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A Critical Approach to Targeting a Soil Improvement Research Grouting Program

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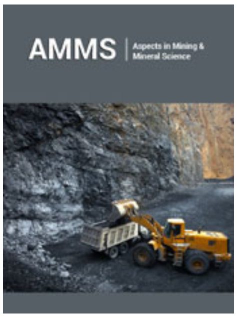

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Abstract

Improvement of the mechanical properties and behavior of soils by permeation grouting, using either suspensions or chemical solutions, is frequently required to ensure the safe construction and operation of many structures. Suspensions have lower costs 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. This paper summarizes the main observations that emerged from the review of the available literature concerning (a) the use of cement suspensions for soil improvement by injection impregnation and (b) the scope of fine cement suspensions in terms of their embeddability and penetrability.

Keywords: Permeation grouting; Suspensions; Injectability, Fine-grained cements

Introduction

The use of permeation grouting is a method of improving the properties and mechanical behavior of the soil that generally has a high cost, and its choice depends on the relative cost compared to other alternatives. The method is based on replacing water (or air) in soil voids or rock mass cracks by grout injected under low pressure so as not to disturb the soil formation. It is the oldest injection method and is usually applied to soil zones of relatively small volume that are located at a great distance from the ground surface. The method is used in technical projects with the aim of: (a) controlling underground flows, (b) increasing the shear strength of the soil formation, (c) reducing deformations or subsidence, and (d) filling voids [1]. The use of fine cement suspensions for improving soil by grouting has shown significant growth in recent years. It significantly expands the scope of Portland standard cement suspensions and outperforms chemical solutions regarding their effectiveness and environmental impact.

However, a relatively small number of related products are available internationally, which, due to their exclusivity, have an increased cost of use. In this context, it is expected that the Greek cement industry is interested in developing new cements of finer particle size than the common Portland cements, based on domestic production, which are cheaper than imported fine-grained cement and can provide an alternative to chemical solutions.

Fine-Grained Cement

The usual procedures for improving and strengthening soils by impregnation involve either the use of suspensions or the use of chemical solutions. These two major categories of injections have different scopes, costs, and effectiveness. Suspensions based on common Portland cement can effectively penetrate coarse-grained soil materials (gravels and coarse sands) with a permeability coefficient of 10^{-1}cm/s. For the impregnation of soils with a lower permeability coefficient (up to 10^{-4}cm/s), various types of chemical solutions can penetrate soil formations such as fine-grained sands and coarse-grained silts. Besides the high cost, chemical solutions are disadvantaged compared to cement suspensions in terms of their permanence and the low strength they impart to the impregnated soil. More importantly, many of the raw materials used and/or the products of chemical reactions are considered harmful to the environment and human health due to their toxicity.

To address these problems, new materials have been developed over the last twenty-five years as an alternative to chemical solutions. These are highly fine-grained cements that, as suspensions in water, can penetrate and effectively impregnate the voids of soil formations down to fine-grained sands. The significant advantage of these materials over chemical solutions is that they are composed entirely of inorganic components and thus do not cause any unpleasant environmental effects. The research and development of fine-grained cement is much more intensive today than in the ’80s, but a uniform and internationally accepted framework defining the required properties and particle size characteristics of such materials has not yet been established.

The European standard EN 12715:2000 defines fine-grained cement as cement with a characteristic grain size, d_{95}, of less than 20μm and a Blaine fineness of more than 8000cm^2/gr. Products meeting these criteria are commercially available and produced in various countries such as the United States, Japan, Brazil, Canada, Germany, France, Brazil, Canada, France, Switzerland, and Sweden. The volume of applications of fine-grained cement has been systematically increasing over the last 20 years. Due to stricter environmental protection legislation and lower costs compared to chemical solutions, fine-grained cement seems to be gradually replacing chemical solutions in impregnation injections. Fine-grained cement has been used mainly to control groundwater flows and/or to improve soil strength in applications including dams, tunnels, water supply, bridges, and large construction projects.

Suspensions of Fine Cement

To determine the composition and assess the suitability of a suspension concerning the needs of a project, it is necessary to document its properties. The properties that constitute the main selection criteria are viscosity and rheological behavior, stability, setting times, rate of strength development and ultimate strength. In terms of these properties, fine cement suspensions have advantages and disadvantages compared with suspensions of ordinary cement. To determine the composition and assess the suitability of a suspension about the needs of a project, it is necessary to document its properties. The main selection criteria are viscosity and rheological behavior, stability, setting times, rate of strength development, and ultimate strength. In terms of these properties, fine cement suspensions have advantages and disadvantages compared with suspensions of ordinary cement.

Cement suspensions’ viscosity and rheological behavior are essential properties and play a crucial role in an impregnation program. In general, the rheological behavior of cement suspensions classifies them as non-Newtonian fluids, and the Bingham model is used to describe them, which is considered to be simplifying but, at the same time, quite effective and very practical. According to the Bingham model, the main rheological characteristics of cement suspensions are consistency and plastic viscosity. Cohesion affects the injectability and penetrability of the grout and generally defines the grout’s penetration length into the soil. The plastic viscosity controls the impregnation rate and the grout’s behavior when it is flowing. Typically, standard cement suspensions have lower viscosity and cohesion values than fine cement suspensions. The increase in viscosity caused by grinding the cement to produce a fine-grained product can exceed one order of magnitude for suspensions prepared with the same water-to-cement ratio. For this reason, it is necessary for fine cement suspension applications to use fluidity improvers.

The exudation mechanism is considered very important because it gives information about the behavior of cement suspensions at rest. For this reason, both the rate of exudation and the final exudation rate are considered during the design and selection process. The final exudation rate is critical because it determines whether the cement slurry is stable. According to EN 12715:2000, a stable suspension is one that has a swelling rate equal to or less than 5% after 2 hours of preparation. In general, suspensions of common cement are only considered stable when the water-to-cement ratio is less than approximately 0,8:1. In contrast, fine-grained cement provides the possibility of preparing stable suspensions with considerably higher water-to-cement ratios, which can be as high as 1,6:1. The use of stable suspensions in an impregnation injection program facilitates storage of the suspension after preparation without the need for continuous agitation and ensures that the soil pores are filled with suspension.

The control of coagulation times, particularly the initial coagulation time, is important at the design and selection stage of suspensions. A short initial clotting time (<4 hours) causes difficulties in performing injections and increases the possibility of serious equipment failure. Long time (>24 hours) causes significant delays in performing injections and significantly reduces their effectiveness. Increasing the fineness of the cement granules leads to a decrease in both initial and final setting time, which becomes more pronounced as the water-to-cement (W/C) ratio decreases. Suspensions of typical cement exhibit initial and final setting time values that generally range from 2 to 15 hours and from 5 to 25 hours, respectively, while suspensions of fine-grained cement range from 1 to 8 hours and from 1 to 15 hours, respectively.

The cement’s fineness positively influences the strength development rate, especially early. Fine-grained cement, derived from pure Portland cement, exhibits higher short-term strengths than common cement. This is attributed to fine-grained cement’s higher specific surface area, allowing for faster hydration. In the long term, however, the effect of the fineness of the cement is not univocal but also depends on the water-to-cement ratio of the suspension. It has been observed that, generally, for low water-to-cement ratios (W/C≤1:1), suspensions of fine cement give lower strengths than common cement, while for higher ratios, the opposite is true. Sediments resulting from suspensions of fine-grained cement with water-to-cement W/C ratios equal to 0.7:1, 2:1, and 3:1 show unconfined compressive strength values that are approximately equal to 150%, 30%, and 20%, respectively, of those resulting from suspensions with water-to-cement ratios equal to 1:1.

Suspensions of Fine Cement Suspensions

As noted, impregnation injections are predominantly carried out using suspensions or chemical solutions. Suspension of common cement ensures effective improvement of the properties of coarse-grained soil materials (gravel and coarse sands) with a permeability coefficient of 10^{-1}cm/s. However, their use in finer soils leads to ineffective impregnation injections either because of their limited penetration and incorporation capacity or because of the strong filtering effect of fine soils. The development of fine-grained cement has attempted to solve this problem so that it can be used in applications requiring impregnation injections in fine sands or even finer soils (e.g., coarse-grained silts) while acting as a substitute for harmful chemical solutions. The literature review revealed that, indeed, fine-grained cements can be used to reinforce such formations, but in the majority of cases full impregnation requires the use of suspensions with a water-to-cement ratio (W/C) higher than 3:1, which probably calls into question the quality of the improvement finally achieved.

It has been shown experimentally that the embeddability and penetrability of cement-based suspensions are significantly influenced by factors such as the type and fineness of the cement, the water-to-cement ratio of the suspension, the grain size and degree of compaction of the soil formation, the type and dosage of additives and chemical conditioners, the mixing process and the impregnation pressure. The size relationship between the voids in a soil formation and the suspension's granularity largely determines the suspension's penetration radius into the soil and, consequently, the method's applicability. Based on results obtained from laboratory and field tests, empirical relationships have been formulated, called "Groutability Ratios', which relate the size of the voids (grains) in the soil to the size of the cement granules in the suspension. Based on this consideration, it is concluded that fine-grained cement suspensions are superior in entrainment to common cements suspensions. However, it must be stressed that the inclusion criteria do not consider other factors, such as the viscosity of the suspension, but only the particle size characteristics of the soil and cement. Consequently, if the rheological characteristics of suspensions of fine-grained cement are not adequately adjusted (improved), they likely will, in practice, show lower inclusivity than suspensions of ordinary cement.

According to the literature findings, the laboratory investigation aims to simulate the injection process as it occurs in the field, and it is the most representative and widely used method of assessing injectability. Experimental results show that using dilute suspensions improves embeddability compared to dense suspensions, proving that the water-to-cement ratio significantly affects the penetration of suspensions [2-5]. However, this improvement is not directly attributed to the water-to-cement ratio but to the reduction in viscosity due to excess water in the suspension [4]. Of course, dilute suspensions proved susceptible to the filtering effect under high impregnation pressures, highlighting the impact of impregnation pressure on entrainment [2,4]. It was also observed that an improvement in injectability is achieved when fine-grained cements are slag - instead of pure Portland - because they are less reactive, have higher setting times. Their grains do not form aggregates with the same ease and speed during injection [6,7]. Suspension of fine-grained cement has a higher viscosity. Still, research has shown that the use of superplasticizers achieves a satisfactory reduction in viscosity and, therefore, a significant improvement in injectability [4,8,9].

In addition to the laboratory investigation of the penetration of cement suspensions in soil formations, systematic research efforts have been made in recent years to estimate embeddability by formulating empirical relationships [10] and using analytical and numerical prediction methods [11,12]. These latter investigations aim to simulate the injection process and to formulate equations governing this process. However, also through these research approaches, the importance of the laboratory-experimental study, which consists of carrying out laboratory interventions to check the reliability of the results of these models, is highlighted.

Conclusion

The following general objectives define the scope of a laboratory-scale injection research project:

a. Production of cement. Selection of three different industrially produced cement and their milling to obtain three additional particle size compositions covering the particle size composition of fine-grained cement.

b. Properties and behavior of the suspension of the twelve cements and optimization of their composition.

c. Investigation of the inclusivity and penetrability of the suspensions, evaluation, and suggestions for improvement of the available inclusivity criteria.

d. Parametric investigation of the effectiveness of injections with the investigated fine-grained cement in relation to the distance from the injection site.

e. Properties and design parameters of soil impregnated with suspensions of fine-grained cement under static and dynamic loading conditions.

f. Comparative evaluation based on available information for other fine-grained cement and/or common Portland cement.

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