

Preliminary experimental study on three-dimensional contact behavior of bonded granules

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Abstract. In order to explore the microscopic contact behaviour of structured sands, devices were developed for specimen preparation and for carrying out tests on mechanical contact behaviour of three-dimensional (3D) bonded spheres. The specimen preparation device can cement two separate aluminium hemispheres by epoxy adhesive with accurate size control. The auxiliary loading devices can carry out compression, tension, shear, bending and torsion tests and any of their combinations. The experimental results show that the peak shear force, bending moment and torque of the bonded hemispheres are normal force dependent; that is, they first increase with the normal force and then decrease after the normal force exceeds a critical value.

1. Introduction

Slope stability has attracted wide range of research using equilibrium methods [1], in-situ monitor methods [2], physical models [3] and numerical simulations [4-5]. The discrete element method (DEM), first proposed by Cundall and Strack [6], has been increasingly applied as well in recent years. Compared with the complex macroscopic constitutive models and parameters in finite element method (FEM) simulations, only a simple and reasonable microscopic contact model and relatively few parameters are required in DEM. More importantly, DEM can naturally simulate large deformations and failure of slopes. Some slope failures can be attributed to the degradation of cementitious geomaterials. Uti and Nova [7] studied the evolution of natural cliffs subject to weathering with DEM. Jiang and Murakami [8] carried out a DEM simulation of the full-process slope failure with focus on very-rapid and extremely-rapid landslide process due to the loss of inter-particle bonding. In these simulations, a simple and reliable bonding contact model is one of the key issues.

A few researchers have investigated the mechanical behaviour of cemented granules through experiments and accordingly some bonding contact models have been proposed for DEM simulations [9, 10]. Delenne et al. [11] firstly presented an experimental verification of a DEM simulation of cemented granules. Kirsch et al. [12] presented a novel experimental setup invented to measure the mechanical behaviour of solid bridges between double-particle systems in the millimetre range. Jiang

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et al. [13, 14] performed an experimental study on the contact behaviour of idealized granules (cemented aluminium rods) with different bond materials (epoxy adhesive and calcium aluminate cement) and different bond geometries (thin and thick bond modes). The mechanical behaviour of cemented rods was tested in simple and complex loading tests (tension, compression, pure shearing, pure rolling, and shear-rolling tests). The test results were used to examine the microscopic contact model which was employed in two-dimensional DEM simulations of structured sands [15].

Following the work in [13, 14], the main objective of this study is to carry out a preliminary experimental investigation of the mechanical behaviour of three-dimensional cemented granules, idealized as a pair of hemispheres glued together by epoxy adhesive. For this purpose, the devices to prepare and test the cemented granules are introduced first. The contact behaviour of the cemented hemispheres was tested in different loading modes, i.e., tension, compression, shear, bending and torsion tests. The effects of normal force on shear, bending and torsion strengths were examined.

2. Sample preparation

The aluminium hemispheres were machined from aluminium alloy blocks with an elastic modulus of 70 GPa and a Poisson's ratio of 0.3, which can match the properties of quartz sand particles. The epoxy adhesive has an average tensile strength of 16 MPa [13]. The epoxy adhesive was chosen because of its stable mechanical behaviour and high workability.

Figure 1 presents the sample preparation device which can be used to prepare high-quality reproducible cemented hemisphere pairs. The preparation device is composed of a bearing platform, three moulding modules and three fixing plates, which can be assembled by bolts.

A systematic preparation process was established after a large numbers of trials. First, the three moulding modules are assembled and a thin layer of petroleum jelly was evenly spread on the hemispherical concavities to make it easy to remove the prepared cemented granules from the moulding modules. Second, the hemispheres are cleaned with acetone and are placed into the lower six concavities (facing upward at this stage). Then, the bearing platform is fixed on the moulding modules with four bolts. The assembled device is then turned upside down so that the upper six concavities are exposed. Third, a certain amount of epoxy adhesive is filled into the cylindrical grooves. Then, another six hemispheres are put into the upper concavities and the three fixing plates are fixed on the moulding modules with nine bolts. Finally, the preparation device is kept in an electric oven at 100°C for 1.5 h to shorten the solidification time of epoxy adhesive from 24 h to 1.5 h. After cooling, the six prepared pairs of cemented hemispheres are carefully removed from the device and placed in a sealed box under a constant temperature of 20°C and humidity of 80% to cure for 20 days.

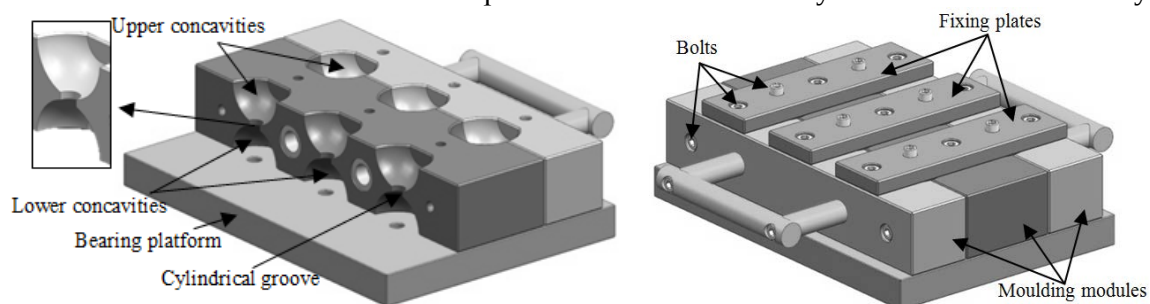


Figure 1. Devices for preparation of cemented hemispheres

3. Loading tests

3.1 Compression tests

The compression tests were carried out using a compression-auxiliary device, as shown in Figure 2(a). The auxiliary device is a rigid block with a cylindrical hollow. Four "windows" are opened to observe the deformation of the cement material. The cemented hemisphere pair was inserted into this hollow

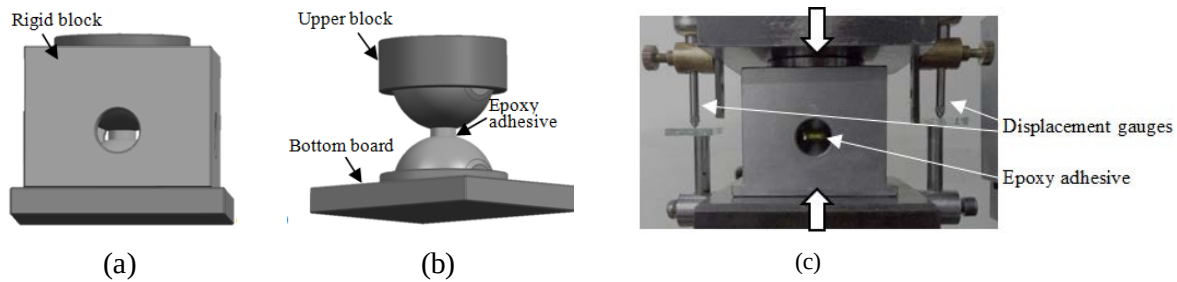


Figure 2. Compression test: (a) and (b) 3D schematic diagrams of the compression-auxiliary device; (c) physical test

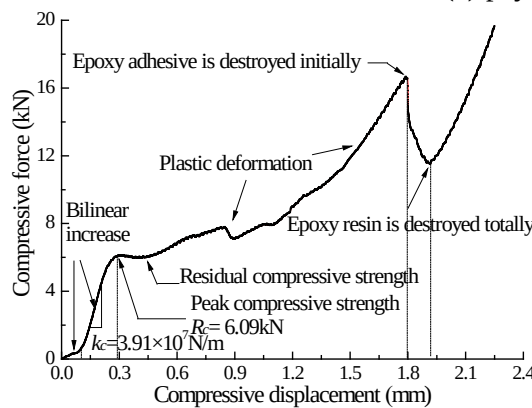


Figure 3. Compressive force-displacement relationship of the cemented hemispheres

so that any lateral displacement was constrained. The cemented hemisphere pair was then seated on the bottom board and capped with the upper block. The assembled compression-auxiliary device was then seated on the pedestal of the biaxial compression system and centered for the test. Petroleum jelly was used to reduce friction at interfaces. During the compression test, the pedestal was continuously moved upward at a constant rate of 0.1 mm/min. Two displacement gauges were attached on both sides to measure compression displacement. The vertical load was measured by a load cell installed inside the biaxial compression system.

Twenty-five cemented hemisphere pairs have been tested in compression. Figure 3 presents a typical relationship between the compressive force and displacement obtained in one test. Figure 3 shows that the compressive force initially increases bi-linearly up to the first peak, R_c , when the compressive displacement is 0.29 mm. The bi-linearity is possibly due to initial contact defects between the cemented hemispheres and the compression-auxiliary device. The compressive force then decreases slowly to a residual strength, followed by the second-stage nonlinear increase up to another peak when the compressive displacement reaches 1.8 mm. The epoxy adhesive experiences a clear plastic drum-like deformation mode in this stage. Then, the cementation is abruptly damaged and the two hemispheres start to contact.

In the compression test, the measured compressive stiffness k_c is 3.91×10^7 N/m and the peak compressive strength R_c is 6.09 kN. By normalizing this compressive strength with the cross-sectional area A of the cylindrical bond between the two hemispheres, the compressive strength expressed in stress is $\sigma_c = 77.5$ MPa ($\sigma_c = R_c/A$, $A = \pi(d/2)^2$, $d = 10.0$ mm). The compressive Young's Modulus E is 0.54 GPa ($E = k_c \cdot H_{center}/A$, $H_{center} = 2.0$ mm).

3.2 Tension tests

The tension tests were carried out with a tension-auxiliary device, as illustrated in Figure 4. The device includes two rigid blocks with grooves where the cemented hemispheres can be fixed. Four fixing bolts are used to fix hemispheres in the other direction. Four vertical rods are arranged in such a way as shown in Figure 4(b) that the compressive forces from the biaxial compression system act to push the two blocks apart, leading to a tensile force in the epoxy adhesive. The four rods can move freely in the pilot holes.

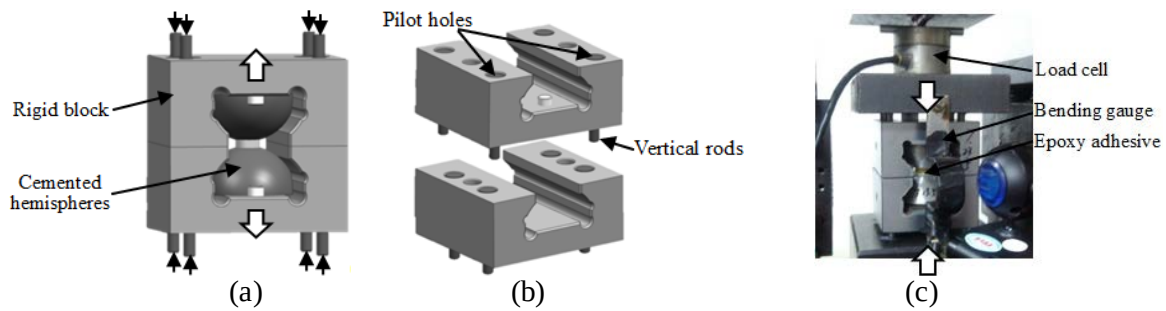


Figure 4. Tension test: (a) and (b) 3D schematic diagrams of the tension-auxiliary device; (c) physical test

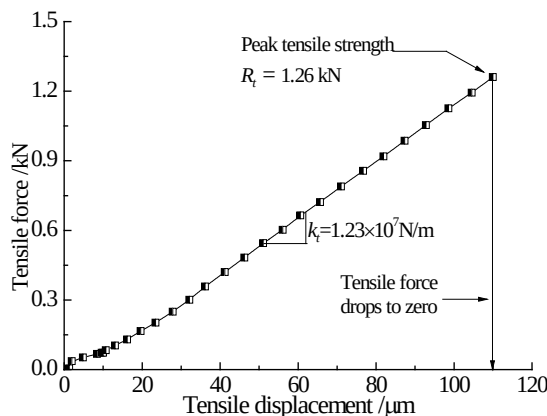


Figure 5. Tensile force-displacement relationship of the cemented hemispheres

During the tension tests, the vertical load, measured by a load cell, was applied at a constant tension rate of displacement of 0.1 mm/min. Two bending gauges (with higher accuracy than a displacement gauge [20, 21]) were attached on both sides to record the tensile displacements. Figure 5 presents the tensile force-displacement relationship of the cemented hemispheres in one tension test. The tensile force increases linearly until the tensile displacement reaches 0.11 mm, and then drops to zero suddenly as the bond split apart in the middle.

In the tests, the measured tensile stiffness k_t is 1.23×10^7 N/m, and the peak tensile strength R_t is 1.26 kN. The tensile strength expressed as a stress is $\sigma_t = 16.06$ MPa ($\sigma_t = R_t/A$, $A = \pi(d/2)^2$, $d = 10.0$ mm). The tensile Young's Modulus E ($E = k_t \cdot H_{\text{center}}/A$, $H_{\text{center}} = 2.0$ mm) is 0.29 GPa, smaller than the value obtained from the compression test.

3.3 Shear tests

The shear tests were carried out with a shear-auxiliary device, as illustrated in Figure 6. Similar to the tension-auxiliary device, this device includes two rigid blocks with grooves to fix the hemispheres. A vertical insert that is fixed in a rectangular groove in the upper block is used to transfer normal force from the biaxial compression system to the cemented hemispheres. Two horizontal inserts are fixed on the upper and lower blocks respectively so that the horizontal forces applied by the biaxial compression system can shear the cemented hemispheres. The two horizontal rods are aligned along the same axis that passes the center of the epoxy adhesive. Before shearing, a vertical (normal) force smaller than R_c in Figure 3 was first applied. This vertical force was maintained constant throughout the test by a servo-control mechanism. Then, the horizontal (shear) force was applied at a constant shearing rate of 0.1 mm/min. The shear force was measured by two load cells, attached on the two horizontal pedestals of the biaxial compression system. Two displacement gauges were used to record the shear displacement.

Figure 7 presents the shear force-displacement relationship of the cemented hemispheres under different normal forces (i.e., $F_n = 0.2, 1, 2, 3, 4$ kN). The shear force initially increases linearly to a

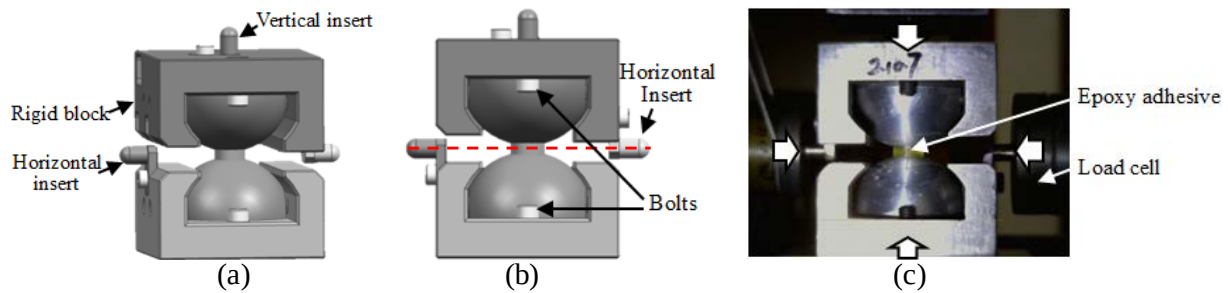


Figure 6. Shear test: (a) and (b) 3D schematic diagrams of the shear-auxiliary device; (c) physical test

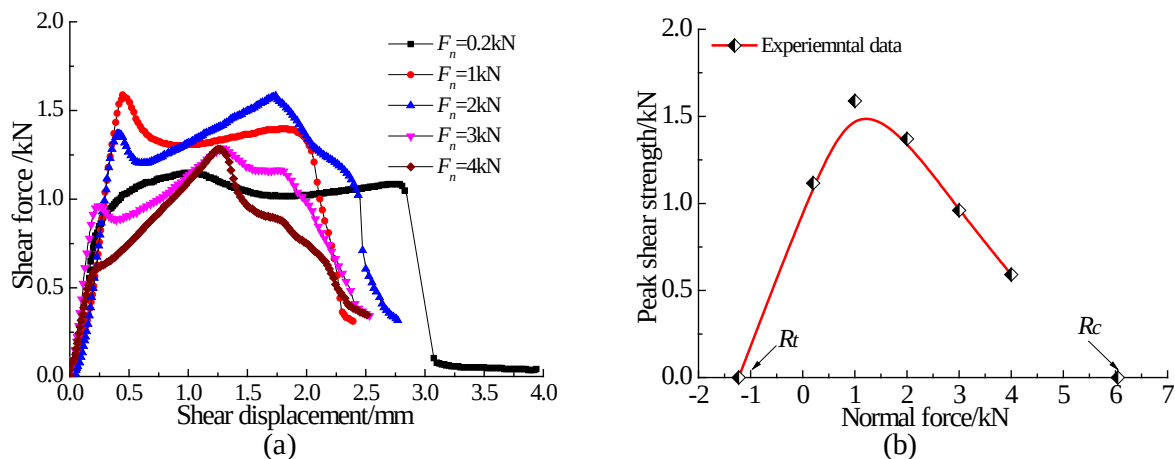


Figure 7. Mechanical behavior of cemented hemispheres in shear tests: (a) shear force-displacement relationship; (b) variation of the peak shear strength versus the normal force

peak value with the shear displacement, and then decreases to a residual strength with a little further shear displacement. Possibly due to friction, the shear force continues to increase with the shear displacement until the bond becomes detached from sphere surfaces. Figure 7(b) shows that the normal force has a significant effect on the shear strength. The peak shear strength first increases with the normal force and then decreases after the normal force exceeds a critical value of 1.2 kN. In shear tests conducted on sand particles artificially bonded with Portland cement, Nardelli & Coop [16] observed qualitatively similar shear force-displacement curves, but the effect of the normal force was only to increase the shear force monotonically, perhaps because the normal forces were not large enough to be close to the peak compressive strength.

3.4 Bending tests

The bending tests were carried out using a bending-auxiliary device, as shown in Figure 6. The bending-auxiliary device is similar to the shear-auxiliary device except that both the two horizontal inserts are fixed on the upper block with a vertical interval (forming a bending arm) so that the horizontal forces applied by the biaxial compression system can bend the cemented hemispheres. Two load cells were used to measure the horizontal forces which were then multiplied by the bending arm to obtain the applied bending moment. Two displacement gauges were used to measure the rotational displacements of the cemented hemispheres, which can be used to obtain the rotational angle. Similarly to the shear test, a vertical (normal) force smaller than R_c in Figure 3 was applied before bending and maintained constant throughout the following test.

Figure 9(a) presents the moment-rotational angle relationship of cemented hemispheres obtained with different normal forces (i.e., $F_n = 0.2, 1, 2, 3$ kN). The bending moment increases linearly up to a peak value until the rotational angle reaches nearly 1.5° , and then decreases with the rotational angle. Note that the rotational stiffness under different normal forces is almost the same, whereas the peak

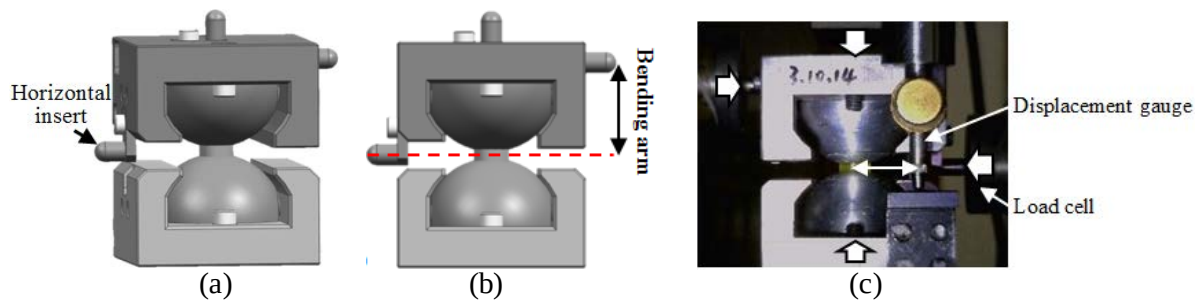


Figure 8. Bending test: (a) and (b) 3D schematic diagrams of the bending-auxiliary device; (c) physical test

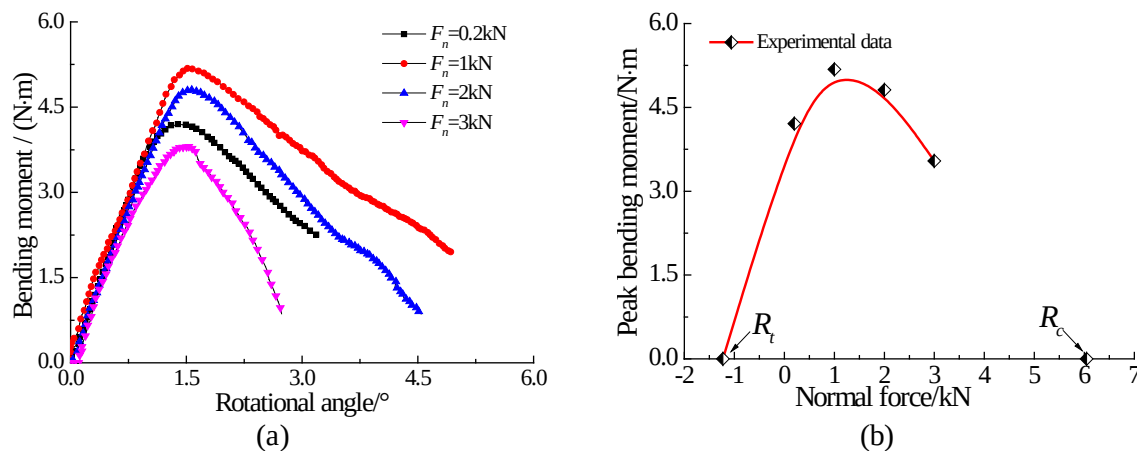


Figure 9. Mechanical behavior of cemented hemispheres in bending tests: (a) bending moment-rotational angle relationship; (b) variation of the peak bending moment versus the normal force

bending moments vary. Figure 9(b) shows that the peak bending moment increases up to a peak value until the normal force approaches 1.2 kN, and then decreases with the normal force.

3.5 Torsion tests

The torsion tests were carried out using a torsion-auxiliary device, as shown in Figure 10. The torsion-auxiliary device is similar to the shear-auxiliary device except that both the two horizontal inserts are fixed on the upper block with a horizontal interval (forming a torsion arm) so that the horizontal forces applied by the biaxial compression system can twist the epoxy adhesive. Two load cells were used to measure the horizontal forces which were then multiplied by the torsion arm to obtain the applied torque. Two displacement gauges were used to measure the horizontal displacements of the two horizontal rods, which were then used to obtain the torsional angle. Similar to the shear test, a vertical (normal) force smaller than R_c in Figure 3 was first applied and maintained constant throughout the torsion test. Figure 11(a) presents the torque-torsional angle relationship of the cemented hemispheres

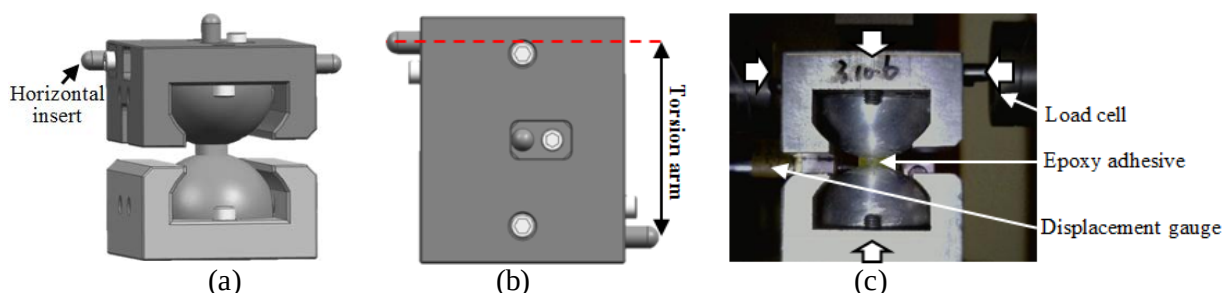


Figure 10. Torsion test: (a) and (b) 3D schematic diagrams of the torsion-auxiliary device; (c) physical test

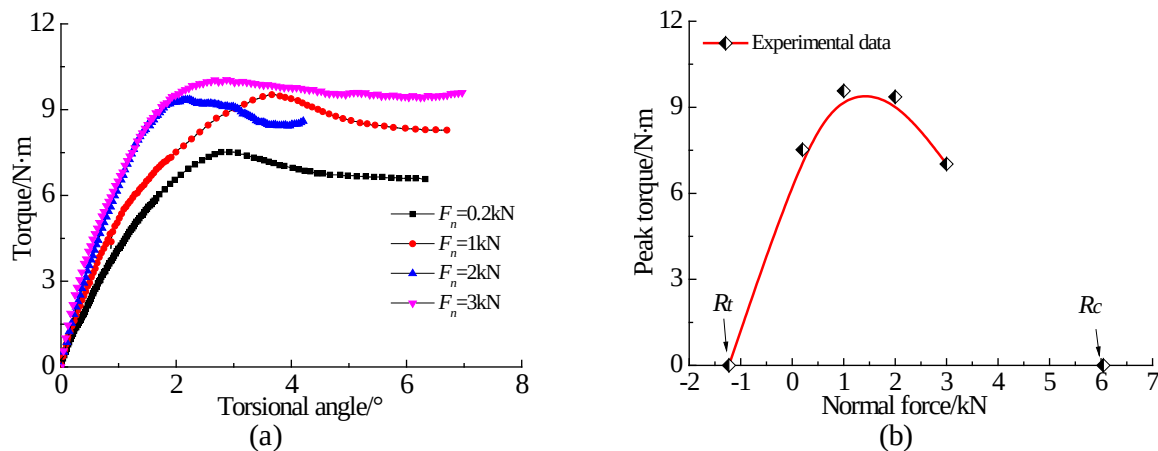


Figure 11. Mechanical behavior of cemented hemispheres in torsion tests: (a) torque-torsional angle relationship; (b) variation of the peak torque versus the normal force

under different normal forces (i.e., $F_n = 0.2, 1, 2, 3$ kN). Figure 11(a) shows that the torque increases up to a peak strength and then drops to a residual strength slowly. Figure 11(b) presents the relationship between the peak torque and the normal force. The peak torque increases firstly until the normal force reaches a critical value $F_{ncr} = 1.2$ kN, and then decrease with the increase of normal force.

4. Conclusion

An experimental study on the three-dimensional mechanical behavior of cemented granules, idealized as a pair of aluminum hemispheres glued by epoxy adhesive, was carried out in different loading modes (compression, tension, shear, bending and torsion tests). Several conclusions can be reached. (a) The preparation device is effective to prepare cemented hemispheres of high quality. The auxiliary devices in different loading modes are useful to transfer loads from a biaxial compression system to the cemented hemisphere pair in the desired way. (b) In the compression test, the compressive force increases with compression bi-linearly to the first peak strength, and after a slight decrease, continues increasing to the second peak value until the bond is broken. In the tension test, the tensile force increases linearly up to its peak with tension and then drops abruptly to zero. (c) The normal force has a significant influence on the peak strengths in shear, bending and torsion tests. That is, the peak shear force, bending moment and torque first increase with the normal force and then decrease after the normal force exceeds a critical value.

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References

- [1] Duncan J M, Wright S G 1980 The accuracy of equilibrium methods of slope stability analysis *Eng. Geol.* **16** 5-17
- [2] Xu X, Shang M, Deng Y H 2014 Analysis about the classification of Landslide Monitoring Method *Appl. Mech. Mater.* **638-640** 360-364
- [3] Milledge D G, Bellugi D, McKean J A, et al. 2014 A multidimensional stability model for predicting shallow landslide size and shape across landscapes *J. Geophys. Res. Earth Surf.* **119** 2481-2504
- [4] Yashima A, Moriguchi S, Uzuoka R, et al. 2013 Large Deformation Analysis for Coastal Geo-

- Disasters Using Continuum and Discrete Modeling *Springer Geol.* **62** 13-29
- [5] Fuchs M, Torizin J, Kühn F 2014 The effect of DEM resolution on the computation of the factor of safety using an infinite slope model *Geomorphology* **224** 16-26
- [6] Cundall P A, Strack O D L 1979 Discrete numerical-model for granular assemblies *Géotechnique* **29** 47-65
- [7] Utili S, Nova R 2008 DEM analysis of bonded granular geomaterials *Int. J. Numer. Anal. Methods Geomech.* **32** 1997-2031
- [8] Jiang M J, Murakami A 2012 Distinct element method analyses of idealized bonded-granulate cut slope *Granular Matter* **14** 393-410
- [9] Jiang M J, Yu H S, Leroueil S 2007 A simple and efficient approach to capturing bonding effect in naturally microstructured sands by discrete element method *Int. J. Numer. Methods Eng.* **69** 1158-1193
- [10] Jiang M J, Yu H S, Harris D 2006 Bond rolling resistance and its effect on yielding of bonded granulates by DEM analyses *Int. J. Numer. Anal. Methods Geomech.* **30** 723-761
- [11] Delenne J, El Yousoufi M S, Cherblanc F, et al. 2004 Mechanical behaviour and failure of cohesive granular materials *Int. J. Numer. Anal. Methods Geomech.* **28** 1577-1594
- [12] Kirsch R, Bröckel U, Brendel L, et al. 2011 Measuring tensile, shear and torsional strength of solid bridges between particles in the millimeter regime *Granular Matter* **13** 517-523
- [13] Jiang M J, Sun Y G, Xiao Y 2012 An experimental investigation on the mechanical behavior between cemented granules *Geotech. Test. J.* **35** 678-690
- [14] Jiang M J, Sun Y G, Li L Q, et al. 2012 Contact behavior of idealized granules bonded in two different interparticle distances: An experimental investigation *Mech. Mater.* **55** 1-15
- [15] Jiang M J, Yan H B, Zhu H H and Utili S 2011 Modeling Shear Behavior and Strain Localization in Cemented Sands by Two-Dimensional Distinct Element Method Analyses *Comput. Geotech.* **38** 14-29
- [16] Nardelli V, Coop M R 2015 An experimental investigation of the micromechanical behaviour of cemented sand particles *Proc. TC105 ISSMGE Int. Symp. Geomech. from Micro to Macro (IS-Cambridge September 2014)* **2** 1013-1017