Relation between microstructural properties and strength parameters of biocemented sands

Relation entre les propriétés micromécaniques et les paramètres de résistance des sables bio-cimentés

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ABSTRACT: An experimental study has been performed to investigate the biocementation process effect on the micromechanical properties of biocemented Fontainebleau sand. The micromechanical properties such as contact surface, coordination number and other properties of the biocemented samples have been computed for the first time from 3D images with a high resolution obtained by x-ray synchrotron micro-tomography. The evolution of all these properties with respect to the volume fraction of calcite are analyzed and compared between each other (from untreated sand to highly cemented sand). In general, the results point that these properties are affected by the level of biocalcification. The cohesion of the biocemented sand found from previous triaxial tests has been related successfully to the evolution of the cohesive surface and other micromechanical properties within the sand specimen.

1. INTRODUCTION

The Microbial Induced Calcite Precipitation (MICP) technique is considered as one of the most promising techniques of biocementation. In the last 10 years, several research programs have been performed to investigate the efficiency of this technique for different geotechnical problems; in the lab by standard geotechnical tests (Feng and Montoya 2016) and in-situ by large-scale tests. Most of these studies have shown that this technique enhances the mechanical properties of the soil (cohesion, resistance) and decreases the transfer properties such as permeability.

In the present work, we proposed to explore the links between the microstructural properties changes induced by the MICP technique and the mechanical properties of the soils. For that purpose, different biocemented sand specimens have been observed at the European Synchrotron Radiation Facility (ESRF) at a very low resolution to characterize the evolution of the micromechanical properties (contact surfaces and coordination number) as a function of the cementation level. Finally, it is shown that the Coulomb cohesion, which represents one of the most important parameter in soil strength, can be related to these micromechanical parameters.

2. MATERIAL AND METHOD

2.1. IMAGE ACQUISITION AND TREATMENT

Different biocemented samples with different amount of calcite have been prepared to evaluate their mechanical strength under triaxial conditions. After 20% of axial strain the triaxial tests have been stopped and safe sub-samples of about 3 mm in length with different calcite amount (see table 1) have been taken along these triaxial samples, in order to characterize their microstructural changes using micro-tomography observations.

Table 1: Characteristics of the scanned sub-samples

Sub-sample	S1	S2	S3	S4	S5	S6
Initial porosity (%)	40	40	38	38	37	38
calcite (% in mass)	3	5	7	9	12.6	16.9

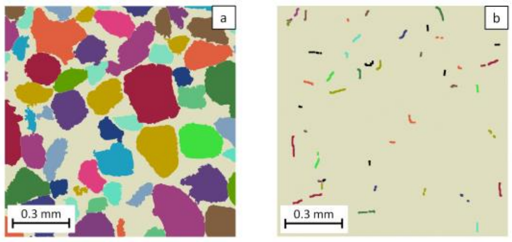
The scan of these sub-samples was performed using X-ray synchrotron micro-tomography on the ID19 beamline at the ESRF in Grenoble. A resolution of $(0.65\ \mu m)^3$ /voxel was chosen in order to visualize precisely calcite crystals, which have a typical size of 10 micrometers. The field of view is (3250 x 3250 x 2000 voxels), i.e (2.11 x 2.11 x 1.3 mm^3) to obtain 3D images large enough to be representative of the material. These 3D images were then treated in order to separate the three phases: sand, calcite and pores.

2.2. MICROSTRUCTURAL PROPERTIES

To determine the pertinent micromechanical properties such as the contact surface, the coordination number, the cemented grains (sand + calcite) in each 3D trinary image have been separated (watershed method) and labeled by using the Visilog software. This algorithm has been developed based on the work of Beucher (1991). After this treatment, one can easily remove the calcite from the image to get the 3D images of the sand grains only. This image can be considered as the initial state of the sand before calcification.

Coordination number: A Matlab code has been developed in order to determine the coordination number before and after calcification. This code allows to identify each contact between grains and to label them (Figure 1). This operation has been applied in all the 3D images. Classical statistical tools can then be applied to compute the coordination number. Let us remark that this computation neglects the grains which are localized at the borders of the 3D images in order to avoid boundary effects.

Figure 1: a) Labeled grains, b) labeled contact surfaces



Contact surface: Several methods (direct voxel counting, marching cube…) have been proposed to quantify curvilinear surface or voxels cloud objects surfaces. In the present work, the method based on Crofton theory (Legland et al. 2007) has been used. This method, based on line interceptions in the computation of surfaces, gives very precise results compared to the other methods in a very short computation time.

3. RESULTS AND DISCUSSION

Coordination number: Figure 2 presents the evolution of the mean coordination number of each sub-sample normalized by the same quantity before biocalcification (sand only). For the sand only, the mean coordination number is approximately equal to 8. This figure shows a slight non-linear increase of the mean coordination with the mass fraction of calcite. For a mass fraction of 16.9%, this increase is around 10%. This evolution can be related directly to the formation of new cemented contacts between the grains.

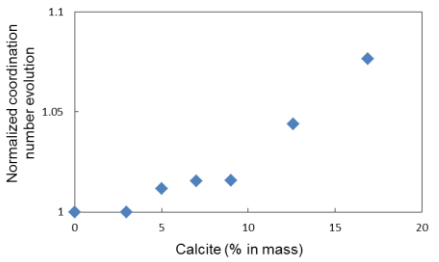


Figure 2: Normalized coordination number evolution versus cementation level

Contact Surface: Figure 3 shows the evolution of the mean contact surface normalized by the same quantity before biocalcification (sand only). This figure shows a linear increase of this mean surface with the mass fraction of calcite. For a mass fraction of 16.9%, this increase is around 4 times compared to the initial contact surface. The added contact surface can be considered as purely cohesive and represents one of the main parameters which control the evolution of the cohesion of the biocemented sand.

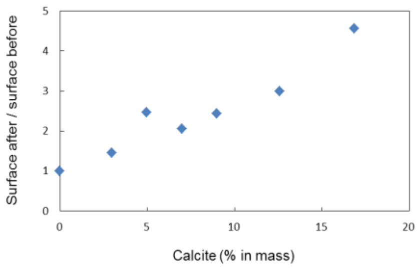


Figure 3: Evolution of normalized contact surface with the cementation level

Coulomb Cohesion: In this paragraph we aim to estimate the Coulomb cohesion from micromechanical properties (cohesive surface, coordination number, etc.). Generally, the Coulomb cohesion (C) in a cohesive sand is directly related to the tensile strength (σ_t) by $C = (2/3)\ \sigma_t$. Richefeu et al. (2006) developed an expression of the tensile strength of cohesive material using the averaging technique. In this work we used this developed relation but instead of the suction force, we introduced another type of bonding force, which is due to cementation agent. This force can be defined by the contact surface (s) of the cement bond and its tensile strength (σ_{ten}) :

$$f_n = s.\sigma_{ten} \qquad (1)$$

In the granular material the tensile strength depends on the intrinsic strength of the cement material and the adhesion of the bond material with the grain surface. Assuming that we have a monodisperse grain assembly and introducing the expression of the cementation force in the expression developed by Richefeu et al. (2006), Coulomb cohesion due to cementation agent in granular media can be written as follow:

$$C = (1/(D_{50}^2)\pi)\varphi.z.s.\sigma_{ten} \qquad (2)$$

Where D_{50} represents the mean diameter of grains, φ the solid fraction inside the specimen, z the mean coordination number and s the contact surface formed by the cementation agent. The last parameter (σ_{ten}) is considered as a model parameter (tensile strength). An estimation of the cohesion of the scanned sample has been performed by using the previous micromechanical properties in the developed expression of the cohesion. Figure 4 shows a calibration of the previous expression by using the computed properties (contact surface and the coordination number) with experimental results presented in the work of Cheng et al. (2012), where the cohesion has been measured by triaxial tests on similar bio-cemented sand samples. The calibrated value of the intrinsic tensile strength (σ_{ten}) is 50 kPa. This value is comparable with the results obtained from the bonding strength measurements between two glass beads linked with calcite, which has been found close to 41 kPa by Lin et al. (2014). The slight difference between the two results is probably due to the different contact adhesion (sand and glass beads).

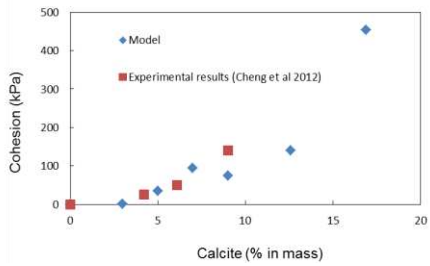


Figure 4: Evolution of the cohesion versus cementation level

4. CONCLUSION

In this work a new imaging method has been presented to estimate the micromechanical properties such as contact surface, coordination number and other parameters (which have not been presented in this paper). This method has been applied successfully on 3D images of biocemented sands which contain 3 phases (sand, calcite and air). The evolution of the coordination number and the contact surface has been determined on a wide range of calcite content (0 to 16.9%). These parameters have been used successfully to estimate the Coulomb cohesion. The calibrated parameter (tensile strength) is comparable to the value obtained in a previous experimental campaign performed on glass beads cemented with calcite cement.

5. ACKNOWLEDGEMENT

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