Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 158 (2016) 39 – 44

Procedia Engineering

www.elsevier.com/locate/procedia

VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING – Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, CNRIG2016

The micromechanical behaviour of a biogenic carbonate sand

Vincenzo Nardelli[a,]*, Matthew R. Coop[b]

[a]*City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong*
[b]*University College London, Gower street, London WC1E 6BT UK. Formerly City University of Hong Kong*

Abstract

An experimental investigation of the micromechanical behaviour of a biogenic carbonate sand from the Philippines was conducted. Mechanical parameters of sands at the micro-scale are required in order to simulate the particle interactions in numerical analyses carried out using the Discrete Element Method (DEM). The tests were performed on particles obtained from the sedimentation of coral fragments and they were carried out by means of a custom-made inter-particle loading apparatus that enabled the investigation of both the normal and tangential loading behaviour at the particle contacts. The normal loading tests showed a reversible behaviour after the first loading, while the tangential loading behaviour of this sand appears to be dependent on the vertical confinement and mainly reversible for small displacement cycles. Also, the inter-particle friction coefficients at larger displacements are substantially higher than those calculated for other sands using the same experimental procedures.

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: carbonate sand; micromechanics; contact behaviour; friction; stiffness

1. Introduction

Carbonate sands are soils that have a sedimentary origin. Calcium carbonate is the predominant mineral in these materials and they are usually the result of the deposition of the skeletal bodies of small organisms (e.g., shells, elements of coral reef, etc.) or chemical precipitation from carbonate-rich water. In recent decades, interest in these

* Corresponding author. Tel.: +852-3442-6528.
E-mail address: vnardelli2-c@my.cityu.edu.hk

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016
doi:10.1016/j.proeng.2016.08.402

materials increased because of their unusual mechanical features, such as high friction angles and high compressibility, which is related to particle crushing [1].

The mechanical behaviour of geomaterials at the micro-scale started to be studied during the 60's of the 20th century by means of custom-made apparatuses [2,3,4], but it gained more interest after the increase in popularity of the Discrete Element Method [5]. New experimental methodologies were developed, in order to study the strength of particles [6] and the contact behaviour of grains [7,8]. Cavarretta et al. [9] studied the effects of environmental conditions on both glass ballotini and particles of quartz sand, highlighting an increase of friction coefficient for relative humidities higher than 40% and for water saturated conditions. Senetakis et al. [10] presented the results of inter-particle shearing tests on a quartz sand, underlining the effect of the normal confinement on the tangential behaviour and showing that water had no clear influence on the frictional behaviour of soil particles.

2. Experimental equipment

The experiments were carried out by means of a custom-made inter-particle loading apparatus that was designed and built at the City University of Hong Kong [8]. The original version of the apparatus was upgraded in order to improve the accuracy of the displacement measurements and increase the variety of testing conditions [11].

The apparatus consists of a stainless steel loading frame, three loading arms and a stainless steel sled (Fig. 1). One loading arm is oriented along the vertical direction while the other two are in orthogonal horizontal directions. Each of them was assembled connecting a micro linear actuator (a), a high resolution load cell (b) and the sled by means of stiff mechanical elements and quasi-frictionless linear bearings. The sled (c) is placed on a polished piece of stainless steel by means of a bearing system made up of three chrome steel balls and can be moved along the horizontal plane by means of the linear actuators. Each load cell has a capacity of 100 N.

During each test, one particle is connected to the vertical arm and another one is mounted on the sled (d) and they can be tested after placing them in contact using the linear actuators. The displacements are measured through three non-contact eddy current displacement sensors (e) having a measuring range of 3mm and a resolution of 10^{-5}mm. The whole apparatus is located inside a Perspex chamber and the relative humidity inside this can be regulated using a humidity controller within the range 15-85%. Also, the particles can be tested under fluids installing a small aluminium and Perspex water bath inside the apparatus.

The apparatus is capable of performing tests applying combinations of either forces or displacements along three directions. A custom-made software is used to send the input commands to the apparatus and to record the test data. Also, two digital micro-cameras (f) are installed inside the chamber in order to determine the correct location of the contact between the particles and to record pictures during the tests.

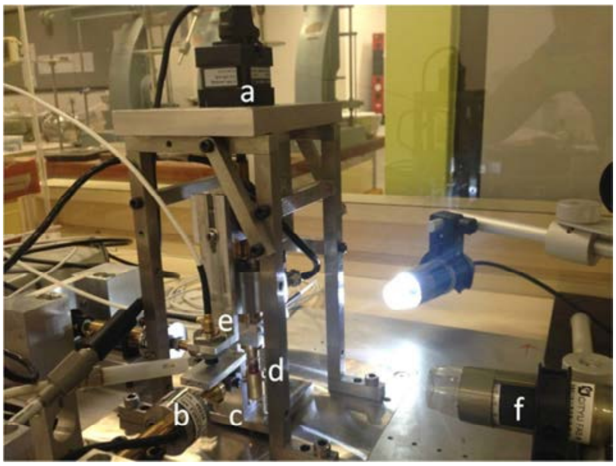

Fig. 1. Inter-particle loading apparatus: a) linear actuator; b) load cell; c) stainless steel sled; d) soil particles during a test; e) eddy-current displacement sensor; f) digital micro-camera.

3. Materials tested and procedures

The material tested is a biogenic carbonate sand from the Philippines. It mainly consists of particles originating from the deposition of pieces of coral, foraminifera, the remains of bivalve shells and marine gastropods. This investigation focussed on the contact behaviour of the coral fragments, which are the most prevalent within the whole sand sample. Figures 2a and b show two images of a coral fragment taken by means of an Environmental Scanning Electron Microscope (ESEM). The surface of the material is characterised by the presence of some sodium chloride crystals (Fig. 2b), which is also confirmed by the chemical analyses carried out on the same fragment (Fig. 2c). The material has a rough surface and micro pores.

As shown in Figure 2c, the main minerals identified within this sand are aragonite and calcite, the two crystal forms of calcium carbonate ($CaCO_3$). Calcite is characterised by a Young's modulus of 73-84GPa and a shear modulus of 28-32GPa [12,13]. The surface roughness of this sand was analysed by means of the optical interferometer, measuring an average RMS roughness of 0.51μm, with a standard deviation of ±0.12μm.

The sand particles were selected according to their rounded shape among those available. The particles were glued onto brass holders (Fig. 2d) by means of super glue prior to being tested, waiting at least 24 hours to let the glue harden. Roundness and sphericity were estimated for each particle by visual observation, using the chart of Krumbein and Sloss [14]. Average values of 0.8 and 0.9 were determined for roundness and sphericity, respectively. The average diameter of the particles tested was 2.59mm, with a standard deviation of ±0.25mm.

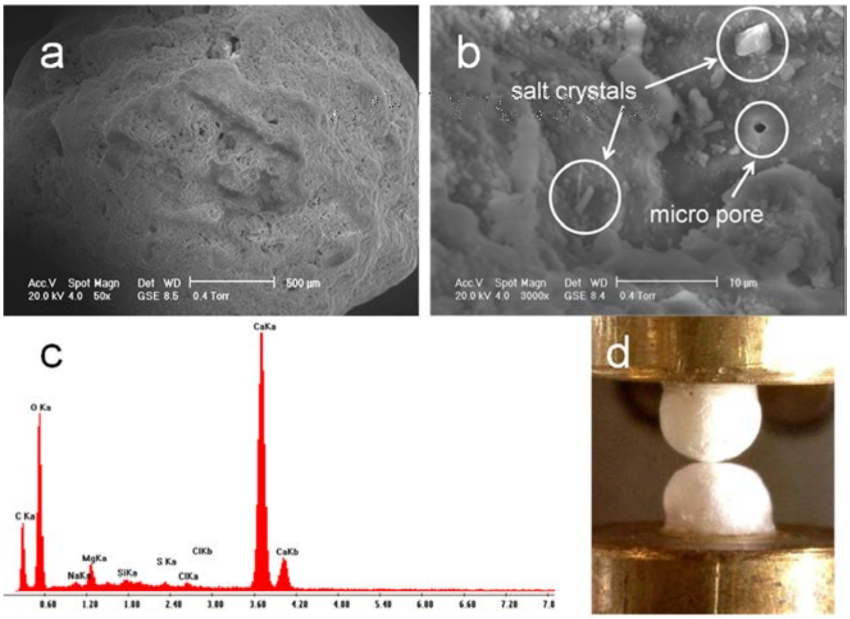

Fig. 2. a) ESEM image of a carbonate sand particle; b) detail of the particle microstructure; c) chemical components of particle; d) two particles during a test.

4. Results

The results of normal and tangential loading tests are illustrated in this section. All the test data were corrected for the compliance of the apparatus and the tangential loading data were also corrected for the friction between the sled and the bearing system. The normal loading tests were performed compressing the particles in the vertical direction, which is orthogonal to the plane of contact of the particles. This can be regarded as a radially unconfined compression at the contact. Tangential loading tests were carried out shearing the particles while confining them at the contact by means of a constant normal force.

4.1. Normal loading

Figure 3a shows the results of a typical normal loading test on two particles of carbonate sand, obtained applying a displacement rate of 0.2mm/h at their contact. Three cycles were performed, the first two reaching 25N and the third up to 10N. The average contact stress reached during the first two cycles is very high, within the order of magnitude of 1000kPa, calculated following the contact theory of Hertz [15]. The test was performed at a constant relative humidity of 55%. The graph shows a non-linear elastic relationship between normal force and displacement during the first cycle, until a brittle behaviour at the contact of the particles can be observed. This is related to unrecoverable deformations, probably caused by plastic deformations of the particles asperities within the contact area. The second and the third cycles also show a non-linear elastic behaviour, but much stiffer than the loading path of the first cycle and almost completely reversible. Some hysteresis can be also observed during the unloading-reloading paths.

Two theoretical curves obtained from the Hertzian theory of contact are also illustrated in Figure 3a, along with the experimental results. An equivalent radius R^*=0.67mm and a Poisson ratio ν=0.3 were used, along with Young's moduli E=11GPa and E=75GPa for the first loading and the reloading path, respectively, which were estimated through curve fitting. The equivalent radius was calculated from the measurement of the particle diameters, summing the reciprocals of the particle radii, as proposed by Hertz [15]. In first loading, the agreement between the theoretical and the experimental curves is quite accurate until 15N although with an artificially low E value, while the theoretical curve fits the unloading-reloading paths quite well for loads higher than 2N. The theoretical reloading curve shows that a Young's modulus comparable with those found in literature for calcite enables a good curve fitting.

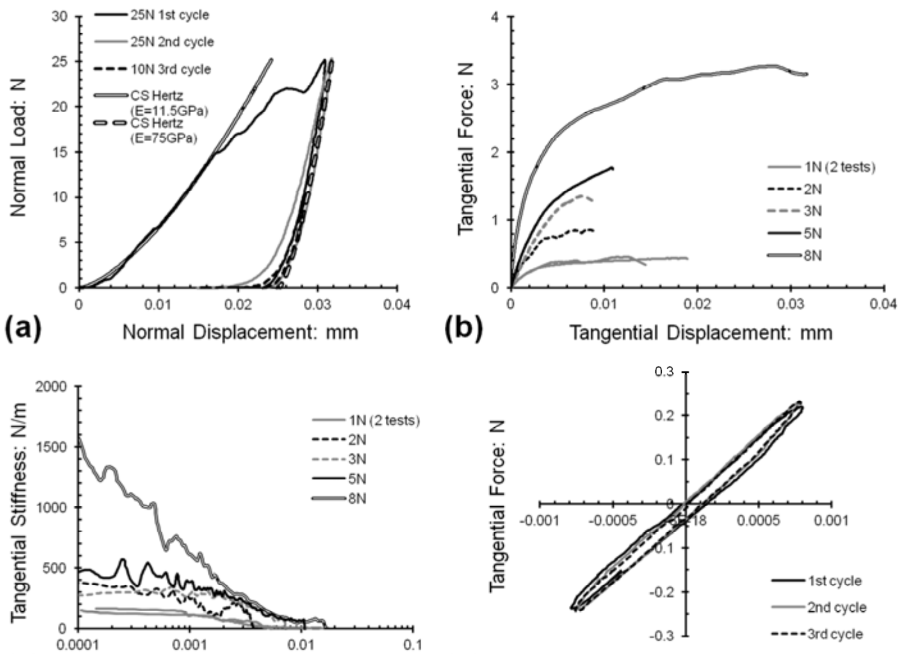

Fig. 3. a) Cyclic compression curves for a pair of carbonate sand particles and comparison with Hertz contact model [15]; b) tangential load-displacement curves for carbonate sand under different normal loads (1-8N); c) tangential stiffness-displacement curves for carbonate sand under different normal loads (1-8N); d) cyclic tangential loading behaviour of carbonate sand particles within small displacements (±0.8 m).

4.2. Tangential loading

Figure 3b shows the results of six tangential loading tests performed under constant normal loads between 1 and 8N, submerging the particles in distilled water. All the tests were carried out applying a tangential displacement of 0.02mm/h, except the test performed under 8N, where the particles were sheared at 0.05mm/h. The data show a non-linear behaviour followed by transition towards a steady state, which is not abrupt and should correspond to particle sliding. For some tests, a clear steady state is not evident, probably because of the rough particle morphology and/or the brittle behaviour of the particles asperities. Figure 3c shows the test results in terms of tangential stiffness plotted against tangential displacement, which was calculated as tangent stiffness. The effect of the confining load on stiffness appears clear, especially for displacements larger than 1μm.

Figure 3d illustrates the results of a cyclic tangential loading test on a pair of carbonate sand particles under a normal force of 3N, which were sheared at a velocity of 0.02mm/h, applying displacements of ±0.8μm, which were reached before the onset of particle sliding. The response of the particles appears reversible and small hysteresis loops can be observed.

An analysis of the effect of the environmental conditions is shown in Figure 4, where the maximum tangential forces were plotted against the normal load during each test. The tests were grouped according to their humidity conditions: low relative humidity (LH, RH<30%), high humidity (HH, RH=80-85%) and water saturated conditions (W). The coefficient of sliding friction estimated for water saturated conditions (μ_w=0.39) appears to be slightly lower than those determined for the other two conditions (μ_{LH}=0.42 and μ_{HH}=0.46, respectively) probably because of a lubricant effect of water or the dissolution of salt crystals on the particles surfaces, which may reduce their roughness. However, these values are tentative given the data scatter and a general trend cannot be identified clearly. An average value of inter-particle friction angle of 23.8° was determined for all the tangential loading tests performed.

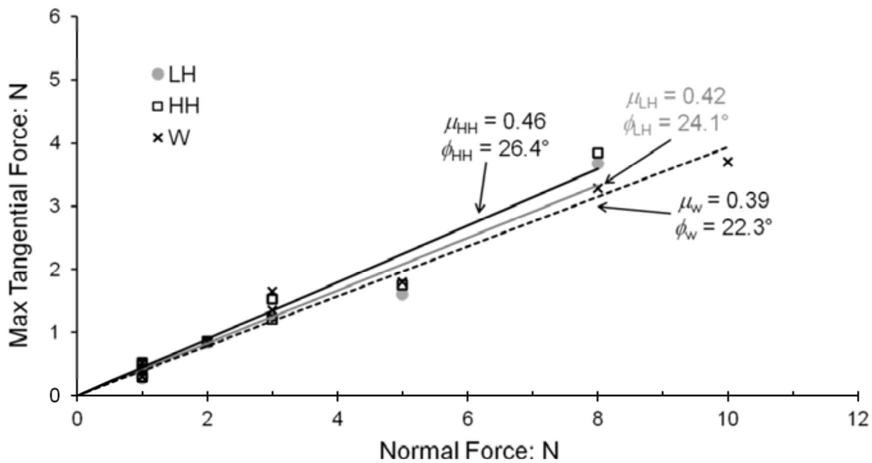

Fig. 4. Influence of the environmental conditions on the inter-particle friction coefficient of carbonate sand particles. LH: low relative humidity (RH<30%), HH: high relative humidity (RH=80-85%), W: water saturated conditions.

5. Conclusions

This work highlighted the mechanical behaviour of biogenic carbonate sand particles at the micro-scale. It was shown that the normal loading response evolves towards a stiffer and reversible behaviour after a first loading to high loads. Also, the elastic properties of the bulk material seem appropriate to describe its response through the Hertz model, after an initially soft first loading response.

The biogenic carbonate sand exhibits a behaviour that is dependent on the normal load applied during tangential loading, with tangential stiffnesses that increase with the increase of normal confinement. Also, the cyclic tangential loading test has underlined the reversibility of the particles behaviour within small displacements. A possible small effect of the environmental conditions was observed, with coefficients of sliding friction slightly lower for water saturated conditions, which may be related with a lubricant effect of water and salt dissolution on the particle surfaces.

The average values of inter-particle friction coefficient for this carbonate sand are much lower than those determined by Coop [1] for the Dogs Bay sand using triaxial testing, who measured an average angle of friction at critical state of 40.3°. Also, this sand exhibits inter-particle friction coefficients much larger than those measured by Senetakis et al. [10] for Leighton Buzzard quartz sand (9.9°), which may be related with the different surface roughness (0.38μm with a standard deviation of ±0.19μm for the LBS quartz sand, [16]) and different mineralogy and surface hardness of these two sands. An effect of hardness might be supported by the presence of wear on the particle surfaces that was visible by means of the digital microscopes, which was not evident on the LBS quartz sand particles after testing.

Acknowledgements

The Authors would like to thank Dr Béatrice Baudet for the use of the interferometer at the University of Hong Kong. The technicians of City University of Hong Kong, Mr Y.H. Tsang and Mr C.K. Lai are acknowledged for their technical help and Mr M. Chiang for the use of the ESEM. This work was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CityU 112712).

References

[1] M.R. Coop, The mechanics of uncemented carbonate sands, Géotechnique 40(4) (1990) 607–626.
[2] H.M. Horn, M.S. Deere, Frictional characteristics of minerals, Géotechnique 12(4) (1962) 319-335.
[3] A.E. Skinner, A note on the influence of interparticle friction on shearing strength of a random assembly of spherical particles, Géotechnique, 19(1) (1969) 150-157.
[4] D.C. Procter, R.R. Barton, Measurements of the angle of interparticle friction, Géotechnique 24(4) (1974) 581-604.
[5] P.A. Cundall, O.D.L. Strack, A discrete numerical model for granular assemblies, Géotechnique 29(1) (1979) 47–65.
[6] Y. Nakata, A.F.L. Hyde, M. Hyodo, H. Murata, A probabilistic approach to sand crushing in the triaxial test, Géotechnique 49(5) (1999) 567-583.
[7] I. Cavarretta, M.R. Coop, C. O'Sullivan, The influence of particle characteristics on the behaviour of coarse grained soils, Géotechnique 60(6) (2010) 413-423.
[8] K. Senetakis, M.R. Coop, The development of a new micro-mechanical inter-particle loading apparatus., Geotechnical Testing Journal 37(6) (2014) 1028-1039.
[9] I. Cavarretta, I. Rocchi, M.R. Coop, A new inter-particle friction apparatus for granular materials, Canadian Geotechnical Journal 48(12) (2011) 1829-1840.
[10] K. Senetakis, M.R. Coop, M.C. Todisco, The inter-particle coefficient of friction at the contacts of Leighton Buzzard sand quartz minerals, Soils and Foundations 53(5) (2013) 746-755.
[11] V. Nardelli, M.R. Coop, An experimental investigation of the micromechanical behaviour of cemented sand particles, Proc. of the TC105 ISSMGE Int. Symp. on Geomechanics from Micro to Macro, Cambridge, UK, 1-3 September 2014, 2 (2015) 1013-1018.
[12] G. Mavko, T. Mukerji, J. Dvorkin, The rock physics handbook: tools for seismic analysis in porous media, Cambridge University Press, 1998.
[13] J.C. Jaeger, N.G.W. Cook, R. Zimmerman, Fundamentals of rock mechanics, Fourth edition, Wiley-Blackwell, 2007.
[14] W.C. Krumbein, L.L. Sloss, Stratigraphy and Sedimentation, San Francisco, W. H. Freeman and Company, 1963.
[15] H. Hertz, Über die Berührung fester elastischer Körper, J. Reine und Angewandte Mathematik, 92 (1992) 156-171.
[16] F.N. Altuhafi, M.R. Coop, Changes to particle characteristics associated with the compression of sands, Géotechnique, 61(6) (2011) 459-471.