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Efficiency of soil groutability criteria for cement suspension grouting

Efficacité des critères d'injectabilité dans le sol pour des injections des ciments en suspension

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ABSTRACT: The design of permeation grouting projects in soil formations is based on the suspension groutability, which is frequently predicted with the utilization of simple groutability criteria. The effectiveness of the groutability estimations made by applying available criteria is documented in the present study. Toward this end, a database was created comprising published experimental results obtained from 489 injection tests and was used for comparison with the estimations of eight different sets of known groutability criteria. The outcome of the injection tests is successfully predicted by the groutability criteria at a rate ranging between 50% and 69%. The groutability criteria adapted to the finer 25% of the sand gradation, provide the maximum rate of successful predictions (almost 70%) which is 4% to 19% higher than those of the other criteria.

RÉSUMÉ: La conception des projets d'imprégnation par injection dans les formations de sol, est basée sur la capacité d'injectabilité en suspension, qui est souvent prévue à l'aide d'utilisation des critères simples d'injectabilité. L'étude présente documente l'efficacité des estimations d'injectabilité faites en appliquant les critères disponibles. À ce fin, une base de données contenant les résultats expérimentaux publiés, obtenus à partir de 489 tests d'injection, a été créée. Elle a été utilisée pour des raisons de comparaison avec les estimations de huit ensembles différents des critères d'injectabilité connus. Les critères d'injectabilité sont capables à prévoir avec succès le résultat des tests d'injection à un taux de 50% à 69%. Les critères d'injectabilité adaptés à la plus fine fraction granulométrique (25%) des sables, fournissent le taux maximal des prédictions réussies (près de 70%), qui est supérieur de 4% à 19% à celui des autres critères.

Keywords: permeation grouting; cement suspensions; sands; groutability criteria; injection test database

1 INTRODUCTION

The safe construction and operation of many structures frequently requires improvement of soils by permeation grouting with cement suspensions. 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 in the last decades and utilized in grouting projects. The design of 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 based on the results obtained mostly from one-dimensional and, in some cases, from multi-dimensional injection tests.

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. Consequently, the study reported herein aims toward the documentation of the dependability of the available groutability criteria. For the purposes of this investigation, the groutability estimations made by applying criteria for a variety of cement grouts and soils are compared with published results obtained from 489 one-dimensional laboratory injection tests of cement grouts into sand columns of various lengths, multi-dimensional and large scale injection tests.

2 GROUTABILITY CRITERIA

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 continuing with 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. 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. 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 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.

Based on the results of 131 one-dimensional injection tests conducted with suspensions of ordinary and fine-grained cements of three different types and 54 clean sands with different gradations, Markou et al. (2018) observed that the sizes and percentages of the finer sand grains ($d \leq d_{25}$) affect substantially the outcome of the injection process. For this reason, they proposed the "new groutability criteria" shown in Table 1, which are adapted to the finer 25% of the sand gradation (Markou et al. 2018). These "new groutability criteria" are based on a "modified uniformity coefficient", $C_{u,25}$, and a "modified groutability ratio", N_f, 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. As explained previously, these modified parameters were chosen to correspond to the finer 25% of the sand gradation. The sands are divided in two groups according to the $C_{u,25}$ values (Table 1). In sands with $C_{u,25} < 1.60$ (first group), "satisfactory" groutability is generally achieved when $N_f > 27$, and when $N_f < 27$, groutability is "questionable" or "impossible". In sands with $C_{u,25} > 1.60$ (second group), "satisfactory" groutability is achieved when $N_f > 24$, when $9 < N_f < 24$, "satisfactory" groutability can also be achieved with suspensions of $W/C \geq 2$, and when $N_f < 9$, groutability is generally "questionable" or "impossible".

Table 1. 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)	$N_4 = \frac{b_{fic}}{(d_{95})_{grout}} = \frac{0.15 \cdot (d_{50})_{soil}}{(d_{95})_{grout}}$	$N_4 > 5$ 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 $N_6 > 2$	---------
Markou, Christodoulou, Petala and Atmatzidis (2018)	$C_{u,25} = \frac{(d_{15})_{soil}}{(d_{2.5})_{soil}}$ $N_f = \frac{(d_{2.5})_{soil}}{(d_{85})_{grout}}$	For sands with $C_{u,25} < 1.60$: $N_f > 27$ For sands with $C_{u,25} > 1.60$: $N_f > 24$ or $9 < N_f < 24$ and $W/C \geq 2$	 $N_f < 27$ $N_f < 9$ or $9 < N_f < 24$ and $W/C < 2$

3 EXPERIMENTAL MEASUREMENTS OF GROUTABILITY

After an extensive literature review, the measurements from 467 one-dimensional tests into sand columns with a height ranging from 10 cm to 192 cm were gathered and available information regarding the grouts and soils used and the tests performed is presented in Table 2. Although one-dimensional tests allow for adequate laboratory simulation of the injection process and for the conduct of more tests due to the saving of materials and time, they are considered as a simplification of the actual three-dimensional field conditions. Therefore, as shown in Table 3, the results of 22 large scale injection tests (Bouchelaghem et al. 2001) and multi-dimensional injection tests conducted in the laboratory (Shimoda and Ohmori 1982; Mittag and Savvidis 2003; Kim et al. 2009) or in the field (Van der Stoel 2001), were also used in the present study. In terms of gradation, all cements with d_{95} < 20 μm and Blaine specific surface over 800 m^2/kg can be considered as "microfine" because they satisfy the requirements of standard EN 12715 (CEN 2000). Accordingly, the tests were conducted with ordinary and mostly microfine cement suspensions of W/C ratios ranging from 0.5 to 10. From the gradation characteristics shown in Tables 2 and 3, it can be observed that sands with different grain sizes and gradations were injected with the cement grouts. In a few cases, the sands contained fine-grained material (soil with particle sizes smaller than 0.074 mm).

Table 2. Data of research studies based on one-dimensional injection tests

Reference	Cements						Grout	Soils						Injection Tests			
	No.	Blaine (m^2/kg)	Grain Sizes				Grout W/C Ratios	No.	Gradation Characteristics					No.*	Sample Dimensions		Injection Pressure (kPa)
			d_{99} (µm)	d_{95} (µm)	d_{90} (µm)	d_{85} (µm)			d_{50} (mm)	d_{15} (mm)	d_{10} (mm)	$d_{2.5}$ (mm)	$C_{u,25}$		Height (cm)	Diameter (cm)	
Shimoda and Ohmori (1982)	1	815	10.0	8.0	6.5	6.0	2, 3, 4	1	0.20	0.175	0.17	0.12	1.46	3 (0)	24.8	-----	-----
Krizek et al. (1986)	1	820	10.0	8.5	7.5	6.0	2, 4, 6	2	0.15, 1.50	0.13, 0.43	0.12, 0.35	0.11, 0.25	1.18, 1.72	6 (6)	150	10	517
Paillere et al. (1989)	10	295-408	45.0-160.0	30.0-140.0	26.0-120.0	22.0-100.0	0.75-2	3	0.85-2.00	0.68-1.74	0.63-1.70	0.21-1.65	1.05-3.21	27 (13)	36	-----	-----
Zebovitz et al. (1989)	1	820	10.0	8.5	7.5	6.0	2, 4, 6	3	0.24-1.50	0.17-0.43	0.15-0.35	0.09-0.25	1.72-1.89	12 (11)	132	10.6	586
Miltiadou (1991)	17	298-408	64.0-200.0	31.0-136.0	25.0-110.0	22.0-96.0	0.5-1.5	2	0.90, 2.00	0.72, 1.74	0.70, 1.70	0.63, 1.65	1.15, 1.05	44 (21)	36	-----	75
De Paoli et al. (1992)	3	-----	8.0-20.0	6.0-15.0	5.0-12.0	4.0-9.0	1-5	2	0.16, 0.32	0.15, 0.24	0.145, 0.22	0.14, 0.17	1.07, 1.41	30 (16)	50	4	70
Uchikawa (1994)	4	338-1030	15.0-75.0	10.0-55.0	8.0-45.0	7.8-35.0	2	3	0.18-0.55	0.12-0.46	0.11-0.45	0.10-0.40	1.13-1.20	12 (3)	-----	-----	-----
Sano et al. (1996)	1	900	9.5	8.0	7.0	6.5	10	1	0.18	0.10	0.09	0.08	1.25	9 (5)	192	5	-----
Perret (1997)	2	1200, 400	11.0, 60.0	10.0, 50.0	8.0, 40.0	7.5, 30.0	0.5-2	4	0.34-1.50	0.20-0.80	0.15-0.75	0.10-0.65	1.23-2.50	7 (4) 4 (3)	36 25	2.2 2.2	76 11
Santagata and Collepardi (1998)	3	-----	9.0-20.0	6.5-18.0	5.5-14.0	4.3-11.0	0.5-1.35	4	0.50-1.00	0.35-0.50	0.35-0.46	0.20-0.30	1.61-2.24	12 (10)	46	3.8	200
Bouchelaghem and Vulliet (2001)	1	1200	11.0	10.0	9.0	8.0	4	1	0.50	0.17	0.15	0.03	5.67	1 (1)	83	7	50
Akbulut and Saglamer (2002)	1	300	120.0	60.0	45.0	35.0	0.8-3	10	0.40-3.00	0.35-2.70	0.32-2.50	0.30-0.60	1.26-7.71	38 (10)	20	10	250
Mittag and Savvidis (2003)	1	-----	12.0	9.0	7.5	5.5	5	1	0.25	0.15	0.12	0.085	1.76	5 (5)	100	10	700
Santagata and Santagata (2003)	1	-----	10.0	7.5	6.0	4.5	1.5-5	3	0.55-1.40	0.25-0.35	0.17-0.32	0.09-0.24	1.46-3.33	14 (1)	46	4	200
Akbulut and Saglamer (2004)	1	306	120.0	75.0	60.0	35.0	1, 1.5, 2	1	2.00	0.85	0.70	0.50	1.70	3 (3)	20	10	100
Maalej (2007)	1	1200	12.0	10.0	8.5	7.5	5	1	0.24	0.18	0.16	0.12	1.50	1 (1)	110	8	1000

* The total number of injection tests is accompanied by the number of successful injection tests in parentheses.

Table 2. continued

Reference	Cements						Grout	Soils						Injection Tests			
	No.	Blaine (m^2/kg)	Grain Sizes				*W/C* Ratios	No.	Gradation Characteristics					No.*	Sample Dimensions		Injection Pressure (kPa)
			d_{99} (μm)	d_{95} (μm)	d_{90} (μm)	d_{85} (μm)			d_{50} (mm)	d_{15} (mm)	d_{10} (mm)	$d_{2.5}$ (mm)	$C_{u,25}$		Height (cm)	Diameter (cm)	
Mollamahmutoglu et al. (2007)	1	625	30.0	15.7	13.3	11.9	1	4	0.60-1.00	0.26-0.58	0.24-0.55	0.12-0.45	1.29-2.31	16 (9)	10	9.6	650
Axelsson et al. (2009)	1	-----	20.0	16.0	13.0	10.0	1, 3	3	0.18-0.56	0.13-0.32	0.12-0.30	0.09-0.28	1.14-1.60	4 (1)	90	10	260
Mollamahmutoglu and Yilmaz (2011)	1	900	20.0	15.0	11.0	6.5	1	8	0.60-1.60	0.16-0.74	0.12-0.64	0.10-0.49	1.39-2.30	20 (14)	10	9.6	1000
Tekin and Akbas (2011)	1	900	20.0	15.0	11.0	8.8	1	14	0.25-1.75	0.12-0.51	0.10-0.36	0.075-0.08	1.50-6.80	14 (9)	10	9.6	100
Miltiadou-Fezans and Tassios (2013)	22	-----	48.0-190.0	31.0-136.0	24.0-110.0	21.9-99.0	0.75	5	0.90-2.00	0.72-1.74	0.70-1.65	0.63-1.64	1.05-1.15	54 (30)	36	-----	75
Markou et al. (2018)	12	384-942	9.7-68.0	8.2-57.0	6.8-45.0	6.0-39.0	1, 2, 3	54	0.105-2.83	0.082-2.25	0.079-2.15	0.075-2.04	1.05-8.89	131 (81)	36.5	7.5	200

* The total number of injection tests is accompanied by the number of successful injection tests in parentheses.

Table 3. Data of research studies based on multi-dimensional injection tests

Reference	Cements						Grout	Soils						Injection Tests			
	No.	Blaine (m^2/kg)	Grain Sizes				*W/C* Ratios	No.	Gradation Characteristics					No.*	Sample Dimensions		Injection Pressure (kPa)
			d_{99} (μm)	d_{95} (μm)	d_{90} (μm)	d_{85} (μm)			d_{50} (mm)	d_{15} (mm)	d_{10} (mm)	$d_{2.5}$ (mm)	$C_{u,25}$		Height (cm)	Diameter (cm)	
Shimoda and Ohmori (1982)	2	815, 432	10.0, 80.0	8.0, 55.0	6.5, 42.0	6.0, 35.0	2, 3, 3.5	1	0.20	0.175	0.17	0.12	1.46	4 (2)	69	70	225.5
Bouchelaghem et al. (2001)	1	1200	11.0	10.0	9.0	8.0	3	1	0.50	0.17	0.15	0.03	5.67	1 (1)	120	150	-----
Van der Stoel (2001)	1	-----	20.0	18.0	16.0	14.0	3	3	0.05-0.17	0.008-0.080	0.002-0.065	0.002-0.003	4-32	3 (3)	-----	100	420
Mittag and Savvidis (2003)	1	-----	12.0	9.0	7.5	5.5	5	1	0.25	0.15	0.12	0.085	1.76	3 (3)	75	75	700
Kim et al. (2009)	1	-----	50.0	27.0	20.0	16.0	0.67	2	0.80,	0.64,	0.60,	0.50,	1.28,	11	70	60	4000

	3.00	2.22	2.10	1.80	1.23	(6)

* The total number of injection tests is accompanied by the number of successful injection tests in parentheses.

4 EFFICIENCY EVALUATION OF GROUTABILITY CRITERIA

The effectiveness of the groutability criteria was quantified by computing for each injection test the values of the groutability ratios using the Equations shown in Table 1, by determining the groutability estimations according to the limits associated with the relevant groutability criteria of Table 1, and by comparing these estimations with the results of the 489 injection tests used in the present study. The groutability estimations were considered successful when they were in agreement with the experimental results. The numbers and the percentages of the successful groutability estimations are summarized in Table 4 for each research study and in total. As

Table 4. Performance of soil groutability criteria

Groutability Criteria / Reference	Mitchell (1981) N_1	Mitchell (1981) N_2	Krizek et al. (1992)	Huang et al. (2007)	Huang et al. (2013)	Incecik & Ceren (1995)	Axelsson et al. (2009)	Miltiadou & Tassios (2013)	Markou et al. (2018)
Shimoda & Ohmori (1982)	0	0	0	0	0	0	0	3	3
Krizek et al. (1986)	3	6	6	6	6	6	3	3	3
Paillere et al. (1989)	10	11	17	13	13	16	13	16	17
Zebovitz et al. (1989)	11	11	11	11	11	11	7	7	11
Miltiadou (1991)	11	23	26	21	21	24	20	27	30
De Paoli et al. (1992)	16	16	16	16	16	16	20	21	21
Uchikawa (1994)	7	4	10	4	3	7	6	9	10
Sano et al. (1996)	0	5	5	5	5	5	0	4	4
Perret (1997)	6	6	6	6	7	6	6	5	5
Santagata & Collepardi (1998)	10	10	10	10	10	10	10	11	12
Bouchelaghem & Vulliet (2001)	0	1	1	1	1	1	1	0	0
Akbulut & Saglamer (2002)	14	15	29	10	10	22	21	29	23
Mittag & Savvidis (2003)	5	5	5	5	5	5	0	0	5
Santagata & Santagata (2003)	1	1	1	1	1	1	1	1	1
Akbulut & Saglamer (2004)	0	0	3	3	3	3	0	0	1
Maalej (2007)	1	1	1	1	1	1	0	0	0
Mollamahmutoglu et al. (2007)	9	9	9	9	9	9	9	11	11
Axelsson et al. (2009)	1	1	3	1	1	2	4	3	4
Mollamahmutoglu & Yilmaz (2011)	12	7	12	14	14	14	14	10	10
Tekin & Akbas (2011)	9	9	10	9	9	10	10	12	5
Miltiadou-Fezans & Tassios (2013)	29	32	35	30	30	34	33	42	47
Markou et al. (2018)	77	81	81	81	81	81	78	90	104
Shimoda & Ohmori (1982) *	4	4	4	4	2	4	2	2	2
Bouchelaghem et al. (2001) *	0	1	1	1	1	1	1	0	0
Van der Stoel (2001) *	0	0	0	0	2	0	0	0	0
Mittag & Savvidis (2003) *	3	3	3	3	3	3	0	0	3
Kim et al. (2009) *	6	6	6	6	6	6	6	11	6
Overall Performance	245 **50%**	268 **55%**	311 **64%**	271 **55%**	271 **55%**	298 **61%**	265 **54%**	317 **65%**	338 **69%**

* Studies based on multi-dimensional injection tests. All the other studies were based on one-dimensional tests.

also shown in Table 1, the criteria based on the N_1 and N_2 ratios were examined either separately (Mitchell 1981) or in combination (Krizek et al. 1992; Huang et al. 2007; 2013) and the results are presented accordingly in Table 4.

In terms of overall performance (last line of Table 4), the percentage of successful predictions of the criteria proposed by Markou et al. (2018) is almost equal to 70%. This percentage is 4% to 19% higher than all the percentages presented in Table 4, indicating a better performance of these new criteria in comparison with the other groutability criteria. The criteria proposed by Miltiadou-Fezans and Tassios (2013) and used by Krizek et al. (1992) exhibit reasonably good performance as they provide total rates of successful predictions equal to 65% and 64%, respectively. All the other available criteria present inferior percentages ranging from 50% to 61%. The overall performance of all criteria is nearly identical to their performance in the one-dimensional injection tests, since the maximum differences in the corresponding percentages of successful predictions are equal to ±1%. Moreover, all criteria estimated correctly the result of the 22 multi-dimensional injection tests, at rates ranging from 41% to 64%. More specifically, the best three criteria in terms of overall performance (Markou et al. 2018; Miltiadou-Fezans and Tassios 2013; Krizek et al. 1992) present percentages of successful predictions in the multi-dimensional injection tests equal to 50%, 59% and 64%, respectively. However, the aforementioned percentages are significantly affected by the relatively small number of multi-dimensional injection tests because each successful prediction produces an increase of the percentage equal to 5%. The cases of unsuccessful predictions can be attributed to the fact that the groutability criteria of this type are based generally on characteristic grain sizes of soil and grout and do not take into account significant factors for suspension groutability, such as W/C ratio or viscosity (Markou et al. 2018).

5 CONCLUSIONS

Based on the results of this investigation the following conclusions can be advanced:

- The groutability criteria (Markou et al. 2018) based on a “modified uniformity coefficient” and a “modified groutability ratio”, corresponding to the finer portion of the sand gradation ($d \leq d_{25}$), present the best overall performance as they yield a percentage of successful predictions almost equal to 70%, which is 4% to 19% higher than those of all other available criteria. Thus, these criteria appear to be an adequate and simple tool for the groutability prediction of cement suspensions in sands with different gradations.
- The groutability criteria proposed by Miltiadou-Fezans and Tassios (2013) and used by Krizek et al. (1992) exhibit acceptable efficiency by achieving a total percentage of successful predictions approximately equal to 65% and presenting a balanced performance in one-dimensional as well as in multi-dimensional injection tests.
- All the other groutability criteria examined in the present study, present inferior performance as they predicted successfully the outcome of the injection tests in 50-61% of the available cases.
- The findings of the present investigation can be used as a guide in permeation grouting applications and, at the same time, can be confirmed by injections conducted in the field (three-dimensional grouting conditions).

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