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The Influence of Contact Friction on the Breakage Behavior of Brittle Granular Materials using DEM

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ABSTRACT

In this study, a numerical triaxial compression test was carried out to investigate the influence of contact friction on the breakage behavior of brittle granular materials using the 3D discrete element method. An commercial software named Particle Flow Code 3D (PFC3D) was applied to undertake these simulations. The cubic numerical model was 30mm wide, 30mm long, and 30mm high, and contained 562 crushable agglomerates. Each agglomerate was made of 57 uniform spheres bonding together by parallel bond and packing in the form of hexagonal close packing(HCP), then ten percent of spheres were randomly deleted to consider the effect of initial flaws. A new method based on Graph theory was developed to track the Particle Size Distribution (PSD) evolution during shearing. Four numerical models with different inter-particle friction coefficients μ ranging from 0.2 to 0.8 were tested and the particle breakage extent was quantified with the Hardin's breakage index and the ratio of broken parallel bond. The results showed that both Hardin's breakage index and the ratio of broken bond increased with an increase in the inter-particle contact friction coefficients. However, the frictional energy dissipation did not demonstrate the same trend. The mechanism of this discordance was discussed in this paper.
keywords: contact friction, particle breakage, granular materials, DEM.

1 INTRODUCTION

Particles of brittle granular materials are easy to break under compression and shearing. The breakage behavior of brittle granular materials is complicated, and has been investigated by many researchers . Previous studies show that particle breakage in brittle granular materials is affected by the relative density, stress level, loading path, as well as the basic attributes of the individual particles, such as particle strength, mineral composition and particle shape, particle size distribution (Laufer 2015). This

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means that the breakage behavior of brittle granular materials is determined by the multi-level interaction of these aspects (Dai, et al. 2015).

As one of the most important micro parameters of granular materials, the effect of inter-particle contact friction on mechanical behaviors has been studied by many researchers (Barreto and O'Sullivan 2012), (Huang, et al. 2014), and (Dai, Yang and Zhou 2015). However, the effect of friction on particle breakage has seldom studied. (Huang, et al. 2015) has investigated the breakage behavior of granular materials under dynamic compression, the influence of friction on particle breakage under static condition has not been reported by previous studies.

In this study, inter-particle contact friction is taken into account. The influence of contact friction on the breakage behavior of brittle granular materials is studied using DEM under conventional triaxial tests.

2 DEM SIMULATION OF PARTICLE CRUSHING

2.1 Modeling a crushable agglomerate

In order to investigate the breakage behavior of granular materials, the fracturing agglomerates method is used, which is first proposed by Robertson (Robertson and Bolton 2001) . In this method, crushable agglomerates are composed of 57 uniform balls with diameters 1/5 time of the agglomerates. These balls are bonded together using contact bond and packed in a form of hexagonal close packing(HCP). During the process of ball generation, a certain proportion of balls are removed to consider initial fracture of realistic granular particles. This approach has been employed to do further researches, such as, investigate the breakage behavior of granular materials under different stress paths (Cheng, et al. 2003), the plastic behavior of crushable granular materials (Cheng, et al. 2004) and creep behavior of crushable granular materials (Kwok and Bolton 2013). Some other researchers have modified this method, and studied particle breakage of granular materials under plane strain condition (Wang and Yan 2013), oedometer condition (Laufer 2015), the energy dissipation of crushable granular materials (Wang and Yan 2012), among others.

In this study, the agglomerates method is used with two modifications. First, agglomerates created in Robertson's method are identical with the same diameters. While in this study, agglomerates generate follow a designated particle size distribution. Second, the parallel bond model is used to replaced the contact bond model used in Robertson's method, because, according to (Wang and Yan 2013), the contact bond model fails to consider rotational resistance which will frequently lead to the absence of a clear, visible physical fracture of an agglomerate formed by the contact bond model. The proportion of removed balls is set 10%. The material properties used in this study are listed in Table 1.

Table 1 Parameters of crushable agglomerates

Density of ball (kg/m3)	2600
Normal and shear stiffness of ball (N/m)	4.0e6
Friction coefficient μ of ball	0.5
Normal and shear parallel bond strength (N/m2)	1.0e8
Normal and shear parallel bond stiffness (N/m3)	4.0e12
Ratio of parallel bond radius to ball radius	0.5
Percentage of spheres removed at random (%)	10

2.2 Particle crushing simulation under triaxial compression tests

The numerical specimen is initially set as 30mm wide, 30mm long, and 30mm high, surrounding by six rigid, frictionless walls. A set of "exo-spheres" following a designed particle size distribution shown in fig.1 were first created with an initial void ratio of 0.429. Then all these "exo-spheres" were replaced by agglomerates. The finial specimen is shown in fig.2, and its PSD is presented in Fig.1 as PSD of Agglomerates. After the all "exo-spheres" are transferred into agglomerates, the specimen was subjected to an isotropic compression. To achieve a relatively dense specimen, a low inter contact friction 0.01 was adopted in this process. A servo system was applied to make sure a complete equilibrium condition is achieved, when the confining stress of the specimen reach a specific value. The confining stresses used in this study were 400, 600, 800, 1000kPa. The subsequent step was conventional triaxial compression test. During this procedure, the confining stress on the lateral four walls are maintained, and the top and bottom walls move towards each other at a constant velocity of 0.05m/s. Four numerical models with different inter-particle friction coefficients μ ranging from 0.2 to 0.8 were tested.

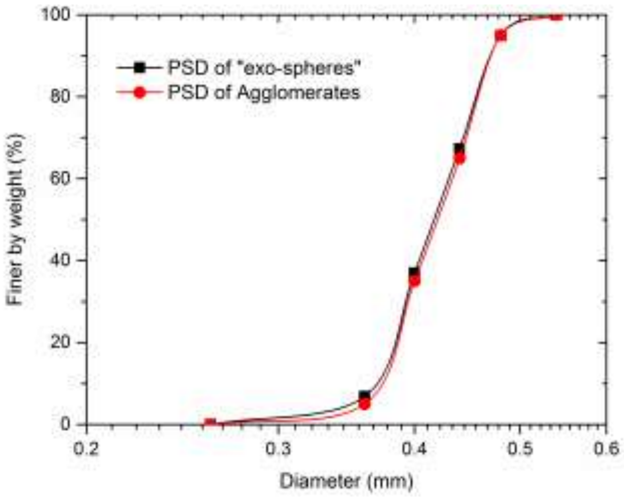


Fig.1 Particle size distribution

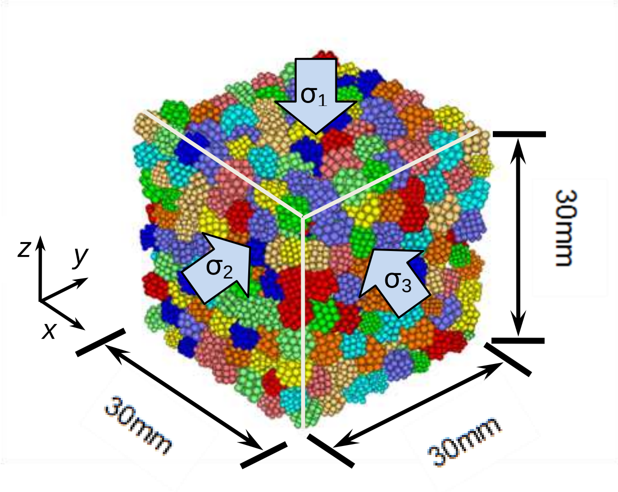


Fig. 2 Configuration of cube model

2.3 Particle breakage tracking and Particle breakage index

There are two particle breakage tracking method used in this study. The first one is tracking parallel-bond breakage number, the other one is tracking the PSD (particle size distribution) evolution. In the first method, a parallel bond breakage monitoring system is developed, and the bond broken number is recorded during the shear process. The PSD tracking method is based on graph theory. In this method, particles are deemed as vertexes, and parallel bonds are deemed as edges, and a group of particles bonded together using parallel bond are deemed as a contacted graph. Then an algorithm is used to obtain the number of contacted graphs. After that, a technique is applied to determine the diameters and mass of each part to get the particle size distribution.

To quantify particle breakage during shearing, two particle breakage indexes are introduced based on the particle breakage tracking method used in this study. Bond broken ratio based on parallel-bond broken number, is defined as follow:

$$B_b = \frac{N_b}{N_p} \tag{1}$$

where B_b is the bond breakage index; N_b is the amount of broken parallel bond after shearing; N_p is the total number of parallel bond before shearing.

Hardin relative breakage index B_r (Hardin 1985) is used here to quantify the amount of particle breakage during shearing. The definition of Hardin relative breakage index B_r is given:

$$B_r = \frac{\int_0^1 (d - d_0)dF}{\int_0^1 (d_u - d_0)dF} \tag{2}$$

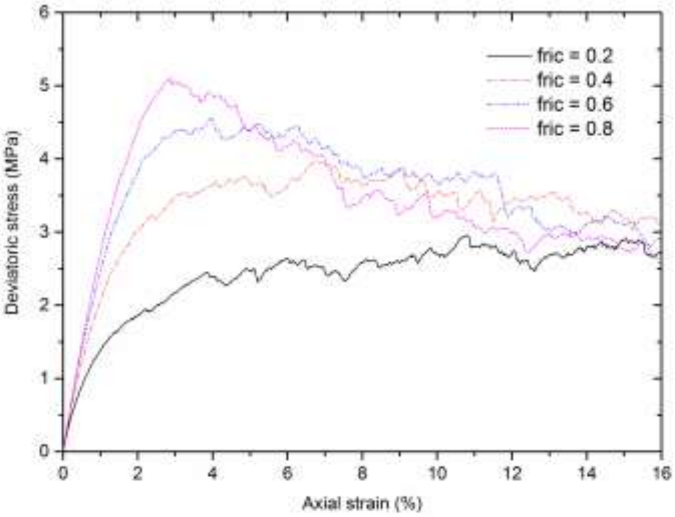
where F is the particle size distribution function; d, d_0 and d_u are the particle size corresponding to the present, initial and final particle size distribution, respectively. Particularly, d_u is taken as 74 *μm* in Hardin's original definition.

3 SIMULATION RESULTS

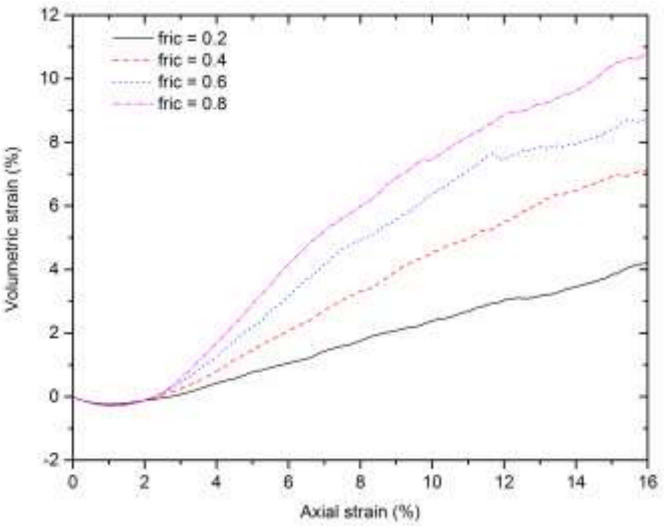
3.1 Stress-Strain-Volume behavior

The stress-strain-volume curves for different friction coefficients μ (0.2, 0.4, 0.6 and 0.8) are shown in Fig.3. Fig.3 illustrates that an increase in friction coefficient μ leads to an increase in a deviatoric stress (as shown in Fig.3(a)) and an increase in a stress ratio (as shown in Fig.3(c)) at the same axial strain. The stress-strain behaviors of the granular materials exhibit a strain hardening characteristic with low friction coefficient μ (0.2, 0.4), and a strain softening characteristic with high friction coefficient μ (0.6, 0.8).

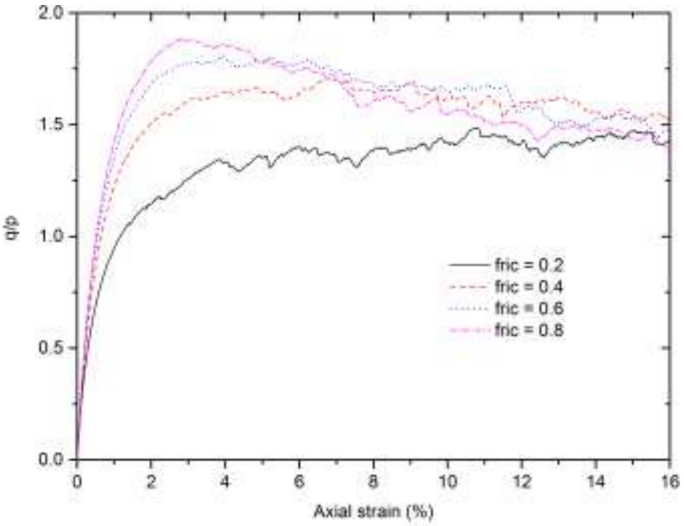
Fig. 3 (b) shows the effect of friction coefficient μ on the volumetric-strain behavior of granular materials. It is clear in Fig.3(b) that in the initial stage all specimens are compressed, then after axial strain reaching 2.0%, all specimens turn to swell. An increase in friction coefficient μ leads to an increase swelling at the same axial strain.



(a) Deviatoric stress vs. Axial strain



(b) Volumetric strain vs. Axial strain



(c) stress ratio vs. axial strain

Fig.3 Stress-Strain-Volumetric behavior of granular materials with different friction coefficients

3.2 Particle Breakage

Friction coefficient μ is one of the most important parameters of granular materials in Discrete element simulation. Various researchers have studied the relationship between friction coefficient μ and the mechanical behaviors of granular materials. However, the influence of μ on particle breakage has not been considered by any researchers. In this study, four specimens containing crushable agglomerates with different μ are tested under conventional triaxial condition. The relationship between friction and particle breakage is studied.

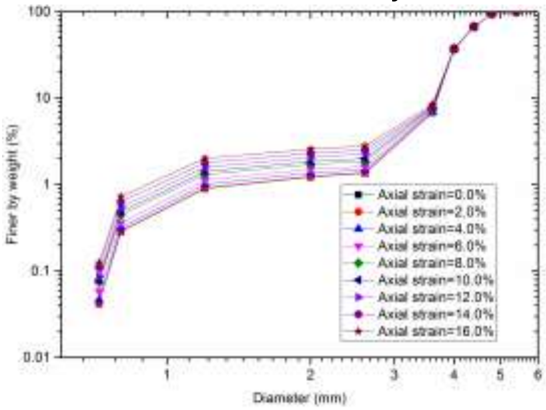
Fig.4 shows the evolutions of particle size distributions of four specimens with friction coefficient μ ranging from 0.2 to 0.8. In order to track the particle size distribution, an algorithm is developed. The diameter of each fragment calculated in this study is defined as follow:

$$D = L_{max} + 2 \cdot r \tag{3}$$

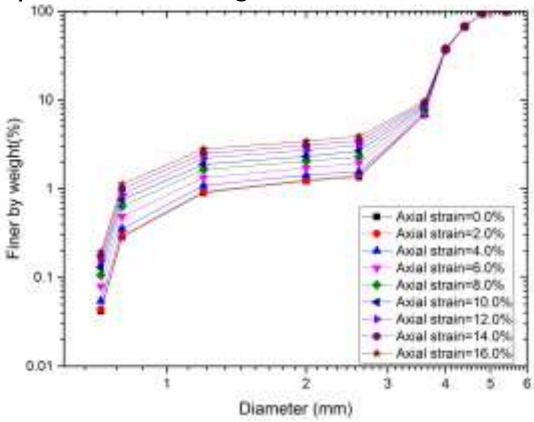
where L_{max} is the largest distance between two sphere centers in one fragments; r is the radius of a sphere in the fragments.

Fig.4 illustrates that a higher μ leads to a higher particle crushing, and the same conclusion can be seen in Fig. 5 and Fig.6. It is also seen in Fig.4 that the largest increase in the particle size distributions lies in the range of $D \approx 0.6 \sim 3.6mm$. This behavior indicates that particle crushing mostly accrues in finer particles.

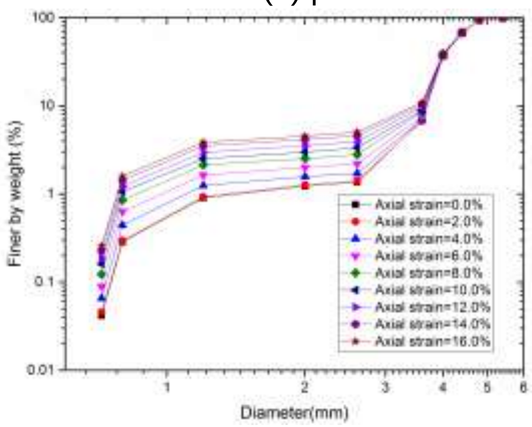
In this present study, two particle breakage indexes were used to quantify particle breakage. The first one is bond broken ratio, the other one is relative breakage index B_r. The evolutions of the bond broken ratio and relative breakage index B_r are shown in Fig. 5 and Fig. 6. It is clear that both bond broken ratio B_b and relative breakage index B_r increase when friction increases at the same axial strain. And it is also shown that B_b is always a little higher than B_r for a given friction coefficient at the same axial strain , that is because bond broken may not lead to particle crushing.



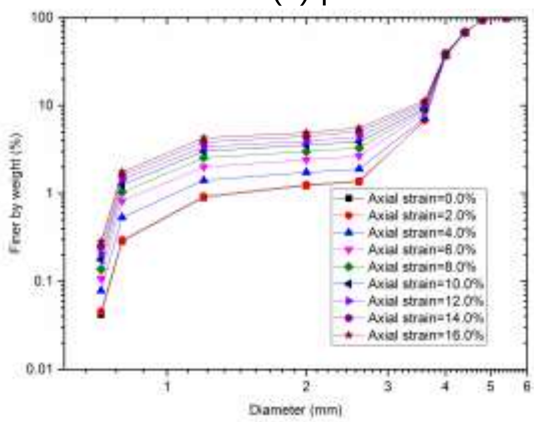
(a) μ =0.2



(b) μ =0.4



(c) μ =0.6



(d) μ =0.8

Fig.4 Evolution of PSD

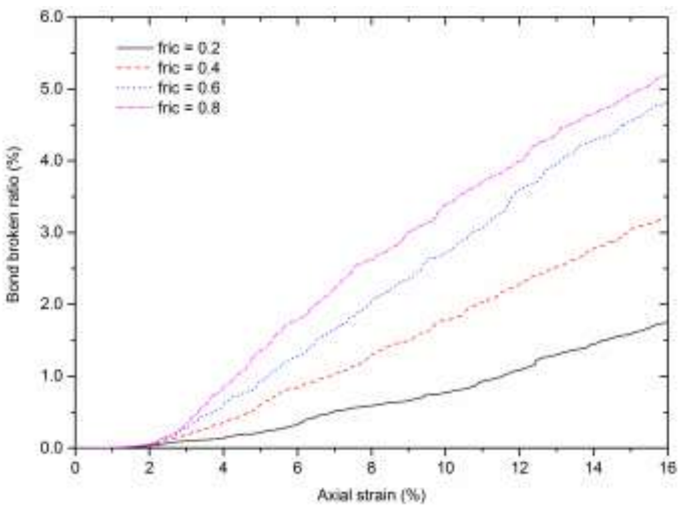


Fig. 5 The evolutions of bond broken ratio with different friction coefficients μ

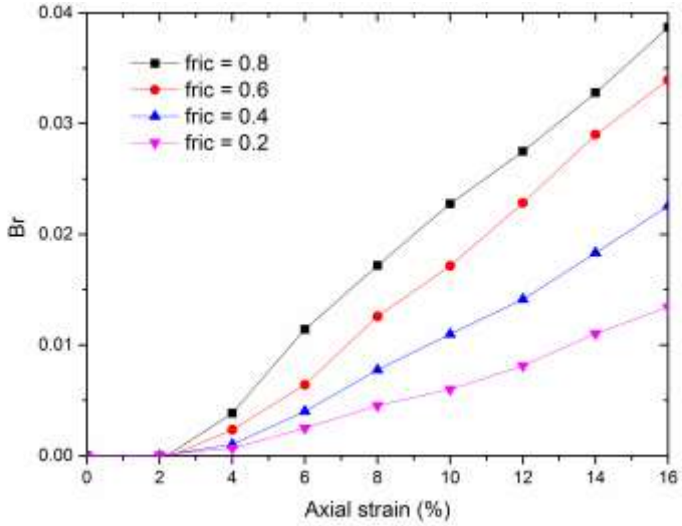


Fig. 6 The evolutions of B_r with different friction coefficients μ

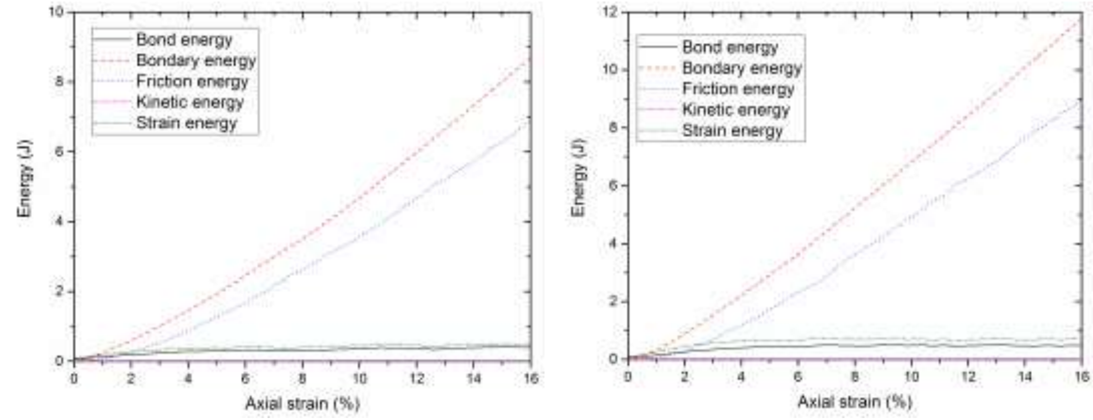
3.3 Energy dissipation

It is very convenient to track energy input/dissipation behavior in PFC3D. PFC3D provides the HISOTRY energy command to monitor energy terms. These energy terms include boundary work E_w, body work E_b done by the gravity force, elastic strain energy E_c stored at particle contacts upon particle deformation, bond energy E_{pb} stored in parallel bonds, inter-particle friction dissipation E_f , kinetic energy E_k . According to previous study, at any stage of shearing, the law of energy conservation gives

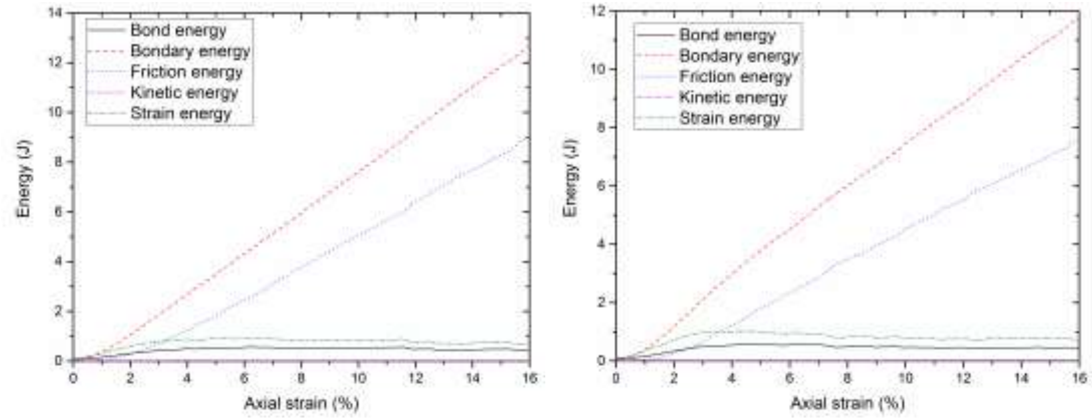
$$E_w + E_b = E_c + E_{pb} + E_f + E_k + E_d \tag{4}$$

In this equation, the terms on the left side are input energy, while the terms on the right side are storage/dissipation energy ones. E_d is the damping energy dissipation which is not given in PFC3D, but can be easily gotten by subtracting given dissipation energy terms from input energy ones. In this study, body work body work E_b is equal to zero, since the gravity is set to zero.

Fig. 7 shows the evolutions of energy terms for different value of friction coefficient μ. It is seen that frictional energy dissipation increases with axial strain, while other energy terms on the right side of Eq.(4) remain constant values after axial strain reaching 3%. And after axial strain reaching 3%, frictional energy dissipation account for the highest proportion of energy dissipation. Note that the ratio of frictional energy dissipation to input energy decreases with an increase in friction.

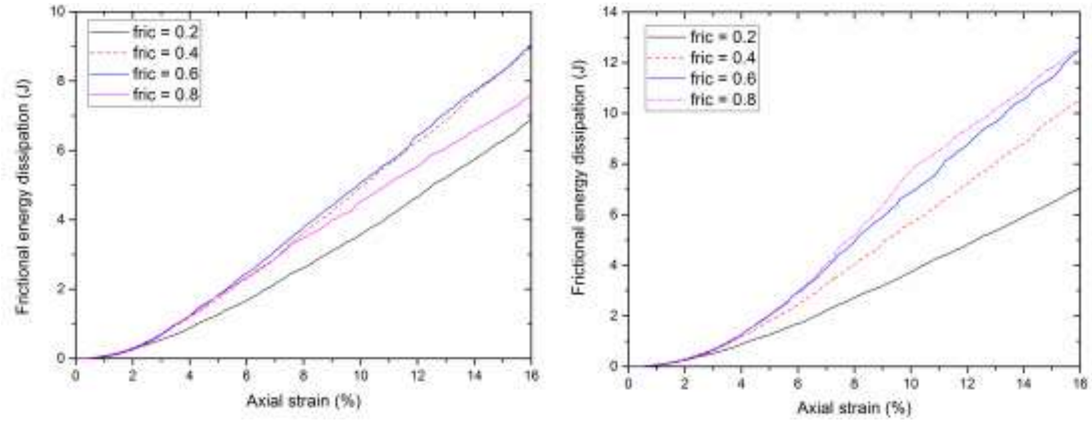


(a) μ = 0.2 (b) μ = 0.4



(c) μ = 0.6 (d) μ = 0.8

Fig. 7 Evolution of energy during shearing process



(a) Crushable specimens (b) Uncrushable specimens

Fig. 8 Comparing evolution of frictional energy dissipation with crushable and uncrushable specimens for different friction coefficients

The evolutions of friction energy dissipations for different friction are given in Fig. 8

(a), and are compared with results of uncrushable specimens presented in Fig.8 (b). According to (Huang, Xu and Hu 2015), the frictional dissipation in frictionless and infinite-friction granular materials are both zero, so there must be a critical friction coefficient where the frictional dissipation reaches a maximum. Comparing Fig.8(a) and Fig.8(b), it is found that for crushable specimens the critical friction coefficient lies in $\mu \approx 0.4 \sim 0.6$, while for uncrushable ones the critical friction coefficient lies in $\mu \approx 0.6 \sim 0.8$. This means an increase in friction coefficient μ leads to an increase in particle crushing, while an increase in particle crushing leads to a decrease in a critical friction coefficient where the maximum friction dissipation reaches.

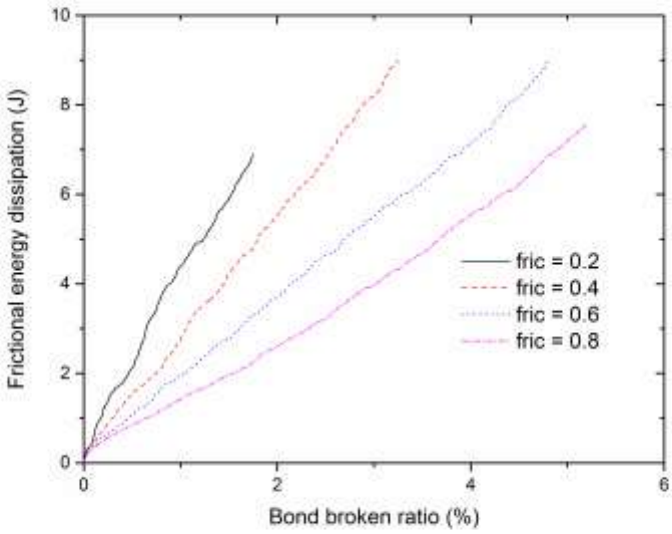


Fig. 9 Frictional energy dissipation against bond broken ratio

Fig. 9 shows friction energy dissipation against the particle breakage behaviors in different granular materials. Corresponding the same amount of bond broken ratio, the friction dissipation decreases with friction coefficient μ.

4 CONCLUTIONS

In this present paper, the breakage behavior of brittle granular materials is discussed by considering the effect of friction. Using DEM simulations of conventional trixial compression tests the effects friction on stress-strain-volumetric behaviors, particle breakage and the interaction of friction and particle breakage on energy dissipations are presented. It is found that as friction coefficient increases there is corresponding increase in peak deviatoric stress, q/p, and the amount of dilation, which agrees with previous researches. Then the effect of friction on particle breakage is investigated. The changes of particle size distributions before and after shearing of different frictions show that particle breakage occurs mainly in finer portion, and an increase in friction leads to an increase in the change of PSD, which means that particle breakage increases with friction. Two particle breakage indices, $\mathrm{B_b}$ and B_r, are used to quantify particle breakage extents. It is clear that both bond broken ratio $\mathrm{B_b}$ and relative breakage index B_r increase when friction increases at the same axial strain, which confirms the previous conclusion. Energy analyses show that an increase in friction coefficient μ leads to an increase in particle crushing, while an increase in particle crushing leads to a decrease in a critical friction coefficient where the maximum friction dissipation reaches. It is also found that the friction dissipation decreases with friction coefficient μ, corresponding the same amount of bond broken ratio.

References

[1] Barreto, D., and O'Sullivan, C. (2012), "The influence of inter-particle friction and the intermediate stress ratio on soil response under generalised stress conditions." *Granul Matter*, 14(4), 505-521.
[2] Cheng, Y. P., Bolton, M. D., and Nakata, Y. (2004), "Crushing and plastic deformation of soils simulated using DEM." *Geotechnique*, 54(2), 131-141.
[3] Cheng, Y. P., Nakata, Y., and Bolton, M. D. (2003). "Discrete element simulation of crushable soil." *Geotechnique*, 53(7), 633-641.
[4] Dai, B. B., Yang, J., and Zhou, C. Y. (2015), "Observed Effects of Interparticle Friction and Particle Size on Shear Behavior of Granular Materials." *International Journal of Geomechanics*, 04015011.
[5] Hardin, B. O. (1985), "Crushing of soil particles." *Journal of Geotechnical Engineering*, 111(10), 1177-1192.
[6] Huang, J., Xu, S., and Hu, S. (2015), "The role of contact friction in the dynamic breakage behavior of granular materials." *Granul Matter*, 17(1), 111-120.
[7] Huang, X., Hanley, K. J., O'Sullivan, C., and Kwok, C. Y. (2014), "Exploring the influence of interparticle friction on critical state behaviour using DEM." *Int J Numer Anal Met*, 38(12), 1276-1297.
[8] Kwok, C. Y., and Bolton, M. D. (2013), "DEM simulations of soil creep due to particle crushing." *Geotechnique*, 63(16), 1365-1376.
[9] Laufer, I. (2015), "Grain crushing and high-pressure oedometer tests simulated with the discrete element method." *Granul Matter*, 17(3), 389-412.
[10] Robertson, D., and Bolton, M. D. (2001), "DEM simulations of crushable grains and soils." *Powders And Grains 2001*, Sendai, Japan.
[11] Wang, J., and Yan, H. (2013), "On the role of particle breakage in the shear failure behavior of granular soils by DEM." *Int J Numer Anal Met*, 37(8), 832-854.
[12] Wang, J., and Yan, H. (2012), "DEM analysis of energy dissipation in crushable soils." *Soils and Foundations*, 52(4), 644-657.
[13] Wang, J. F., and Yan, H. B. (2013), "On the role of particle breakage in the shear failure behavior of granular soils by DEM." *Int J Numer Anal Met*, 37(8), 832-854.