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A theoretical–experimental approach to elastic and strength properties of artificially cemented sand

S. Maghous *, N.C. Consoli, A. Fonini, V.F. Pasa Dutra

Department of Civil Engineering, Federal University of Rio Grande do Sul, Porto Alegre, RS, Brazil

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ABSTRACT

Evaluating the behavior parameters of soils and soil-binder mixes by means of theoretical models that are supported by laboratory tests still remains a key challenge in foundation design. In this context, the paper investigates some aspects of the mechanical behavior of artificially cemented sands (ACS) by means of experimental characterization and micromechanics-based modeling. Particular emphasis is given to the increase in elastic stiffness and strength brought by cementation. Based on the concept of a fictitious continuum medium and the homogenization theory, the effective elastic properties of ACS are evaluated using the Mori–Tanaka and self-consistent schemes. The elastic micromechanical approach is supported by bender element tests. Finally, the effective strength properties of ACS are assessed by means of micromechanics-based failure criterion formulated within the context of non-associated plasticity. Validation and calibration of the theoretical model are achieved by comparison with data from unconfined compression tests.

1. Introduction

Cement treatment of granular soils is a widely used technique in the field of soil improvement, which proved effective for ground stabilization in a large variety of geotechnical works. This kind of reinforcement have been notably applied in pavement base layers, pipe bedding, slope protection for earth dam, as a base layer to shallow foundations and to prevent sand liquefaction (e.g., [1–4]).

Soil–cement is a geo-composite elaborated from highly compacted mixture of granular soil, Portland cement and water. As the cement hydrates, the stiffness and strength of the mixture increase while its permeability reduces, leading to a net improving of the engineering properties of the raw soil. One of the main advantages in improving locally fine-grained soils with cement is to avoid the need of bringing from away great volumes of sand and gravely materials, which might involve high costs that are hardly compatible with the economical constraints.

During the last decades, important laboratory studies ([5–14], to cite a few) have significantly contributed to better understanding the physical mechanisms and macroscopic parameters affecting the behavior of artificially cemented sand, referred to as ACS throughout the paper.

Recent research studies on granular soil–cement blends have sought to establish experimentally a dosage methodology based on the definition of some key parameters that control the mechanical properties of ACS at macroscopic level. It has been notably found that the porosity/cement ratio plays a fundamental role in the assessment of the target stiffness and strength [13]. Representative contributions on this subject are due to works by Consoli and co-authors (see for instance references [15,16,13]).

In spite of the common use of Portland cement in the improvement of local soils and a large amount of experimental works dedicated to characterize many aspects of ACS behavior, there is still a lack of theoretical-based models that could help to accurately analyze the mechanical response of geo-structures involving ACS materials.

In the context of micromechanical modeling, there are few approaches that have dealt with the formulation of the behavior of cement–sand composites. These works specifically focused on the situation of sand reinforced by cement grouting [17–20] and not on artificially cement sand that is the purpose of this paper. It should be emphasized that the distinction between the artificially cemented sand and grouted sand is mainly related to type and degree of cementation, which is usually significantly lower for artificially cement sand. In addition, the volume fraction of cement is controlled in ACS, while it varies in space along the grouted domain due to particle filtration. (e.g., [21,22]).

* Corresponding author. Tel.: +55 51 33 08 35 88; fax: +55 51 33 08 39 99.
E-mail address: samir.maghous@ufrgs.br (S. Maghous).

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Nomenclature

$\underline{a}$	vector
$\underline{\underline{a}}$	second-order tensor
$\underset{\sim}{a}$	fourth-order tensor
$\underline{x}$	position vector labeling locations within the REV
$\underline{\underline{1}}, \underset{\sim}{1}$	second-order, fourth-order unit tensor
$\underline{u}$	displacement vector
$\underline{\underline{\varepsilon}}, \underline{\underline{E}}$	microscopic, macroscopic strain tensor
$\underset{\sim}{A}$	strain concentration tensor
$\underset{\sim}{P}$	Hill polarization tensor
$\underline{\underline{\sigma}}, \underline{\underline{\Sigma}}$	microscopic, macroscopic stress tensor
$\underline{\underline{\sigma}}_d, \underline{\underline{\Sigma}}_d$	microscopic, macroscopic deviatoric stress tensor
σ_d, Σ_d	equivalent microscopic, macroscopic stress
σ_m, Σ_m	mean microscopic, macroscopic stress
k, μ	bulk, shear modulus
$\underset{\sim}{c}, \underset{\sim}{C}$	microscopic, macroscopic stiffness tensor
η	porosity (volume fraction of pores)
e	void ratio
f^r	volume fraction of phase (r)
φ_0^a, φ^h	volume fraction of anhydrous cement, hydrated cement
ϑ_h	volume of hydrates created per unit volume of anhydrous cement
h	hydrostatic tensile strength
T, ϕ	friction coefficient, friction angle
t	dilatancy coefficient

The present paper investigates some aspects of the mechanical behavior of ACS by means of an experimental and theoretical analysis. More precisely, the objective herein is twofold. First, to formulate within a micromechanical and experimental setting the elastic and strength properties of ACS at macroscopic level. Second, to discuss the relevance of the micromechanical modeling basis, particularly the morphological description of ACS at micro-scale, in light of the comparison between experimental and model results.

2. Experimental program

The experimental program was carried out in three parts. First, the geotechnical properties of the studied soil were characterized. Then a number of unconfined compression tests were carried out and the uniaxial (unconfined) compressive strength of the artificially cemented sand (ACS) was determined. Finally, bender element tests were also executed to obtain the elastic properties of the ACS.

2.1. Materials

The Osorio sand used in the testing was obtained from the region of Porto Alegre, in Southern Brazil, and is classified [23] as a non-plastic uniform fine sand (SP) with rounded particle shape and specific gravity of the solids equal to 2.65. Mineralogical analysis showed that sand particles are predominantly quartz. Its grain size curve is shown in Fig. 1. The grain size is purely fine sand with a mean effective diameter (D_{50}) of 0.16 mm, and with uniformity and curvature coefficients of 2.1 and 1.0, respectively. The minimum and maximum void ratios are 0.6 and 0.9, respectively. The angle of shearing resistance at constant volume is about 30°.

High early strength Portland cement (Type III according to [24]) was used as the cementing agent. Its fast gain of strength allowed the adoption of 7 days as the curing time. The corresponding unconfined compressive strength at 7 days curing is equivalent to the unconfined compressive strength at 28 days curing of an ordinary Portland cement (Type I). The specific gravity of cement grains is 3.15. Distilled water was used for the characterization tests and tap water for molding specimens.

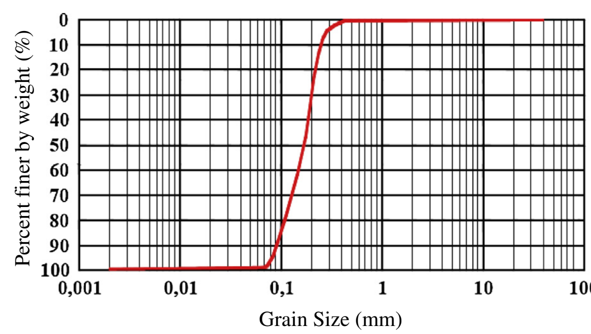

Fig. 1. Grain size distribution of Osorio sand.

2.2. Methods

Molding and curing of specimen as well as testing procedures are summarized below.

2.2.1. Molding and curing of specimens

For all the ACS tests, cylindrical specimens 70 mm in diameter and 140 mm high were used. A target dry unit weigh for a given specimen was then established through the dry mass of soil–cement divided by the total volume of the specimen. In order to keep the dry unit weight of the specimens constant with increasing cement content, a small portion of the soil was replaced by cement. Calculation of the porosity is therefore based on the specific gravity of the composite, which is computed from the soil and cement percentages in the specimens.

After the soil, cement and water were weighed, the soil and cement were mixed until the mixture acquired a uniform consistency. The water was then added while continuing the mixture process until a homogeneous paste was created. The amount of cement for each mixture was calculated based on the mass of dry soil and the moisture content. Cement content is defined as the mass of cement divided by the mass of dry soil. The moisture content is defined as the mass of water divided by the mass of solids (sand particles and cement powder).

The specimen was then statically compacted in three layers inside a cylindrical stainless steel mould, which was lubricated, so that each layer reached the target density. The top of each layer was slightly scarified. After the molding process, the specimen was immediately extracted from the mould and its weight, diameter and height were measured. The samples were then placed inside plastic bags to avoid significant variations of moisture content. They were cured for 7 days in a humid room at 23 °C ± 2 °C and relative humidity above 95%.

2.2.2. Unconfined compression tests

Unconfined compression tests have been used in most of the experimental programs reported in the literature to verify the effectiveness of stabilization with cement and to assess the main parameters controlling the strength of cemented soils. For this study, the procedure described in [25] was adopted. After curing