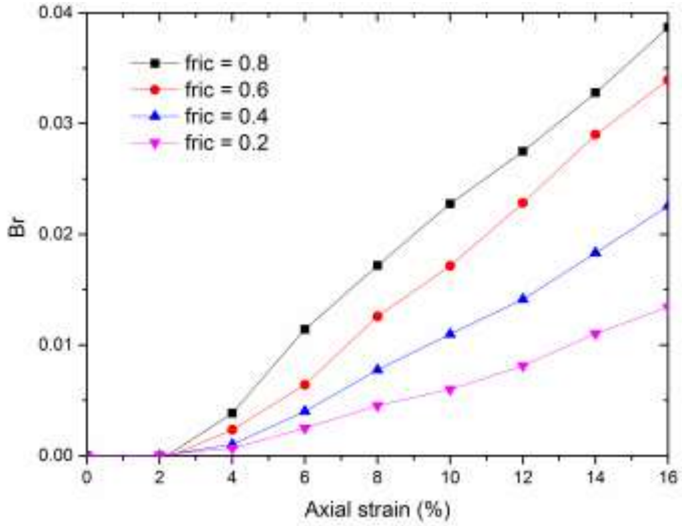


Fig. 6 The evolutions of B_r with different friction coefficients μ

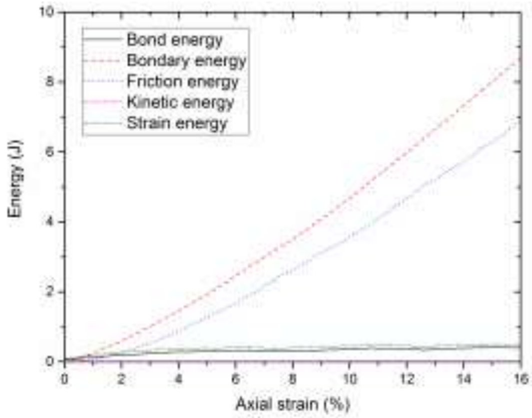
3.3 Energy dissipation

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

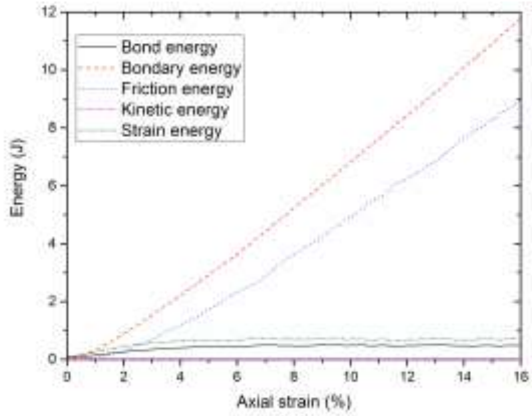
$$E_w + E_b = E_c + E_{pb} + E_f + E_k + E_d \quad (4)$$

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.

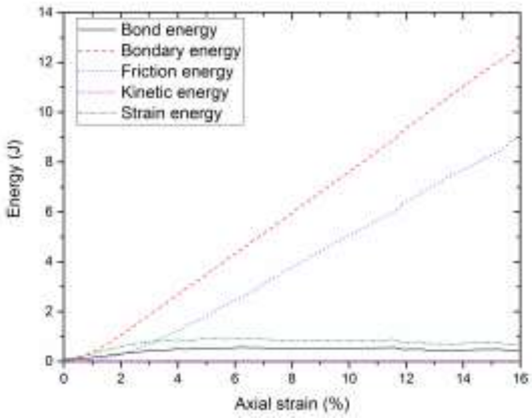
Fig. 7 shows the evolutions of energy terms for different value of friction coefficient μ. It is seen that frictional energy dissipation increases with axial strain, while other energy terms on the right side of Eq.(4) remain constant values after axial strain reaching 3%. And after axial strain reaching 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.



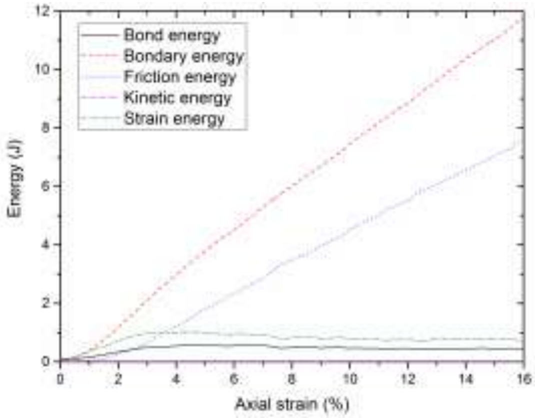
(a) μ = 0.2



(b) μ = 0.4

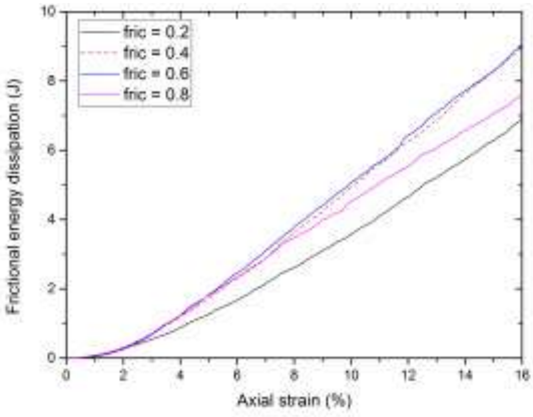


(c) μ = 0.6

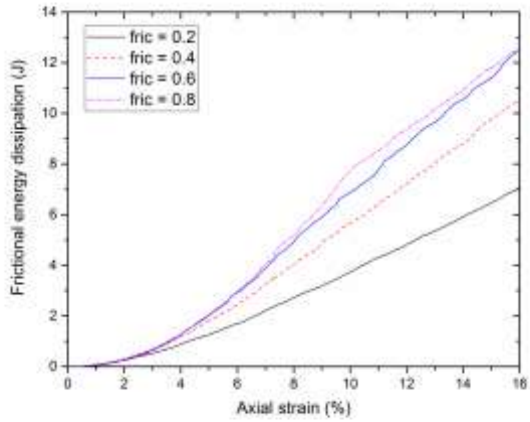


(d) μ = 0.8

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.

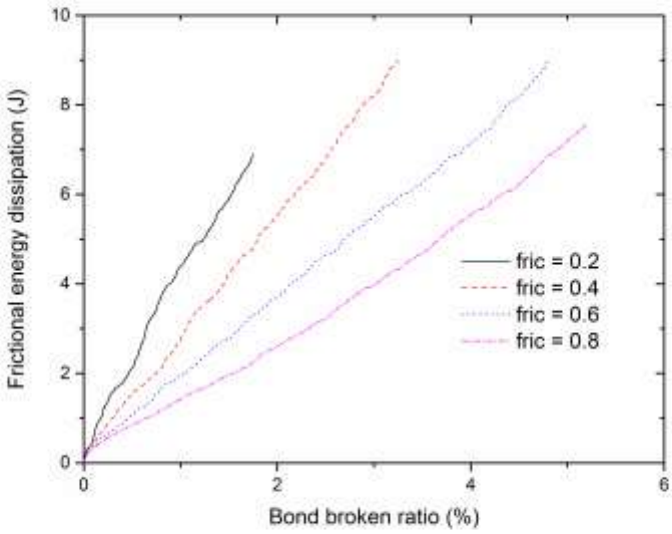


Fig. 9 Frictional energy dissipation against bond broken ratio

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.

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