

The Effect of Water-to-Cement Ratio on the Penetrability of Cement Grouts: An Experimental Investigation

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ABSTRACT— *The use of very fine cement grouts for injection into fine-to-medium sands has been proposed to circumvent problems associated with the permanence and toxicity of chemical grouts and the inability of ordinary cement grouts to permeate soil formations finer than coarse sand. A laboratory investigation was conducted in order to evaluate the penetrability of cement suspensions. Four gradations from CEM I (according to EN 197-1) type of cement were used having nominal maximum grain sizes of 100 μm , 40 μm , 20 μm and 10 μm . The properties of suspensions, with water-to-cement (W/C) ratios of 1:1, 2:1 and 3:1 by weight, were determined in terms of apparent viscosity. Penetrability was evaluated by conducting one-dimensional injections into five different, clean sands using a specially constructed device. Penetrability of cement suspensions increases with increasing water-to-cement (W/C) ratio and cement fineness. Microfine cement suspensions with water-to-cement (W/C) ratios of 2:1 and 3:1 can penetrate into medium-to-fine sands.*

Keywords— Permeation grouting; Suspensions; Water-to-cement ratio; Microfine cements; Grouted sand

1. INTRODUCTION

The safe construction and operation of many technical projects often requires the improvement of the properties and mechanical behavior of the soil formations. The shear behavior of a soil material is of particular interest because it has a direct impact on practical bearing capacity problems [1, 2], stability of slopes and embankments [3, 4, 5] as well as permanent seismic movements of slopes [6, 7]. Permeation grouting is commonly used in geotechnical engineering either to reduce the permeability or improve the mechanical properties of soil and rock [8]. Success in a given grouting operation requires that the grout can be capable of being injected into the soil formation and that the desired improvements in the properties of the formations are attained. Grouts are generally categorized as suspensions or particulate grouts and solutions or chemical grouts. Suspensions are prepared with ordinary Portland or other cements, clays or cement-clay mixtures and fine sands in some cases. Solutions include sodium-silicate formulations, acrylamides, acrylates, lignosulfonates, phenoplasts and aminoplasts as well as other materials that have no particles in suspension. Chemical grouts can be injected in fine sands or coarse silts but are more expensive and some of them pose a health and environmental hazard. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradations. As a result, a number of fine-grained cements, called microfine or ultrafine cements, has been developed and manufactured. The behavior of microfine cements in permeation grouting is the objective of many research efforts [9, 10, 11, 12, 13, 14, 15].

2. MATERIALS AND PROCEDURES

For the purposes of this investigation, a cement of type CEM I, according to EN 197-1, was used. The ordinary cement (designated as F0) was pulverized in order to produce three additional cements with nominal maximum grain sizes of 40 μm , 20 μm and 10 μm , which are designated as F1, F2 and F3, respectively. Characteristic grain sizes and Blaine specific surface values for all cements are presented in Table 1.

All suspensions were prepared using potable water since it is considered appropriate for preparing cement-based grouts. A dosage of superplasticizer equal to 1.4% by weight of dry cement was added to F1, F2 and F3 cement suspensions. The W/C ratios of all suspensions used, was equal to 1:1, 2:1 and 3:1 by weight. This fixed superplasticizer dosage was determined following a laboratory evaluation of the effect of various dosages on the apparent viscosity and the rheological characteristics of the pulverized cement suspensions [10]. Presented in Table 2 are the apparent viscosity values of ordinary cement suspensions without superplasticizer and microfine cement suspensions with superplasticizer, obtained at $t = 30$ min after preparation and at viscometer rotation speed equal to 60 rpm.

Table 1: Cements gradations

Grain sizes ^a Specific surface	Cement type			
	F0	F1	F2	F3
d _{max} ^b (μm)	100	40	20	10
d ₉₅ (μm)	57.0	22.5	11.5	8.2
d ₉₀ (μm)	45.0	19.0	9.7	6.8
d ₈₅ (μm)	39.0	16.6	8.5	6.0
d ₅₀ (μm)	16.6	8.6	4.2	3.2
d ₁₀ (μm)	3.0	2.0	1.2	1.0
Blaine (m ² /kg)	384	529	710	920

^a d₉₅, d₉₀, d₈₅, d₅₀, and d₁₀ correspond to the particle diameter at which 95%, 90%, 85%, 50%, and 10% of the weight of the specimen is finer, respectively.

^b Nominal maximum cement grain size.

Table 2: Apparent viscosity (mPa.s) of cement suspensions

Cement type designation	Nominal maximum grain size d _{max} (μm)	W/C ratio	Apparent viscosity
			(mPa.s)
F0	100	1:1	86
		2:1	16
		3:1	9
F1	40	1:1	5
		2:1	2
		3:1	2
F2	20	1:1	22
		2:1	6
		3:1	4
F3	10	1:1	164
		2:1	9
		3:1	6

The grouted soils were clean and uniform sands with angular grains. Five different sand gradations were used with grain sizes limited between sieve sizes (ASTM E11) Nos. 5 and 10, 10 and 14, 14 and 25, 25 and 50, and 50 and 100, and designated as S1, S2, S3, S4 and S5, respectively. The sands were grouted in dense condition (mean value of relative density, Dr, 98±1%) and were dry prior to grouting. The values of other properties of sands are presented in Table 2.

Table 3: Sand properties

Sand	Specific gravity, G _s	Void ratios		Permeability coefficient, * k ₂₀ (cm/sec)
		Minimum, e _{min}	Maximum, e _{max}	
S1	2.71	0.66	1.06	2.31
S2	2.72	0.68	1.03	0.80
S3	2.72	0.69	1.07	0.22
S4	2.70	0.70	1.06	0.04
S5	2.72	0.72	1.12	0.013

* Sands in dense condition

The special apparatus shown in Figure 1 was used for injecting sand columns with cement suspensions. It allows for adequate laboratory simulation of the injection process and investigation of the influence of the distance from injection point on the properties of grouted sand. The grouting column was made of thick PVC tube with an internal diameter of 7.5 cm and a height of 144 cm and was formed by placing at each end a 5 cm thick gravel layer, between two screens of suitable aperture, and filling the remaining length (134 cm) with dry sand in a dense or loose condition. The sand was saturated, when required by the testing program, by upward flow of water pumped from the grout tank. The rate of discharge of the pump was regulated to be constant and equal to 60 L/h. Injection was stopped when either the volume of the injected grout was equal to two void volumes of the sand in the column or when the injection pressure became equal to 700 kPa. The grout pressure was continuously recorded during the injections, by installing one pressure sensor at the inflow pipe of the grouting column and six pressure sensors on the grouting column, at distances from the injection point equal to 4 cm, 14 cm, 34 cm, 54 cm, 83 cm and 123 cm, respectively. The pressure sensors (PWF-PA pressure

transducers of Tokyo Sokki Kenkyujo) were placed in cyclical openings on the grouting columns using specially designed clamps and were connected to an automatic data acquisition system.



Figure 1: Laboratory equipment for penetrability evaluation [9-15].

3. EXPERIMENTAL RESULTS AND DISCUSSION

The groutability of a suspension grout can be evaluated in terms of: (a) the ability of the grout to enter into the voids of a given soil, and (b) the permeation distance that can be achieved under a predetermined maximum injection pressure. The terms “injectability” and “penetrability”, respectively, were selected to describe these two conditions or criteria. Thus, the penetrability of cement grouts was the objective of the investigation reported herein. All factors relating to penetrability were evaluated experimentally by grouting sand columns with the apparatus shown in Figure 1 and the results obtained, are presented in Table 4. Penetrability was considered “optimal” when the entire amount of suspension penetrates the sand column with low impregnation pressure, “satisfactory” when all or almost the entire amount of suspension penetrates the sand column with increasing impregnation pressure, “marginal” when penetration length is greater than 60 cm with maximum impregnation pressure and “low” when penetration length is less than 60 cm with maximum impregnation pressure.

Table 4: Experimental results

Sand Fraction	Cement type designation	Nominal maximum grain size d_{max} (μm)	W/C Ratio	Penetration Length (cm)	Maximum Pressure (kPa)	Injection Result
S1	F2	20	2:1	>134	<50	Optimal
S2	F0	100	1:1	>134	145	Satisfactory
	F0	100	2:1	>134	<50	Optimal
S3	F2	20	2:1	>134	7	Optimal
	F0	100	1:1	42,4	763	Low
	F2	20	1:1	>134	100	Optimal
	F0	100	2:1	>134	<50	Optimal
	F2	20	2:1	>134	<50	Optimal
	F0	100	3:1	>134	56	Optimal
S4	F2	20	3:1	>134	<50	Optimal
	F2	20	1:1	68.9	729	Marginal
	F2	20	2:1	>134	128	Satisfactory
	F0	100	3:1	70	715	Marginal
S5	F2	20	3:1	>134	89	Optimal
	F2	20	3:1	58.8	822	Low

From the results presented in Table 4, it can be observed that penetrability was “optimal” in S1 and “satisfactory” or “optimal” in S2 (Nos. 5-10 and 10-14) sands for all combinations of suspension composition. Penetrability in S3 (Nos. 14-25) sand is generally considered “optimal” especially for the finer cement suspensions. Injectability of suspensions

with W/C ratio equal to 1:1 was “marginal” in S4 sand. Penetrability in S4 sand is considered “satisfactory” or “optimal” with microfine cement F2 suspensions having W/C ratios of 2:1 and 3:1 respectively. Penetration in S5 (Nos. 50-100) sand was negligible for any cement suspension used. Accordingly, it can be stated that the increase of cement fineness and/or W/C ratio significantly improves the injectability of cement suspensions. On a quantitative basis, microfine cement suspensions with W/C ratios of 2:1 and 3:1 can be injected in medium-to-fine sands.

The effect of W/C ratio on penetrability of cement suspensions has been thoroughly and systematically investigated in the past [8, 16, 17]. In present research effort, escalation of suspensions penetrability exists for all W/C ratios, in injections performed in the sand fraction 25-50 with cement suspensions of type CEM I and maximum grain size of 20 μm as shown in Table 4. Suspension I-F2-3 (CEM I, F2, W/C ratio equal to 3:1) completely impregnated the soil column with the parallel injection of a suspension volume twice the volume of the soil sample gaps and a maximum impregnation pressure of 89 kPa. Difficulties in flow within the column arose for impregnation performed with suspension I-F2-2 (CEM I, F2, W/C ratio equal to 2:1). The volume of the suspension compressed was determined to be less than twice the volume of gaps in the long soil column with moderate penetration. Finally, the dense suspension I-F2-1 (CEM I, F2, W/C ratio equal to 1:1) did not completely soak the column despite the significant increase in maximum pressure, which was determined at 729 kPa. The penetration length into the soil sand column 25-50 was determined at 68.9 cm. As can be seen from the data in Table 4, the effect of W/C ratio of the suspension is catalytic in terms of the success of an impregnation injection. Increasing the W/C ratio improves the injectability and increases the permeability of the suspensions. Suspensions with W/C ratio equal to 3:1 penetrate more easily into the soil formations, in contrast to the denser ones (W/C ratio equal to 1:1), which either fail to impregnate the soil sand columns or when injected makes it possible to display significantly high values of maximum impregnation pressure.

The effect of W/C ratio on the penetrability of cement suspensions highlights the influence of the viscosity factor on the success of an injection program. It can be deduced from Table 1 that increasing the W/C ratio means reducing the apparent viscosity of the suspensions. Specifically, the suspensions I-F2-1, I-F2-2 and I-F2-3, which were injected into 25-50 sand columns, show viscosity values of 21.0 cP, 6.11 cP and 3.81 cP, respectively for viscometer speed equal to 60 rpm after a time equal to 30 min from mixing of the suspensions. Despite the difference between the values of the viscosity effect for the suspensions I-F2-2 and I-F2-3, there is some correlation between the effect of the W/C ratio on the injectability and penetrability of the suspensions with the values of the viscosity effect which identified in the context of the present investigation.

4. CONCLUSIONS

Based on the results obtained and the observations made during this investigation, the following conclusions may be advanced:

- 1) On a quantitative basis, microfine cement suspensions with water-to-cement ratios of 2:1 and 3:1 can be injected in medium-to-fine sands.
- 2) The increase of water-to-cement ratio significantly improves the permeability of cement suspensions.
- 3) Suspension grouts prepared with very fine cement are an attractive and environmentally safer alternative to chemical grouting.
- 4) The increase of cement fineness improves the injectability of cement suspensions rendering them effective for grouting of medium to fine sands.

The overall problem is extremely complicated, and available information from research efforts and field experiences is sparse; furthermore, each field situation presents its own unique set of circumstances. Accordingly, the results reported herein must be utilized with full awareness of their origin, and caution is urged when attempting to generalize them to other situations not explicitly addressed.

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