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Properties of Environmentally Friendly Cement Grouts for Soil Improvement - A Mini Review

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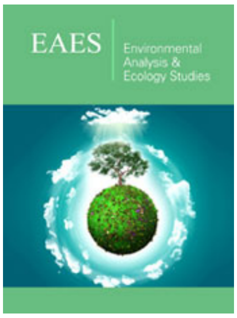

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Abstract

Improvement of the mechanical properties and behavior of soils by permeation grouting, using either suspensions or chemical solutions, is frequently required 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 environmentally friendly materials with very fine gradations. This paper reports on the effect of water-to-cement (W/C) ratio while giving information on the use of additives and chemical improvers in order to improve the suspensions properties such as bleeding and durability.

Keywords: Permeation Grouting; Cement Suspensions; Bleeding; Durability

Introduction

The initial stage of a comprehensive investigation of soil improvement with suspension injections consists of a series of tests to determine suspension properties. Suspension grouts are the most economical solution, but at the same time they show many important disadvantages such as the inability to develop endurance and the difficulty of penetration. The most popular suspension type grouts are those based on cement, which have Portland cement and water as their main components. Depending on the needs of each application (high initial strength, resistance to chemical environment) it is possible to use different types of cement (aluminum, slag, etc.) instead of common cement. In addition, it is possible to add to the grouts some solids (sand, clay) with the main purpose of reducing the cost of injections, while the use of admixtures such as fly ash, slag and silica fume and the addition of chemical improvers (superplasticizers, water reducers, coagulation accelerators etc.) aims to improve some properties. Since then, several research efforts have been made towards documenting environmentally friendly materials with an emphasis on improving the properties of cement suspensions such as bleeding and durability [1-8].

Water-to-Cement (W/C) Ratio

The most important variable that affects the properties of suspensions is the water-to-cement (W/C) ratio, as it determines grout bleed capacity, plasticity and durability. Excess water causes subsidence, low strength, increased shrinkage and low durability [9]. The water-to-cement (W/C) ratio is expressed either by weight or by volume. In practice, for convenience, the volume ratio cement apparent volume is used [10]. In the literature, the water-to-cement (W/C) ratio is mainly expressed as the weight ratio of water and dry cement. Deere [11] presented a table for the conversion of water-to-cement (W/C) ratio from volume to weight ratios and vice versa using as a basis for calculation the apparent weight of cement calculated equal to 1.5 gr/cm3. Based on this table a suspension with a water-to-cement (W/C) ratio of 6:1 by volume has a W/C ratio of 4:1 by weight. Then where the value of water-to-cement (W/C) ratio is reported, it is expressed in weight ratios. The water-to-cement (W/C) ratio has been and continues to be the subject of thorough research due to its importance in the design of suspensions. In the scientific community, two main trends have been formed regarding the selection of the optimal W/C ratio for cement injections. One tendency supports the choice of sparse (or unstable) suspensions and the second view favors the choice of dense (or stable) suspensions. Proponents of the first trend point out that the advantage of a dilute suspension is the possibility of greater penetration due to its low viscosity and low cohesion. They consider that with appropriate pressures and available time they can clog more satisfactorily small cracks or soil pores compared to dense suspensions [12].

The antithesis of those who welcome the use of dense suspensions concerns the advantages they present over the sparse ones. These include: satisfactory filling of soil voids, high mechanical strength, less shrinkage, resistance to chemical attack and the possibility of more accurate prediction of their application [13]. In addition, the possibility of adding chemical improvers is emphasized, which may give low viscosity and consistency to dense suspensions.

In international practice, there is no clear boundary for separating suspensions into sparse and dense water-to-cement (W/C) ratios. Only some guidelines are given that recommend the use of suspensions with W/C ratios of 2:1 and denser [11]. Sampling the bibliographic data, it can be said that the dense suspensions include those that have W/C ratios less than 1.5:1, while the sparse ones with W/C ratios greater than 4:1. This tendency is supported by the proposal of Bremen [14], who proposes the use of W/C ratios between 0.6:1 and 0.9:1 for common cements, while he sets the W/C ratio of 1.6:1 as the stability limit of fine-grained cement suspensions.

Regarding the international practice of performing injections in the field, two application trends have also emerged. The first trend highlights the use, initially, of a basic dilute suspension and its gradual thickening with suspensions that eventually reach a W/C ratio of even 1:1 or even denser [11,12]. The second tendency is to use an initial base suspension, which depends on the application, and to maintain it until the end of the injection by adding, if necessary, some enhancers during the injection [13].

Static Bleeding

The static bleeding of a cement suspension at rest is called the phenomenon in which the cement granules tend to settle under the influence of gravity creating a sediment of a certain density (sedimentation), while the unbound water creates a completely separate volume on the surface. The mechanism of bleeding phenomenon is considered very important, as it provides information on the behavior of cement suspensions at rest in the soil and after the end of an injection [15]. For this reason, the design of the suspensions requires the examination of the phenomenon with emphasis on the determination of the exudation rate and the final exudation rate [9,16]. The rate of exudation refers to the temporal evolution of the phenomenon, while the final percentage of exudation (bleeding capacity or final reduced volume of exudative water) is defined as the volume of water above the sediment, ΔV, at the end of exudation, expressed as a percentage of total initial volume of suspension, Vo. It is also often considered important to determine the final rate of forced bleeding, a phenomenon that can occur in suspensions due to the effect of injection pressure.

Determining forced exudation provides useful information on the behavior of cement suspensions when in the flow state [15]. Stability is the ability of cement suspensions to undergo little or no sweating to remain homogeneous until the injection process is complete and the setting phase begins. According to European Standard EN 12715, a suspension is characterized as ‘‘stable’’ if it has a bleed capacity of up to 5% after 120 min from preparation [3]. In general, pure cement suspensions are considered “unstable”, as only in cases where the W/C ratio is lower than 0.85:1, bleed capacity is significantly reduced. The development of fine-grained cements enabled the preparation of stable suspensions using higher W/C ratios (≤1.6:1) [14,17]. The preparation of stable suspensions is considered necessary for the successful execution of injections as only in this way the satisfactory filling of the soil pores is ensured. The use of unstable suspensions has the opposite effect [18], While at the same time there is a risk of separation of the suspension during flow, which makes it non-compressible [19,20]. For this reason, suspensions with a W/C ratio greater than 1.5:1 should not be used [18].

The reduction of bleed capacity with the reduction of the W/C ratio has been emphasized by many researchers [12,17,21-29], While by Houlsby [10] & Arenzana et al. [30] it is known that the reduction of the water-to-cement (W/C) ratio also leads to a decrease in the exudation rate. It is typically reported that the final bleeding rate of suspensions with a W/C ratio of 3:1 is twice that of suspensions with a ratio of 2:1, which in turn is ten times greater than ratios of 1:1. Several methods have been recorded by which it is possible to maintain the exudation of cement suspensions at satisfactory low levels, in addition to reducing the W/C ratio. The most common of these is the addition of bentonite [14,16,18,25,27,31]. It can be found, however, that this effect of bentonite decreases the higher its content and therefore should not be used at a rate of 4% [32]. According to some researchers, the optimal weight content of bentonite for this purpose is considered equal to 3% [31], while Huang [25] suggests the use of bentonite to reduce bleeding only in cases where the W/C ratio is greater than 0.7:1, due to the large porosity it brings to the mass of the suspension. A similar effect on the exudation of cement suspensions as that of bentonite is caused by the addition of silica fume or fly ash [9,15,16,18].

In this case, however, the content of these materials needed for the success of optimal results is much higher and can reach up to 20% [31], which can lead to alteration of other characteristics of the suspension [18]. The reduction in static and forced bleeding of suspensions with the addition of silica fume is due to the fact that it is a very fine-grained material that has the ability to fill the gaps between the cement grains within the suspensions [15]. In contrast, the addition of sand to cement suspensions has been found to increase bleeding [33]. The effect of superplasticizer addition and/or other chemical enhancers on the static and/or forced bleeding of cement suspensions can be beneficial [14,15,30,34,35]. According to Clarke et al. [36] & Gelade et al. [34], this effect of superplasticizers is due to the fact that they cause repulsive forces between the cement grains, of electrostatic nature, which prevent the formation of agglomerates by increasing the number of grains that remain in suspension.

This phenomenon becomes larger with increasing superplasticizer content, as there is an additional reduction in bleeding of a cement suspension [34,37]. However, in cases where their content exceeds a certain value -which depends on the composition of the suspension and the type of superplasticizer- then separation of the suspension is likely to occur. This is explained as follows [34]: At low or zero superplasticizer content, due to the strong attractive forces, the cement granules form a uniform and dense sediment. Conversely, when the superplasticizer content is high then, instead of the uniform sediment, intense stratification of the cement grains is caused. Larger grains precipitate at high speeds, while smaller grains remain suspended, giving the exudate water high turbidity.

This phenomenon is considered undesirable, as it causes significant alterations in the mechanical and rheological properties of the suspension. Also, it seems that the positive effect of superplasticizers is satisfactory only in those cases where the W/C ratio of the suspensions is low. In particular, it has been observed that the final volume of exudate does not change with the use of superplasticizer in contents from 0% to 2%, for suspensions with W/C ratio equal to 4:1, while any effect of superfluidizers on the exudation of suspensions becomes negligible in proportions of W/C ratios higher than 12:1 [30]. As mentioned above, the preparation of suspensions using fine-grained cements leads to a significant reduction in bleeding capacity. In general, it has been certified by many researchers that increasing cement fineness achieves the preparation of suspensions with low exudation that - under certain conditions - can be stable [17,25,38,39]. In general, it has been recorded that with the use of fine-grained cements it is possible to prepare stable suspensions with W/C ratios up to 1.2:1 [17] or even as 1.6:1 [14].

In addition, the type of cement plays an important role in the behavior of suspensions against bleeding, as slag-containing cements have been observed to perform better [40]. It also seems that as the percentage of slag in the cement increases, so does bleeding rate [40]. Some researchers suggest increasing the time [24] and/or the mixing speed [41] of the suspension components as a measure to improve the bleeding of cement suspensions. According to other researchers, increasing the mixing time only reduces the exudation rate, as the final exudation rate does not change significantly [30,40]. Regarding the mixing speed, Schwarz & Krizek [40] observe that with slow-moving mixers they achieved reductions in the final bleeding rate from 40% to 60% in relation to the use of high-speed mixers. The researchers attribute this improvement to the volume of the suspension to be mixed and not to the mixing speed, which leads to the conclusion that bleeding depends on the energy introduced into the suspension during mixing. However, even the mixing energy does not seem to have a significant effect when it comes to cement suspensions with high W/C ratios (≥4:1) [30].

Durability

Durability as a property of cement suspensions has become very important in this day and age, when the demonstration of environmental awareness by engineers is required. Adding to this is the fact that the maintenance of impregnation injections (e.g. the need to repeat injections after some years) can cause a significant financial burden on a project's budget and therefore such a prospect should be considered prohibitive [13]. From a chemical point of view, the permanence of a suspension is defined as the non-contamination of the soil environment due to possible deterioration of the suspension. From a mechanical point of view, a suspension is considered to be permanent which has no temporary use, but is required to maintain its mechanical properties in the long run [42]. Cement suspensions are generally considered to be quite durable -much more so than chemical solutions [43]- but can undergo significant alterations in extreme environmental conditions. Such are the large fluctuations in temperature, the presence of sulfonates in groundwater aquifers and the chemically "aggressive" environment [9,44]. There are no specific guidelines for the design of suspensions based on durability. However, suspensions with a cement content of 400kg/m3 are considered sufficient to cope with possible exposure to seawater, ice-shock - while still wet - and continuous moisture-drought changes [9]. Also, although considered a function of strength, the permanence of a suspension can be significantly improved by the use of additives, such as fly ash and silica fume, which react with excess calcium hydroxide to produce secondary ettringite [25,39,45]. Other methods that can be used to improve the durability of suspensions against frostbite are the use of fast setting cements and high hydration heat, the use of water-to-cement ratios of less than 0.4:1 and air entrapment in cases where the use of dilute suspensions is required [9].

Discussion

Based on the available literature, the following conclusions can be advanced:

A. A suspension is characterized as "stable" if it has a bleed capacity of up to 5% after 120min from preparation (European Standard EN 12715).

B. It is considered good practice to use stable suspensions because unstable suspensions may provide only a partial filling of soil voids due to bleeding.

C. In general, grouts based on ordinary cements are "stable" when the water-to-cement (W/C) ratio is less than 0.85, while microfine cement-based grouts are stable for W/C ratios up to 1.6.

D. Bleed capacity increases with increasing water-to-cement (W/C) ratio.

E. For the unstable suspensions, use of the superplasticizer usually resulted in increased bleed capacity but the opposite effect was obtained for a limited number of suspensions and, mostly, for the pozzolanic cements.

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