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Review Article

Evaluation of Cement Gradation Effect on the Injectability of Cement Suspensions for Soil Grouting – A Review

Christodoulou D*

Department of Environmental Sciences, University of Thessaly, Greece

***Corresponding author:** Christodoulou Dimitrios, Geo-Environmental Technology and Soil Management Laboratory, Department of Environmental Sciences, School of Technology, University of Thessaly, Larissa, Greece

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Abstract

Grouting is a common technical method with many applications, e.g. it is used for soil stabilization and strengthening, for reduction for water ingress to underground facilities or of the water loss through a dam foundation, etc. Grouts comprise several constituents, which are combined in many ways depending on the in-situ conditions and the outcome desired. The use of very fine cement grouts for injections 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. In this paper, a brief historical review of the research efforts carried out seeking to investigate the effect of cement gradation and specific surface area on the injectability of cement suspensions takes place.

Keywords: Grouting; Suspensions; Fine-grained cements; Gradation; Blaine specific surface

Introduction

The design related on the shear behavior of a soil material is of particular interest because it has a direct impact on practical problems of bearing capacity [1,2], stability of slopes and embankments [3-5] as well as permanent seismic movements of slopes [6-8]. The safe construction and operation of many technical projects often requires the improvement of the properties and mechanical behavior of the soil formations that appear in their area. Various methods are used to improve the soils, such as: the lowering of the well horizon, the vibrational condensation, the dynamic condensation, the preloading and the injections. The category of injections includes: (a) permeation grouting, (b) compensation grouting, (c) condensation injections and (d) high pressure vein injections. Permeation grouting is one of the oldest methods for improving soil formations and has a wide range of applications [9]. The term “injection” means the passage, under pressure, of a fluid material to the required depth from the soil surface. The injection material, which is either a suspension of solid granules in water or a solution of chemicals, displaces the water from the soil pores and coagulates or solidifies in a relatively short period of time.

In general, permeation grouting aims at increasing the shear strength, the density and the stiffness, along with a reduction of the compressibility and the soil permeability. An appropriate injection program may: (a) be performed as part of the preliminary fieldwork prior to the commencement of project’s construction, (b) be part of the construction of the main project, or (c) designed and executed ex post when unforeseen circumstances arise during the construction and/or operation of a project. Several research efforts have been made towards documenting environmentally friendly materials with an emphasis on improving the properties of cement suspensions [10-17].

Effect of Cement Gradation

It is accepted in the international literature that injectability and penetrability of cement-based suspensions improve as cement grain sizes decrease. This finding was the subject of extensive research with the aim of preparing fine-grained cements, the suspensions of which will have the ability to penetrate medium-to-fine sands. Several researchers focused their interest in investigating the properties of fine-grained cements and carried out laboratory impregnations using only some of the available fine-grained cements [18-20].

An important research effort to assess the effect of cement fineness and grain size on injectability was made by Perret et al. [21], who compared suspensions of fine-grained and common type III cement at water-to-cement (W/C) ratio of 0.5:1, 0.6:1, 1.2:1 and 2:1. The sand impregnated was fine Ottawa sand. The granulometric gradation of available cements is shown in (Figure 1).

From the penetration tests conducted, it was observed that the fine cement suspensions penetrated the test sand completely and with great ease. Grouts based on common cement and W/C ratios of 1.2:1 and 2:1 also impregnated the sand column at a very slow rate, however. This conclusion also follows from (Table 1) below.

Laboratory impregnations using three fine-grained cements were also carried out by Santagata and Collepardi [22]. Specifically, three pozzolanic fine-grained cements (P-Z-9, P-Z-17 and P-Z-20) with different fineness (D_{98} = 9, 17, 20 μm) and dense water-to-cement ratios were used. The impregnations were carried out in four sands of different fineness with the trade names: Coarse Po, Ticino, Fine Po and Musone. The granulometric gradation of available cements is shown in (Figure 2).

From the injections results, it emerged that the suspensions of the two finer-grained cements (P-Z-9, P-Z-17) completely penetrated

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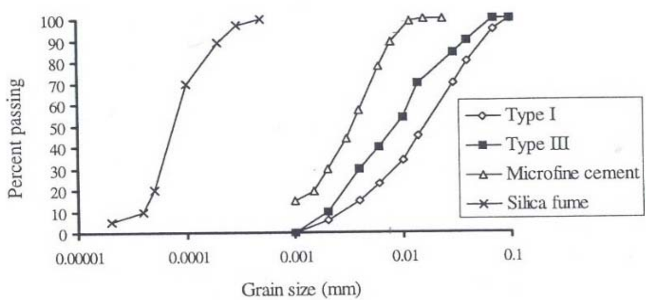

Figure 1: Grain size gradation of available cements [21].

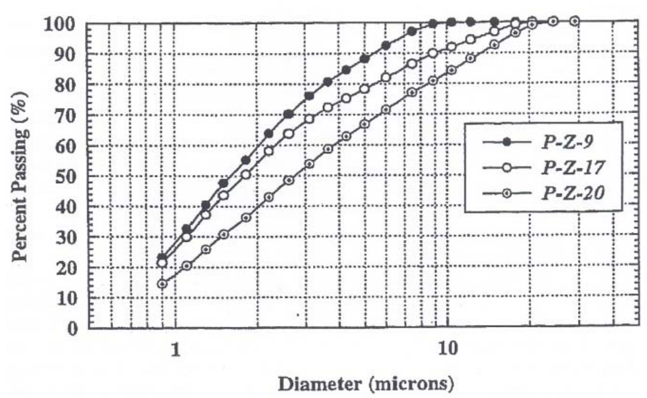

Figure 2: Grain size distribution of the three fine-grained cements [22].

all four available sands. In contrast, the P-Z-20 cement-based suspensions completely impregnated the two coarsest sands, but failed to penetrate the two finer ones (Fine Po, Musone).

Mollamahmutoglu [23] investigates the relationship between cement grain size and injectability by injecting suspensions of an Ordinary Portland Cement (OPC) and a fine Portland cement (Microcem H900). The grain sizes of fine cement range from 2-40 mm, while 80% of common grains range from 10 mm to 100 mm. The sand used is listed as coarse - medium and the W/C ratio was 1.2:1.

From the test results, it was found that the Microcem H900 slurries completely impregnated the sand at a pressure of 80 kPa in contrast to the joint Portland cement grouts, which did not penetrate the test sand. The penetration length reached 1/5 of the column height even when a pressure of 250 kPa was applied.

Similar conclusions were obtained from experimental tests by Yoneda et al. [24], who used four cements with the symbols U, UX, F and N. The grain sizes of the available cements are listed in (Table 2). The W/C ratios chosen were 4:1 and 8:1.

Apart from the injections in which there was complete penetration, the minimum penetration observed was on the order of 7 cm. The general conclusion is consistent with the observations of the other researchers and confirms the view that the smaller the cement grain size, the better the penetration length into the sand.

The importance of the effect that cement grain size has on injectability is also pointed out by Tamura et al. [25], who performed field injections using three different cements: a fine-grained, a

Table 1: Results of impregnations for the two types of cement [21].

Cement	W/C Ratio	Penetration Length (cm)	% of total length	Time (s)
Fine-grained	2:1	37	100	22
Fine-grained	1.2:1	37	100	69
TypeIII	2:1	37	100	210
TypeIII	1.2:1	37	100	320
Fine-grained	0.6:1	20	54	(36)*
Fine-grained	0.5:1	5	14	(2)
TypeIII	0.5:1	5	14	(20)

Table 2: Characteristic sizes of the four cements [24].

Cement	D_{85} (μm)	BlaineSpecific Surface (cm²/g)
U	8.1	10000
UX	8.4	6500
F	13.1	6300
N	29.6	3310

Table 3: Characteristic grain sizes of the three cements [25].

Cement type	D_{50} (μm)	D_{95} (μm)	Specific Density
Fine-grained	4	8	2.95
Colloidal	11	30	2.96
Ordinary Portland Cement	18	60	3.16

Table 4: Penetration lengths of suspensions of various cements [26].

Cement Type	Penetration length (mm) Year 1999	Penetration length (mm) Year2000
TypeI Portland	102	279
Nittetsu Super Fine	1524	1524
Fosroc Ultracem	-	1584
MC-500 Micro Fine	-	1524
U.S. Grout ΤύπουV	1448	254
MBT Rheocem 900	229	610
Lehigh Microcem B	-	813

Table 5: Blaine specific surface of various cements [26].

Cement Type	Blaine specific surface of various cements (cm²/g)
Portland Ordinary Cement Type I	3000 - 5000
Earlyendurance - typeIII	4000 - 6000
Fine-grained	> 8000

colloidal, and a common Portland cement. The grain sizes of the three cements are shown in (Table 3). The grouted soil was a layer of fine Narita sand.

From the injections results, it emerged that the suspensions of the joint and the colloidal cement did not penetrate the sand layer. Penetration into the sand layer was achieved only with fine cement suspension and a W/C ratio of 0.8.

In-situ cementations in sand columns with a height of 1.5 m and an internal diameter of 188 mm were carried out by Warner [26]. A total of seven cements were used for the preparation of the suspensions, of which six were fine-grained and one common. The results of the impregnations carried out during the years 1999 and 2000 are listed in (Table 4).

The conclusions drawn from Warner's field immersions confirm the view that injectability is a multiparametric issue and make clear the difficulty of isolating the effect of each individual factor. This follows from Warner's observation that suspensions of some fine-grained cements with a larger grain size penetrated some soils, while suspensions of other fine-grained cements with a smaller grain size failed to permeate them. This finding, as can be seen, is not consistent with the opinion of most researchers according to which injectability is improved by reducing the size of the cement grains.

Effect of Blaine Specific Surface

Cement specific surface, according to Warner [26], is directly related to its grain size. It is expressed by Blaine fineness, which is a measure of the specific surface of all cement grains in a defined volume. Units of specific surface area are usually cm^2/g or m^2/kg. Warner [26] lists some indicative Blaine specific surface values for different types of cement. These values are shown in (Table 5).

Warner [26], based on experimental observations, found that while some type III early strength cements should exhibit higher Blaine fineness than type I or II cements, this was not reflected in either the maximum grain size or the theirgradation. This was attributed to the properties of the clinker from which the cement was made, the minerals from which the clinker is composed and the manufacturing process. In general, type III cements are finer than type I cements, however Warner [26] found that the larger grains of some type I cements were finer compared to those of some type III cements.

Similar values of the specific surface are also given by Atmatzidis [27], who carried out injections with the fine-grained cement MC-500, whose specific surface was approximately 8200 cm^2/g. For the various common Portland cements, the values given range from 3200 cm^2/g to 4300 cm^2/g.

A reference to the specific surface of two cements: an Ordinary Portland Cement (OPC) and a fine-grained (Microcem H900) and how they affect injectability is made by Mollamahmutoglu [23]. The specific surface of Microcem H900 was of the order of 7700 cm^2/g, while the common one was 4000 cm^2/g. As expected, the fine-grained cement completely impregnated the sand, unlike the joint, which penetrated only 1/5 of the height of the column.

Bremen [28] sets as a minimum value of specific surface, in order to achieve the best possible penetration, that of 4500 cm^2/g. It is clarified that this price refers to common cements and that the proposal is made in order to avoid the use of expensive fine-grained cements.

Discussion - Conclusions

In the present study, the influence of the factors that influence the injectability and penetrability of cement suspensions was investigated based, mainly, on experimental results reported in the international literature. From the literature review carried out, the following conclusions may be advanced:

1) The injectability and penetrability of cement suspensions are improved when the cement grain size is reduced.

2) The injectability and penetrability of cement suspensions are improved when Blaine specific surface is increased.

The conclusions drawn from research efforts confirm the view that injectability is a multiparametric issue and make clear the difficulty of isolating the effect of each individual factor.

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