereas type II sands with $C_{u,25}$ values higher than 1.60, are included in the second group.

The groutability ratio N_f values are correlated in Fig. 8 with the experimental results obtained for sands with $C_{u,25} < 1.60$. It can be seen that in type I sands (Fig. 8a) and in basic and type III sands (Fig. 8b), “satisfactory” injectability is generally achieved when $N_f > 27$, and when $N_f < 27$, injectability is “questionable” or “impossible”. The predictions of this groutability criterion are not always verified experimentally for the 25–50 sand (Fig. 8a) because this criterion, like all the other groutability criteria of this type, does not take into consideration key factors for suspension injectability, such as W/C ratio or viscosity. The experimental results for all type II sands are presented in Fig. 9 together with the corresponding groutability ratio N_f values. It can be observed that, in sands with $C_{u,25} > 1.60$, “satisfactory” injectability is achieved with suspensions of all W/C ratios when $N_f > 24$, “satisfactory” injectability can generally be achieved with suspensions of W/C ratios equal to 2 and/or 3 when $9 < N_f < 24$, and when $N_f < 9$, injectability is “questionable” or “impossible” with suspensions of all W/C ratios used in this investigation. In the case of 5–25/100–200 sand, where “impossible” injectability is observed even when $N_f > 9$ (Fig. 9b), it can be stated that all N_f values obtained, are very close to the limit $N_f = 9$.

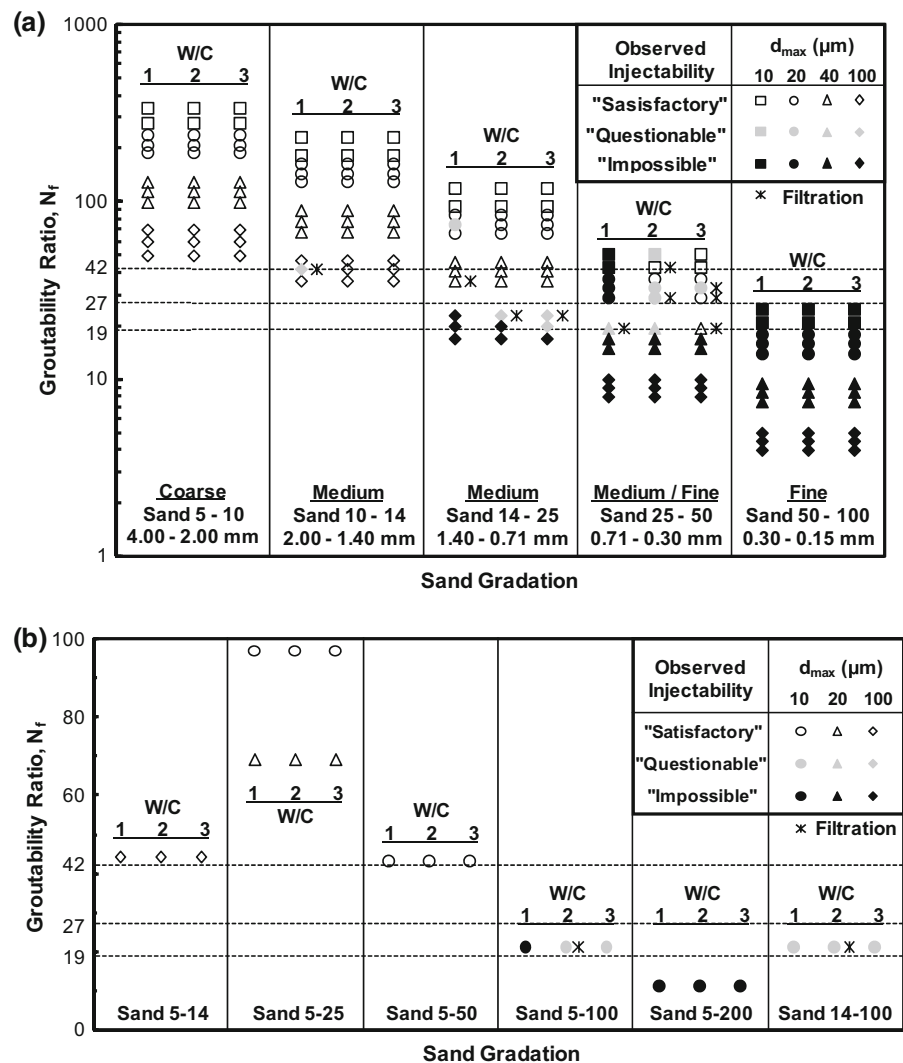
The effectiveness of the new groutability criteria is quantified by comparing their predictions with the results of the 131 injection tests conducted during the

present research. As shown in the last line of Table 6, the percentage of successful predictions of the new criteria exceeds 70% in all three sand types and reaches 83% in type II sands, in which the respective percentages of all the other available criteria range from 60% to 66%. In type I sands, only the Miltiadou-Fezans and Tassios (2013) criteria present a percentage of successful predictions higher by 5% compared to the new ones with all the other criteria having percentages below 60%. In type III sands, the new, the Miltiadou-Fezans and Tassios (2013) and the Akbulut and Saglamer (2002) criteria provide the highest rates of successful predictions (75%) and all the other criteria give percentages equal to 38%. In terms of overall performance, the new criteria present a percentage of successful predictions equal to 79% which is 10% higher than the best of all other available criteria (Miltiadou-Fezans and Tassios 2013). These comparisons substantiate the satisfactory performance of the criteria proposed in this study for the prediction of the injectability of cement suspensions into sands with different gradations.

7 Appearance of Filtration Phenomenon

As explained previously, the injections in the present research were terminated when either the volume of the injected grout was equal to two void volumes of the sand in the grouting column or when the injection pressure became equal to 200 kPa with no grout flow. As a result, during many injection tests, a quantity of grout (up to one void volume of the sand column) was collected at the outlet of the grouting columns with a volumetric container (Fig. 2) and was used for the investigation of the withholding of grout solids in the sand voids. Shortly after completion of the injection, the total amount of the collected grout was homogenized by agitation and a smaller specimen with a weight approximately equal to 250 g was taken from the container to facilitate the drying process. Then, the grout specimen was weighed and oven-dried for 24 h at 105 °C. Subsequently, the dry weight of the cement was determined by weighing the dry specimen. Based on these measurements, the W/C ratio of the suspension gathered at the outlet of the grouting column was quantified with computations equivalent to those used for the determination of the water content of soils. The results obtained with this procedure are considered as

Fig. 8 Development of new groutability criterion and appearance of filtration phenomenon in **a** type I sands and **b** basic and type III sands

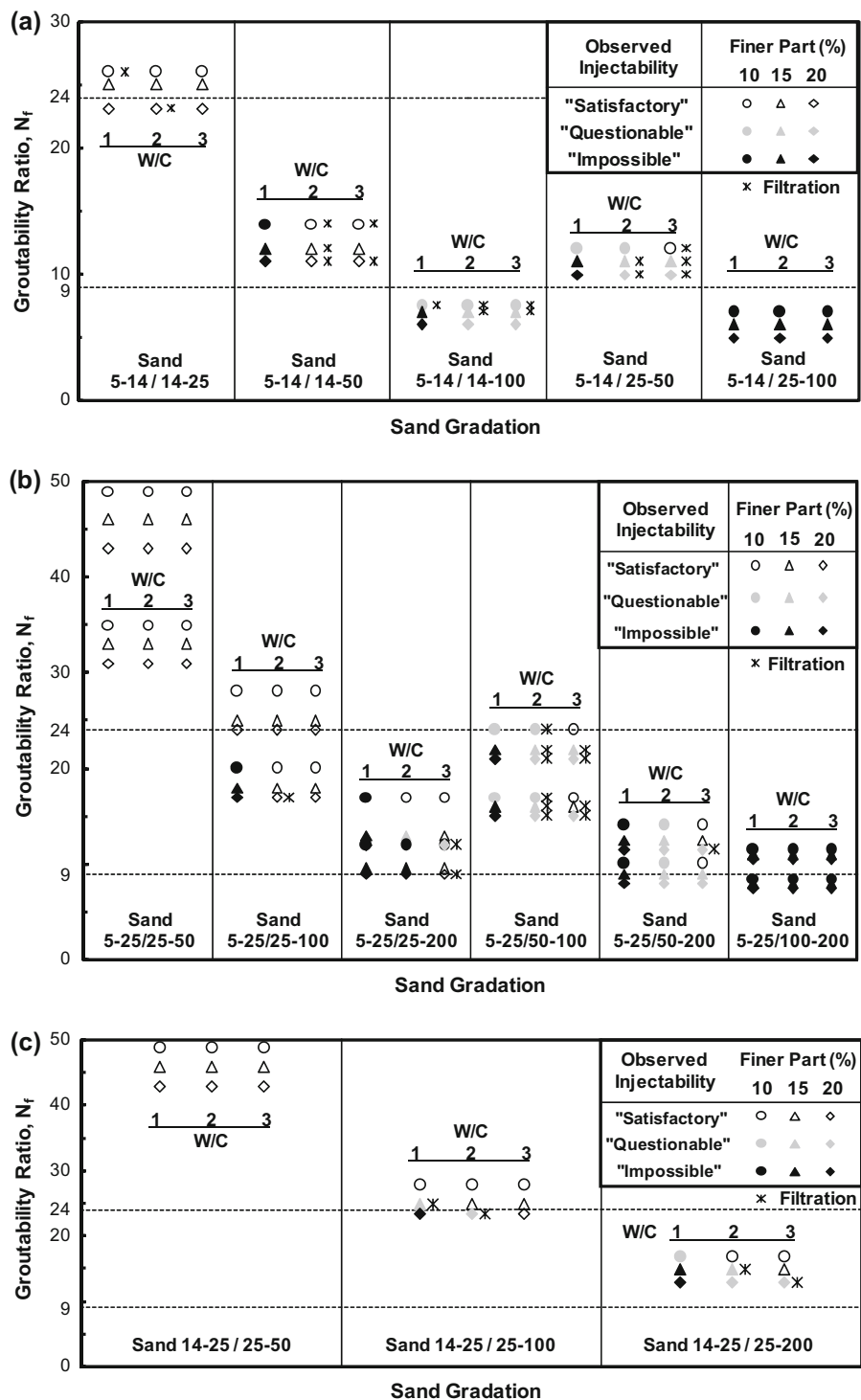


credible because, according to Schwarz and Krizek (1994), the amount of water inevitably bound by the cement (even after oven-drying) due to hydration does not introduce significant error in the computation of the weights of cement and water.

By applying the abovementioned procedure, the 47 cases in which the suspension W/C ratio at the outlet increased substantially (increase > 10%) during injection are marked with asterisks in Figs. 8 and 9 for sands with $C_{u,25}$ values lower and higher than 1.60, respectively. The W/C ratios of the suspensions collected at the outlet of the 14–25 sand columns grouted with cement II/B-M suspensions of $d_{max} = 100 \mu m$ and initial W/C ratios equal to 2 and 3 (Fig. 8a), were as high as 35 and 20, respectively.

Additionally, almost clean water (negligible amount of grout solids) was collected at the outlet of the 5–14/25–50/20 sand column, when grouted with cement II/B-M suspension of $d_{max} = 100 \mu m$ and $W/C = 3$ (Fig. 9a). These observations indicate the appearance of filtration phenomenon, which is sometimes so intense that it leads to an increase by up to 1650% of the suspension W/C ratio during grouting or even to the withholding of nearly the whole amount of grout solids in the sand voids. The occurrence of filtration was not always coupled with high injection pressure, as in almost 35% of the abovementioned cases the maximum injection pressures were relatively low, not exceeding 80 kPa. In all other cases, filtration was not detected since the W/C ratio in the grout outflow from

Fig. 9 Development of new groutability criterion and appearance of filtration phenomenon in type II sands prepared with **a** 5–14, **b** 5–25 and **c** 14–25 basic sand



the sand columns attained values ranging from 0.95 to 1.05, from 1.76 to 2.12 and from 3.01 to 3.26 for suspensions with initial W/C ratios equal to 1, 2 and 3,

respectively. The fact that the W/C ratio values after grout penetration into the sands are, in some of these cases, lower than the initial W/C ratios can be possibly

attributed to the absorption of a quantity of suspension water from the dry sand grains (Perret et al. 1997) and to the amount of water bound by the cement as a consequence of the hydration reactions. However, the potential effect of the last factor on the obtained results does not appear to negate the trustworthiness of the procedure used in the present research for the qualitative investigation of filtration.

By combining the filtration observations with the injectability of cement suspensions into type I and III sands (Fig. 8), it can be seen that the appearance of filtration phenomenon in a certain sand was always accompanied by “satisfactory” and “impossible” injectability of the same suspension in the coarser and the finer sand, respectively. For example, the CEM IV/B suspension with $d_{\max} = 100 \mu\text{m}$ and $W/C = 1$ presented “satisfactory” injectability, filtration and “impossible” injectability in 5–10, 10–14 and 14–25 sands, consecutively (Fig. 8a), and the microfine CEM II/B-M suspension of $W/C = 2$ demonstrated “satisfactory” injectability in 5–50 sand, filtration in 5–100 sand and “impossible” injectability in 5–200 sand (Fig. 8b). Therefore, it can be stated that filtration is a transitional stage between satisfactory and inadequate injectability of ordinary and pulverized cement suspensions, in agreement with Axelsson et al. (2009). The manifestation of filtration also depends on the gradation of cement and/or sand because the penetration of the CEM II/B-M suspensions with $d_{\max} = 100 \mu\text{m}$ in type II sands was accompanied by filtration, frequently very intense, in 17 of the 20 studied cases (Fig. 9a), while the microfine CEM II/B-M suspensions exhibited filtration mostly in 5–25/50–100 sands (Fig. 9b). Eklund and Stille (2008) reported that the grain size and grain size distribution of cement are of great importance to filtration tendency of grouts and that the grain size distribution should be relatively steep (narrow grain size range) between minimum and maximum grain sizes. As shown in Table 2, the differences between the characteristic grain sizes, d_{05} , of ordinary and microfine cements are higher in comparison with the differences between the characteristic grain sizes, d_{10} , of the same cements. Accordingly, the ordinary cements used in the present investigation are more inclined to filtration because they have a wider gradation than the microfine cements.

Based on the results of one-dimensional injection tests in sand columns, Axelsson et al. (2009) reported

that the stoppage of grout flow in the sand voids is governed by a filtration process for the grout grains when the values of the N_4 ratio range approximately from 3 to 5 (Table 1). The values of the N_4 ratio were calculated for the 47 cases in which filtration took place during the present research and it was found that they are in agreement with the range of values proposed by Axelsson et al. (2009) in almost half of the cases in type I sands, whereas they are always greater than 5 in type II and III sands. As explained before, these findings can also be attributed to the sand gradations that are narrow in type I sands and not narrow in type II and III sands. The new groutability criteria proposed in the previous section, were extended to include the prediction of the appearance of filtration as well. As shown in Fig. 8, filtration is expected to occur in sands with $C_{u,25} < 1.60$, when $19 \leq N_f \leq 42$. In sands with $C_{u,25} > 1.60$ (Fig. 9), filtration generally takes place when $9 \leq N_f \leq 24$. Although some cases in Fig. 9 are out of the aforementioned range of values, the limits of the last criterion were kept identical to the ones of the corresponding groutability criterion for simplicity reasons. Nevertheless, the total percentage of successful predictions of these “filtration criteria” is equal to 83% of the 47 cases in which filtration occurred during the current research, indicating that the anticipation of filtration appearance is justifiable when the values of N_f ratio are within the proposed limits.

8 Model for Injectability Prediction

Despite the satisfactory performance of the proposed criteria based on the N_f groutability ratio, it was decided to apply the Binary Logistic Regression method to the available experimental measurements in an attempt to develop a model for the injectability prediction of cement grouts. The new model is considered advantageous because it is not based solely on characteristic grain sizes of grout and soil and takes into consideration suspension viscosity which has an effect on injectability, and because it was generated by injection tests on sands with a variety of gradations. Logistic Regression, also called a logit model, is a method applicable to a broader range of research situations than discriminant analysis. It is a non-linear transformation of the linear regression in which the independent variables are combined to estimate the

probability that a particular event will occur or not. So, it is useful when the aim is the prediction of the presence or the absence of an outcome. The probabilities of the sure occurrence and the sure non-appearance of the event are denoted by 1 and 0, respectively. The independent variables may be a mix of metric or non-metric. The dependent variable is categorical (usually dichotomous) and when it has two categories, the method is called Binary Logistic Regression. More information about the Logistic Regression method is provided by Hosmer and Lemeshow (2000) and Agresti (2007). A Binary Logistic Regression model has the following form:

$$\ln\left(\frac{p}{1-p}\right) = b_0 + b_1 * x_1 + b_2 * x_2 + \dots + b_n * x_n \quad (1)$$

which is equivalent to:

$$p = \frac{1}{1 + e^{-[b_0 + b_1 * x_1 + b_2 * x_2 + \dots + b_n * x_n]}} \quad (2)$$

where x_i , $i = 1, 2, \dots, n$ are the independent variables, b_i , $i = 0, 1, \dots, n$ are the constant terms of the independent variables, p is the probability of occurrence of an outcome ($0 \leq p \leq 1$ or $0\% \leq p \leq 100\%$) and $1 - p$ is the inverse of p , i.e. the probability of non-occurrence of an outcome. The terms $p/(1 - p)$ and $\ln[p/(1 - p)]$ are called “odds” and “logit”, respectively.

The first step for the development of the injectability prediction model was the selection of the variables. The dependent variable should represent efficiently the success or failure of injection. The independent variables should represent factors affecting substantially the injectability of cement grouts into sands with different gradations. It is important that variables do not hinge on the materials and procedures used in the present research. Consequently, the probability of success (satisfactory injectability) of the injection was selected as the dependent variable with input values equal to 1 or 0 for successful and unsuccessful injections, respectively. The dependent variable was correlated to independent variables pertinent to the suspension and the sand. Different independent variables were tested in order to result in the most appropriate ones for the model. More specifically, the characteristic grain sizes, d_{10} and d_{15} , of the sand and the characteristic grain sizes, d_{85} , d_{90} and d_{95} , of the

cement were examined because they are used in the majority of the available criteria for the estimation of soil groutability (Table 1). As it was shown earlier, the synthesis of the finer portion of the sand gradation ($d \leq d_{25}$) affects significantly the injectability of cement suspensions. This effect was taken into consideration by incorporating alternatively the characteristic grain size, $d_{2.5}$, and the “modified uniformity coefficient”, $C_{u,25} = d_{15} : d_{2.5}$, of the sands into the injectability prediction model. The combined effect of the cement type and fineness, the W/C ratio and the superplasticizer addition on grout injectability was taken into consideration by including the suspension apparent viscosity, which is influenced by these suspension composition parameters (Pantazopoulos et al. 2012), in the independent variables. The apparent viscosity values obtained at $t = 30$ min after preparation and at viscometer rotation speed equal to 60 rpm (Table 3) were utilized, since a time margin of 30 min from grout preparation is regarded as suitable for grouting applications. By investigating the effect of the injection pressure on grout penetrability (Markou et al. 2015), it was observed that the penetration length of cement suspensions into sand columns increases with increasing injection pressure, in agreement with the observations of other researchers (Akbulut and Saglamer 2002; Santagata and Santagata 2003). For this reason, the maximum injection pressure was used as independent variable in the development of fuzzy linear regression models for the penetrability estimation of cement grouts (Markou et al. 2015). However, as confirmed by other research efforts (Akbulut and Saglamer 2002; Mollamahmutoglu 2003), the increase of injection pressure is not by itself adequate for penetrability improvement in cases where the size relation between the sand voids and the cement grains does not favor the penetration of suspension into the sand (Markou et al. 2015). Accordingly, the injection pressure was not included in the independent variables of the model reported herein because the injectability of a suspension grout is determined mostly by the size relation between the sand voids and the grout solids.

The measurements from the 131 one-dimensional injection tests conducted during this research effort were utilized for the determination of the model. As described in the previous sections, the injection tests were conducted with a variety of suspensions and limestone sands with different gradations. The

different combinations and the variations of the aforementioned independent variables led to the examination of numerous models by applying the Binary Logistic Regression method with suitable statistical software. As a result, the characteristic grain size d_{85} of the cement, the characteristic grain sizes $d_{2.5}$ and d_{15} of the sand and the apparent viscosity were found to represent more effectively the problem confronted and were selected as the final independent variables. After a large number of trials, the model proposed for injectability prediction has the following form:

$$\ln\left(\frac{p}{1-p}\right) = 1.571 * \left[\ln\left(\frac{d_{2.5}}{d_{85}}\right)\right]^2 + 1.933 * [\ln(d_{15})]^3 - 0.075 * visc - 4.893 \quad (3)$$

where p is the probability of success of the injection, d_{85} is the grain size of the cement in mm at which 85% by weight of the specimen is finer, $d_{2.5}$ and d_{15} are the grain sizes of the sand in mm at which 2.5% and 15% by weight of the specimen is finer, respectively, and $visc$ is the suspension apparent viscosity in mPa·s, obtained at time $t = 30$ min after preparation and at viscometer rotational speed equal to 60 rpm. The assessment of the numerical form of the model was achieved by performing the necessary statistical analysis. The conditions that must be satisfied so that the model is statistically acceptable, are: (a) the numerical form of the model must be statistically significant, (b) the predictor (independent) variables must be closely related with the dependent variable but they must not be related to each other, (c) the independent variables must be able to describe and explain the model, and (d) the achievement of good fit of the model to the sample (i.e. the set of measurements used for the development of the model). By checking the model with the statistical analysis software, it was found that it met all the above requirements after excluding 22 of the 131 measurements comprising the initial sample. Based on the data processing of the remaining 109 experimental measurements, the resulting coefficient of multiple determination, R^2 , of Eq. (3) is equal to 0.84. This acceptable R^2 value indicates that the independent variables are able to describe adequately the dependent variable and the satisfactory conformity of the model to the experimental data.

The ability of the proposed model to give trustworthy results is initially shown by the fact that it estimated correctly the result of the 109 injection tests used to create it, at a rate of 94%. This percentage is higher than all the percentages presented in Table 6 and resulted from approximately the same set of measurements, indicating a better performance of the proposed model in comparison with the available or new groutability criteria. The validity examination of the model was continued using injection tests that had not been used for its generation. By importing for each injection test, the set of experimental data corresponding to the independent variables in Eq. (3), the probability of success of the injection, p , was computed. When the value of p was greater or lower than 0.5 (or 50%), the injectability was considered satisfactory or unsatisfactory, respectively. The model predictions were considered successful when they were in agreement with the experimental results. This comparison was made at first with the 244 cases in the present research, for which the injection result was not obtained experimentally but, as explained earlier, it was found by applying rational hypotheses after taking into consideration the results of the injection tests. As a result, the percentage of successful injectability predictions of the model was as high as 87%. For completeness reasons, it was considered significant to compare the model predictions with the injection test results of other studies as well. After an extensive literature review, the measurements from 96 one-dimensional tests into sand columns with a height ranging from 10 to 150 cm (Krizek et al. 1986; De Paoli et al. 1992b; Perret 1997; Bouchelaghem and Vulliet 2001; Santagata and Santagata 2003; Mollamahmutoglu et al. 2007; Tekin and Akbas 2011; Mollamahmutoglu and Yilmaz 2011) or multi-dimensional tests (Bouchelaghem et al. 2001; Kim et al. 2009) were gathered. The tests were conducted with ordinary and mostly microfine cement suspensions of W/C ratios ranging from 0.5 to 6 and a variety of sands with $d_{2.5}$ ranging from 0.03 mm to 1.80 mm, d_{15} ranging from 0.12 mm to 2.22 mm and C_u ranging from 1.18 to 12.50. The $d_{2.5}$, d_{15} and C_u ranges of those sands are comparable to the $d_{2.5}$, d_{15} and C_u ranges of the sands tested in the research reported herein (Tables 4 and 5). Although the viscosity values of the suspensions used in these 96 injection tests are available making the implementation of the model feasible, they were not obtained at $t = 30$ min after

preparation and at viscometer rotation speed equal to 60 rpm as required by the model. However, these values were applied to the model leading to a reasonably good performance given that the percentage of successful predictions of the model was almost equal to 60%. All the abovementioned findings corroborate the suitability of the proposed model for the injectability prediction of cement grouts in sands.

9 Conclusions

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

1. The use of microfine cements, produced by pulverizing ordinary cements, improves the injectability of cement suspensions rendering them effective for grouting of medium-to-fine sands. Suspension injectability is improved by increasing W/C ratio and decreasing apparent viscosity, is controlled by the synthesis (grain sizes and overall percentage) of the finer portion of the sand gradation ($d \leq d_{25}$) and is not significantly affected by cement type.
2. 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 some groutability criteria.
3. The criteria proposed by Miltiadou-Fezans and Tassios (2013) were applied without limitations in all cases available in this study, achieving a percentage of successful predictions almost equal to 70% and exhibiting the best performance in comparison with the existing groutability criteria.
4. New groutability criteria based on a “modified uniformity coefficient” and a “modified groutability ratio”, corresponding to the finer portion of the sand gradation ($d \leq d_{25}$), are proposed in this study. These new criteria yield a percentage of successful predictions almost equal to 80% which is 10% higher than that of the best of all other available criteria (Miltiadou-Fezans and Tassios 2013).
5. The appearance of filtration is a transitional stage between satisfactory and inadequate suspension injectability, depends on the gradation of cement and/or sand and can even lead to the withholding of nearly the whole amount of grout solids in the sand voids. The new “filtration criteria” proposed in the present study, predicted successfully the filtration occurrence in 83% of the available cases.
6. The Binary Logistic Regression analysis of the injection test results obtained during this research effort, has led to the development of a model for injectability prediction. Factors pertinent to the suspension and the sand, which affect substantially the injectability of cement grouts, are represented by the independent variables of the model. The resulting coefficient of multiple determination, R^2 , is equal to 0.84 indicating satisfactory conformity of the model to the experimental measurements. The predictions of the model are in very good and reasonable agreement with the experimental results of this study and other studies, respectively. Therefore, the new model appears to be an efficient tool for the injectability prediction of cement suspensions in sands with different gradations.

As with a large number of similar laboratory investigations reported in the literature, the experimental investigation reported herein was limited to one-dimensional grout flow (a simplification of the actual three-dimensional field conditions). However, the injection process is adequately simulated on a laboratory scale and, on the basis of the results obtained, the injectability of the microfine cement suspensions developed during this research effort, is sufficiently documented. The conducted measurements of grout injectability, accompanied by the study of the effect of several parameters pertinent to the suspension and the limestone sand and the detection of the appearance of filtration, contribute to the integrated knowledge of the suspension grouting process. Finally, there are adequate indications that the injectability of cement suspensions in sands with different gradations can be predicted successfully by means of the criteria or the model

developed in this study. Accordingly, the findings of the present research can be used as a guide in permeation grouting applications and, at the same time, can be confirmed by injections conducted in the field.

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