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Influence of Water Content in the UCS of Soil-Cement Mixtures for Different Cement Dosages

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Abstract
Soil-Cement mixtures are artificially structured materials with stable fabric due to the presence of artificial bonds. This type of materials is used in several geotechnical applications such as in pavement base layers in transportation infrastructures. In this paper artificially cemented silty sands are studied adopting dosages of 10% and 13% of Portland cement (by weight of dry soil). In order to analyze the impact of the molding water content in the Unconfined Compressive Strength (UCS) of the mixtures through time, the mixtures were prepared for water to cement ratios varying between 0.6 and 2.0 and tested for different curing periods (3, 7, 14 and 28 days). UCS test results are interpreted considering the presence of bonds connecting the grains. The definition of a bonding parameter is adopted aiming to quantify the improvements achieved for the different cases investigated and considering curing periods.

Keywords: soil-cement mixture; UCS; water content; water to cement ratio.

1 Introduction

Soil-Cement mixtures are often used as pavement base layers in transportation infrastructures such as roads and airports. The strength and the lifespan of these materials and the possibility of including part of the in situ natural soil in the mixture are known advantages of adopting this soil improvement solution.

The mechanical properties of the mixture are expected to be influenced by the original properties of the soil and cement used and strongly depend on the moisture conditions and the cement dosage adopted. Cement to soil ratio (in terms of weight), molding water content, voids ratio or porosity, degree of compaction and compaction method (Davies and Fendukly, 1994; Kenai et al., 2006; Viana da Fonseca et al., 2009; Consoli et al., 2011; Consoli et al., 2012; among others), are parameters

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usually used to characterize such kinds of mixtures. Among them, water to cement ratio (in terms of weight) or voids to cement ratio (in terms of volume) (see for example Consoli et al., 2011; Rios et al., 2012 and Consoli and Foppa, 2014) are the most popular.

The strength and stiffness of soil-cement mixtures are often evaluated through unconfined compression tests. Unconfined Compressive Strength (UCS) is the only property considered in this paper. The results of an extensive set of UCS tests were performed in a mixture of silty sand and Portland Cement Type I, in which the samples were prepared adopting dosages of 10 and 13% of Portland cement (by weight of dry soil), adopting water to cement ratios varying between 0.6 and 2.0. Different curing periods (3, 7, 14 and 28 days) were investigated for each case.

Knowing that a soil-cement mixture can be defined as a structured geomaterial with artificial bonds (hydrated cement minerals) connecting the soil particles, strength can be associated to the presence of these bonds. Cement dosage and the water available for the mixture, as well as the curing period affect the amount and dispersion of such bonds and their strength, and for this reason 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 cases investigated. Such topic is explored in this paper knowing that the contribution of the bonds depends on curing time and mixing parameters.

2 Bonds and Degree of Bonding

Bonds are defined in this paper as the physical connections of the grains due to the presence of hydrated cement minerals. These bonds are responsible for an increase of compressive strength and stiffness and they often provide tensile strength to granular materials. The degree of bonding is related with the amount of bonds present, which translates their significance to the overall behavior. Such behavior depends on the volume occupied by the cement (bond density), assuming that bonds have mechanical and chemical properties similar to those of the cement used in the mixture. Like for cement, bonds properties depend on curing conditions.

The degree of bonding can be quantified by parameter b proposed by Gens and Nova (1993), where b=0 in the absence of bonds and b=b_{max} when all bonds are intact. This parameter was originally defined for soft rocks to account with the presence of natural bonds connecting the clay minerals, resulting from diagenesis. Such bonds can break when the material is subjected to loading paths (stress and suction changes) explaining the physical degradation and evolving behavior of such complex materials. Arroyo et al. (2011) and Arroyo et al. (2012) considered this concept to simulate the influence of bonds generated by a Portland cement type I in a mixture with a clayey soil. Neri (2013) used it to explain the behavior of a sand, also treated with Portland cement type I. Both studies found this approach reliable for simulating the behavior of the two different kinds of artificially cemented soils.

If stiffness and strength depend of bonds presence, it is natural to assume that these mechanical properties will reduce with decreasing amount of bonds (or with decreasing degree of bonding). The limit case is the destructured material, when there are no bonds. This is the reference case assumed by Gens and Nova (1993). Accordingly to these authors, parameter b is defined as the increase of isotropic yield stress caused by the bonds relatively to the isotropic yield stress at the reference state, p_c (Equation 1, where p_{cb} is the isotropic yield stress of the bonded material).

$$p_{cb}= (1+\mathrm{b})\, p_{cb} \tag{1}$$

In alternative, for a fixed dosage of cement it is also natural to assume that stiffness and strength will increase with increasing curing time. In this case $b=0$ for the minimum curing time considered (typically 3 days) and maximum for the maximum curing time considered (assumed 28 days in this work). Considering Equation 1 and the definition of *b*, the reference case is now when curing time is minimum and not in the absence of bonds. Such is the approach adopted in this paper.

Equation 1 can be generalized to translate the Unconfined Compressive Strength, by replacing yielding stress by the ultimate axial stress value (or the unconfined compressive strength) of the specimen σ_u and of the reference material $\sigma_{u,ref}$ (Equation 2).

$$\sigma_u = (1+b)\ \sigma_{u,ref} \tag{2}$$

Parameter *b* is expected to increase along time because of the hydration of cement during curing. The evolution of this parameter along time is not expected to follow similar paths for the different dosages of cement and water to cement ratios adopted because of the different characteristics of the bonds. Indeed, the cement minerals create a network of bonds surrounding the sand particles and allow the formation of a stable open structure.

For the same cement dosage it can be assumed the same amount of bonds. However, bonds geometry and their dispersion in the granular medium depends on the amount of water available when cement hydration starts. When small amounts of water are used in the mixture, the formation of concentrated bonds is expected because water is concentrated at the grains contact forming meniscii, and therefore the hydrated minerals will concentrate there. When large amounts of water are used, the hydrated minerals get dispersed over the grains surfaces forming crystals and the overall texture of the material is more homogeneous. Both geometries are shown in Figure 1 and result from the interpretation of scan electron photographs also included in the figure. These differences in bond distribution are expected to affect UCS and its evolution with curing time and, for this reason will also affect the evolution of parameter *b*.

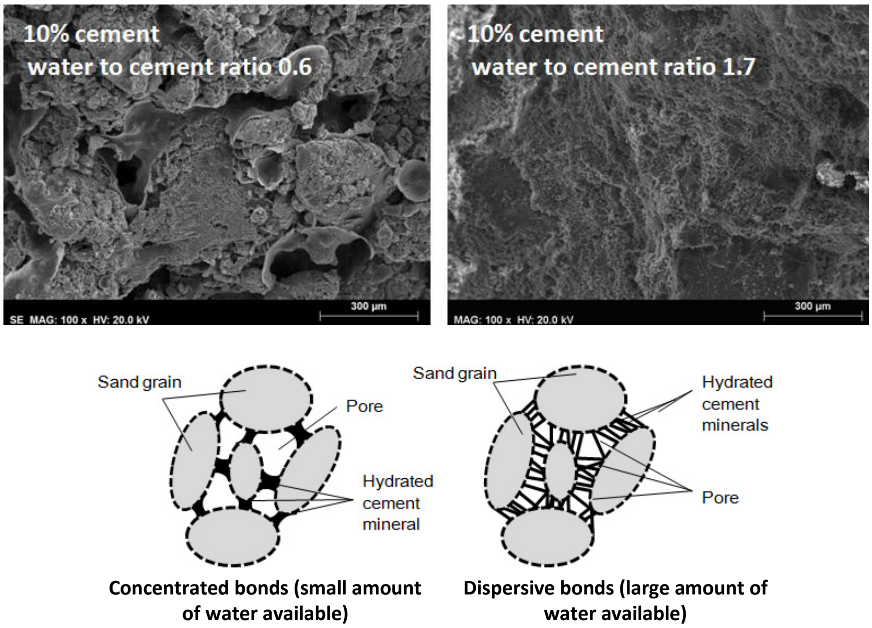

Figure 1: Expected geometries for the bonds considering the amount of water available in the mixture

Such differences in bonds geometry provide different contribution to global stability and therefore are expected to reflect in UCS. The discussion in this paper is focused in this topic.

3 Samples Preparation and Experimental Setup

The mixtures studied were prepared in the laboratory by adding, to a silty sand, 10% and 13% of Portland Cement Type I (CEM I 42,5R) by weight of dry soil. The cement dosages are respectively, 150 and 200 kg/m^3. The mixture was performed mechanically (see Figure 1a) and the water to cement weight ratios adopted were varying between 0.6 and 2.0. Tap water was used. The soil dosage (1500 kg/m^3) was kept constant in order to obtain porosity variations only as a function of the volume occupied by the cement (bonds). This last is assumed because the main objective of this study is analyzing the effects of the molding water in the bonds themselves and, as it was observed by some authors (e.g. Consoli et al., 2011), the porosity to cement ratio (in terms of volume) has great significance for the UCS of soil-cement materials.

The samples were molded inside cylindrical PVC molds (7 cm diameter and 14 cm height; Figure 1b). For the lower molding water contents (w/c of 0.6 and 1.3) the mixture was lightly compacted by layers (4 layers) using a tamping rod, while for larger amounts of molding water the mixture was poured in the molds avoiding the formation of air bubbles. The samples were submerged in tap water while curing (Figure 2c), however they were removed from the molds after 3 days of cure. Three samples were prepared for each case and curing time.

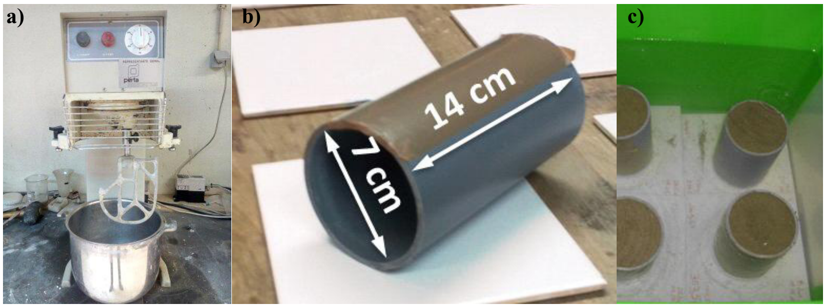

Figure 2: a) the mechanical mixer; b) the PVC mold; c) the samples curing submerged in tap water.

The procedure adopted for the Unconfined Compressive Strength tests is based in ASTM D2166-00. Loading was applied in a conventional triaxial chamber (empty), adopting a constant rate of 0.2 mm/min for axial deformation. The samples were visually checked in order to understand if rupture was satisfactory for cylindrical specimens of mortar or concrete (NP EN 12390-3:2009). Those providing unsatisfactory ruptures were rejected.

Figure 3a presents the curves of axial stress versus axial strain obtained for the samples prepared with 13% of cement and 0.6 water to cement ratio (samples 1 and 3) for 28 days of cure. A marked peak can be observed, indicating localization. This surface is shown in Figure 3b. The UCS value corresponds to the maximum axial stress recorded.

The differences in bond geometries previously shown in Figure 1 apparently did not affected the shape of the curves, but only in the dispersion of UCS. Indeed, for the samples with disperse bonds it was observed larger homogeneity of samples as mixture is easier for large amounts of water.

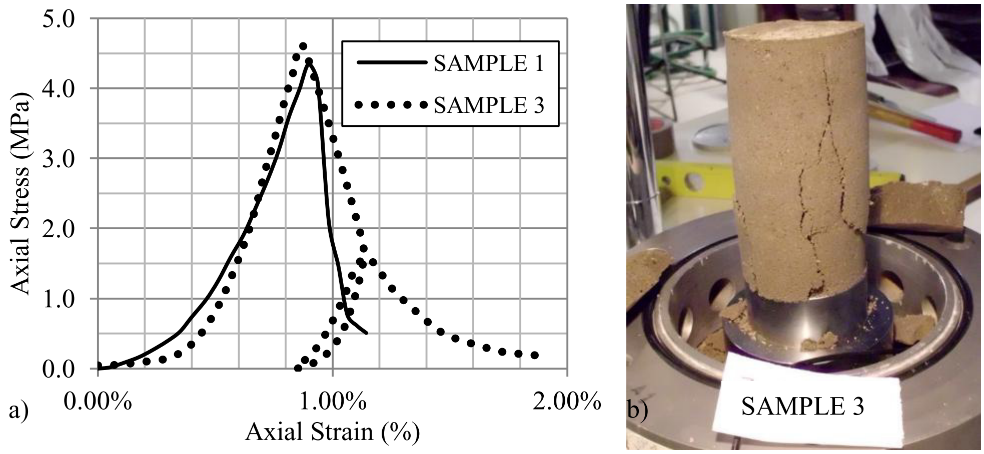

Figure 3: For 12% cement, 0.6 water to cement ratio and 28 days of cure - a) deviator stress versus axial strain for samples 1 and 3; b) rupture of sample 2.

4 Results

4.1 UCS Versus Water/Cement Ratio Along Time

Figure 4 presents the UCS values obtained for 10% and 13% of cement (150 kg/m^3 in Figure 4a and 200kg/m^3 in Figure 4b) as a function of the water to cement ratio for diferent curing periods (3, 7, 14 and 28 days). The average values obtained for each case, for each curing period, were used to draw the curves also presented in this figure. The nomenclature adopted in this study is the cement dosage (in kg/m^3) followed by the curing period (in days) (e.g., 150_3 means 150 kg/m^3 tested after 3 days of cure).

The UCS values found are function of the molding water content. For each cement dosage there is an intermediate value for the water content corresponding to a maximum UCS. This point is more evident for 28 days of cure. These UCS curves have shape similar to that expected for a compaction curve and for this reason the water/cement ratio for which UCS is maximum can be considered to be the optimum water/cement ratio for that dosage defined in terms of compressive strength achieved.

In what it concerns compaction, maximum strenght is found when dry density is maximum, which is at the maximum at optimum point. However it is worth to note that the dry specific density of the treated material is not expected to vary much for the different water/cement ratios, only the amount of water is varying. Thereby, the different UCS found only depend on the properties of the bonds resulting from the amount of water available, as already discussed. This means that there is an optimum amount of water for which the amount of bonds and their configuration provides the best connection to the grains.

Finally, the curves found for the two cement dosages studied at the end of 28 days of cure can now be compared. As expected, UCS increases with increasing cement dosage, however the amount of water for the maximum values is smaller for the largest dosage studied. Such result is typical of cement treated materials (Viana da Fonseca et al., 2009). Basically, the increase in cement dosage corresponds to an increase in the amount of bonds present in the mixture. Apparently, the geometry of the bonds does not have significant influence on UCS at the end of the curing period analysed.

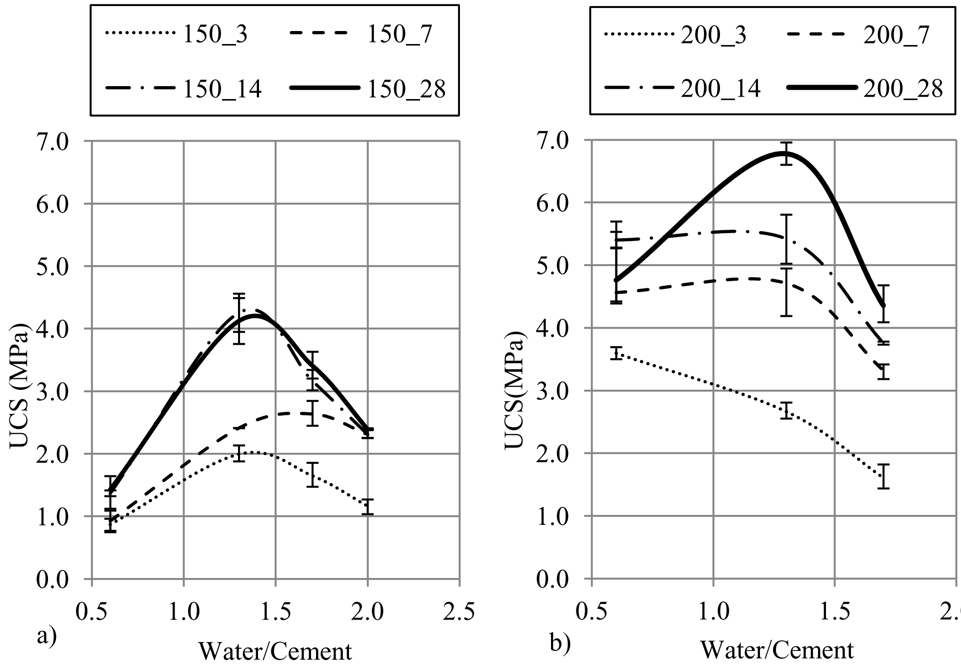

Figure 4: Unconfined Compressive Strength for each curing period as a function of the water to cement ratio for a) 10% of cement and for b) 13% of cement.

4.2 Evolution of the Degree of Bonding With Cure

As mentioned before, the evolution of the degree of bonding along the curing time is analyzed considering the improvement of compressive strength relatively to a reference state. Parameter *b* is given by equation 2 and it was computed considering the UCS for the curing periods studied, adopting the value of UCS after 3 days of cure as reference. The values found for the two cement dosages and for the different water to cement ratios studied are presented in Figure 5 (dosages of 150 kg/m^3 are in Figure 5a and of 200kg/m^3 are in Figure 5b).

As expected, the values of *b* after 28 days of cure increases with cement dosage. There are some inconsistencies in the results whenever *b* reduces with curing time, but they can be explained by experimental error. Overall, *b* parameter shows the bi-linear trends expected, which corresponds to the largest increment during the first days of cure followed by a smooth evolution until reaching an almost constant value. Such result is typical of soils treated with cement, mortar and concrete.

When comparing the samples prepared with the same dosage, it can be seen that the increase along time of UCS is less marked for the samples prepared with water to cement ratio of 0.6. These samples have concentrated bonds as previously shown in Figure 1, and therefore the grains have punctual connections between themselves. The less marked difference in the evolution of *b* may indicate that the number of connections at the end of the 28 days is similar to that at the end of 3 days, even if the strength of each connection increases with curing time. In case of dispersive bonds, even if no new connections are formed during cure, they become stronger along time and, because the number of contacts is very large, UCS increases.

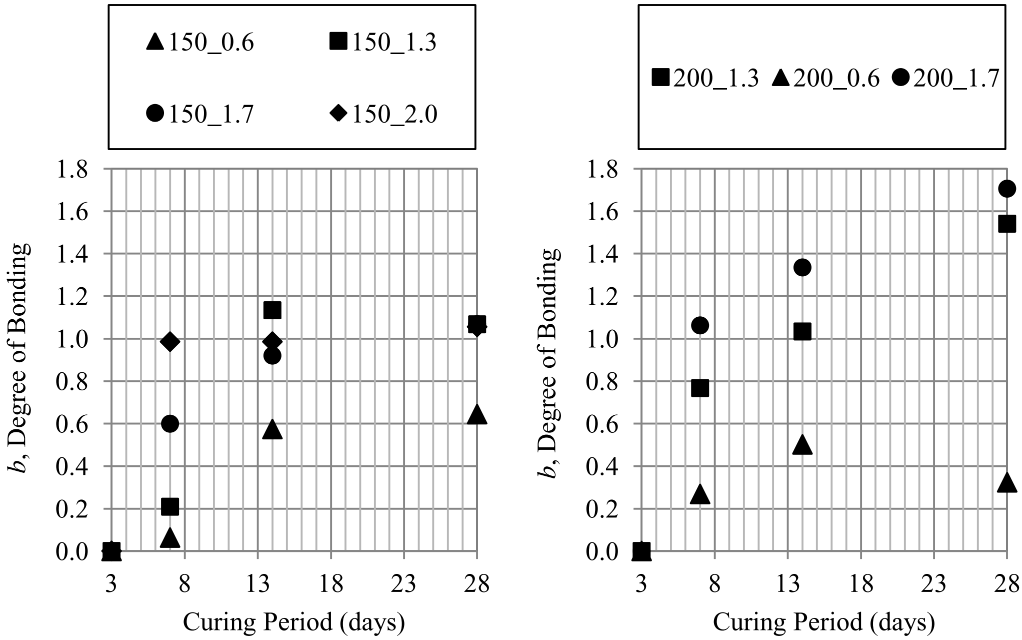

Figure 5: Evolution of *b* for each curing period for the different dosages of cement: **a)** 10%; **b)** 13%.

To conclude, it is worth to note that parameter b can be associated to the speed of cure but not to the maximum strength achieved because it is relative to an initial value different for each dosage. Indeed, the smallest values for *b* were found in the samples prepared with lower water contents, however the minor values of UCS for each cement dosage were not found for these samples, as previously shown in Figure 4. For this reason, the speed of cure cannot be associated to the maximum strength achieved.

5 Conclusions

In this study, the evolution, along curing, of the degree of bonding was analyzed considering data from unconfined compressive strength tests performed in samples prepared with different dosages of cement (10% and 13%) and with different water to cement ratios for which dosage. The following main conclusions can be taken:

- UCS is always larger for the highest dosage of cement, independently from the water to cement ratio adopted for the mixture.
- Independently from the dosage of cement, there is a clear optimum water content providing the maximum UCS value.
- Compressive strength develops faster with time when larger water to cement ratios are adopted;

UCS evolution along time was explained by the number of connections, which is large in case of large water to cement ratios, when connections are dispersed. Strength earned along cure in this case is homogeneous, while remains punctual and therefore less significant for overall behavior when connections are concentrated. Such result must be confirmed through other type of tests, for example by performing tensile strength tests. The tensile strength of these mixtures can provide useful information about the bonds development as the tensile strength is expected to be essentially result of the cement.

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