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Bonding effect on the evolution with curing time of compressive and tensile strength of sand-cement mixtures

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Abstract

Soil-Cement mixtures are used in several geotechnical applications and consist of artificially structured materials with stable fabric due to the presence of artificial bonds, which are the hydrated cement minerals coating the aggregates (soil particles). An extensive experimental study was performed on samples of an artificially cemented silty sand prepared by adopting three different dosages of cement and different water-cement ratios for each dosage. Realistic values for the dosages and water-cement ratios were adopted considering soil-cement mixtures performed by compaction or by grout injection. The unconfined compressive strength (UCS) and indirect tensile strength (ITS) of the mixtures were measured for different curing times. The values found were related to the water-cement ratio adopted for the mixing process, because of the dependency between the porosity of cement and the geometry of the bond minerals observed in electron scanning microscope images. The bond geometry varied considerably depending on the amount of water used in the preparation, particularly in the case of low cement dosages. The definition of degree of bonding was adopted to describe the evolution along curing time of UCS and ITS considering the values measured after 3 days of curing as reference points. This degree of bonding is useful for the definition of constitutive models for artificially structured materials. This parameter was indirectly related with the bond geometry; that is, the paths of strength evolution found were similar for samples with dispersed bonds. The improvement of tensile strength and compressive strength are correlated through a constant, independent of the dosage and water-cement ratios adopted for the mixture. Several authors have found identical values for this constant when studying compacted sand-cement mixtures. The particular structure resulting from the preparation process adopted does not affect this constant, however it affects the maximum UCS and ITS achieved for each cement dosage studied. This maximum depends on the water-cement ratio, and therefore this ratio is an important design parameter to be considered when prescribing compacted or grouted solutions.

Keywords: Curing; Compressive strength; Tensile strength; Admixture; Bonding; Strength evolution

1. Introduction

The study of soil-cement mixtures is of great interest mainly for road paving (road bases or subbases, e.g. Davies and Fendukly, 1994; Consoli et al., 2010; Xuan et al., 2012) and deep treatments by grout injection (e.g. Porbaha et al., 2000; Fang et al., 2001; Horpibulsuk et al., 2012; Farouk and Shahien, 2013). Besides strength achieved and the lifespan of these materials, another known advantages of adopting this soil improvement

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solution is the possibility of including part of the *in situ* soil in the mixture.

The mechanical properties of the mixture (stiffness and strength) are influenced by the original properties of the soil and the cement used and strongly depend on the amount of water and cement dosage adopted. Other parameters influencing the behavior of such kinds of mixtures are cement to soil ratio (in terms of weight), molding water content and workability or grout fluidity, void ratio or porosity, degree of compaction and compaction method, or injection parameters (Davies and Fendukly, 1994; Kenai et al., 2012; Viana da Fonseca et al., 2009; Consoli et al., 2010; Consoli et al., 2011a, 2012; Rios et al., 2012; Consoli and Foppa, 2014; among others) and the pH and ions present in the water (see Porbaha et al., 2000).

An extensive set of unconfined compression strength tests and Brazilian splitting tests was performed in mixtures of silty sand and Portland Cement Type I. The samples were prepared by adopting the dosages of 150, 200 and 250 kg/m^3 of Portland Cement (respectively, 10%, 13% and 17% of cement by weight of dry soil). Each dosage was prepared with water-cement ratios (w/c) of 0.6, 1.2 and 1.8. Different curing periods (3, 7, 14 and 28 days) were investigated for each case. The lower water-cement ratio adopted mimics a compacted material, while the higher ones mimic grouted materials assuming homogeneous mixtures. This is a different approach from that employed in existing studies. Typically, in studies on the mechanical behavior of soil-cement mixtures, the focus is on compacted materials as they are easier to prepare and to control *in situ* than grouted materials. In addition, in the existing works, lower percentages of cement (between 2% and 10%) are investigated, and the same are prepared with low w/c (water contents about 10%, which correspond to w/c between 0.1 to 0.5 for those dosages) (Clough et al., 1981; Consoli et al., 2010, 2011a,b, etc).

Strength is associated with the presence of artificial bonds, which are the hydrated cement minerals connecting the soil particles. The dosage of cement and the water available for the mixture, as well as the curing period, affect the amount and dispersion of such bonds and this is reflected in the improvement of the mechanical properties (strength and stiffness) of the mixture over time. The different structures (assumed to be the geometry of the bonds) are confirmed in this paper by scanning electron images and by mercury intrusion porosimetry tests. Only compressive and tensile strengths are investigated, as these are considered to be directly related to the soil structure. In the case of shear strength, a residual state is reached, and it therefore does not depend on dosage (Clough et al., 1981).

The concept of degree of bonding defined by Gens and Nova (1993) for soft rocks was adjusted to artificially cemented materials and used to compare all the cases investigated concerning unconfined compressive strength (UCS) and indirect tensile strength (ITS). The relationship between the two is also determined as it is usually adopted in the constitutive modeling of structured and cemented materials. Such an approach is becoming more popular (see for example Arroyo et al., 2011, 2012; Consoli and Foppa, 2014, and Rios et al., 2016).

In this paper, the degree of bonding is indirectly related to the structure resulting from the cement dosage and amount of water used in the mixture. This parameter quantifies the improvement of strength considering strength at the end of 3 days of curing as the reference state and is useful for constitutive modeling, as will be shown. Previous studies in the literature are focused on relating UCS and ITS with cement dosages, porosities in the hardened state, or a combination of both to account for the volume of cement filling the voids (Clough et al., 1981; Consoli et al., 2010). The findings are based on the experimental results from tests carried out on compacted materials, as already mentioned. Such approaches do not consider the geometry of the bonds, but only their presence and quantity in the mixture. In these works, the geometry of the bonds is not considered important because only compacted materials are treated, and the bonds are therefore expected to be concentrated. In addition, rather than provide direct information for constitutive modeling, only the UCS and ITS is quantified without considering any reference state. In this paper, while the geometry of the bonds is not quantified, it is used to distinguish the curves of strength earned along curing time for the samples prepared with different water-cement ratios.

2. Samples preparation and experimental setup

The soil studied is a non-plastic silty sand with 12% of particles with diameters smaller than 0.075 mm and a solid particle relative density, Gs, of 2.64. The mixtures studied were prepared in the laboratory by adding 10%, 13% and 17% of Portland Cement Type I (CEM I 42, 5R, solid particle relative density $Gc = 3.10$) by weight of dry soil. The cement dosages adopted are 150 kg/m^3, 200 kg/m^3 and 250 kg/m^3, respectively. The mixture was performed mechanically following ASTM D1632-07 (2007) and the water-cement weight ratios (w/c) adopted were 0.6, 1.2 and 1.8. The larger amounts of water reproduce grouts (Porbaha et al., 2000) and their fluidity/ injectability requirements. Tap water was used. The soil dosage (1500 kg/m^3) was kept constant in order to obtain dry volumetric weight variations only as a function of the volume occupied by the hydrated cement minerals (bonds). This last is assumed because the main objective of this study is to analyze the effects of the molding water in the bonds themselves and, as has been reported (e.g. Consoli et al., 2010, 2011a,b), the total porosity to cement ratio (in terms of volume) has great significance on the unconfined compressive strength (UCS) of soil-cement materials.

The samples were molded inside cylindrical PVC molds (7 cm diameter and 14 cm height). For the lower molding water contents ($w/c = 0.6$) the mixture was lightly compacted by layers using a tamping rod in order to keep the same amount of sand in the mixture. This was done by controlling the weight of the material in each layer. For larger

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