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Quasi-static diametrical compression of characteristic elastic–plastic granules: Energetic aspects at contact

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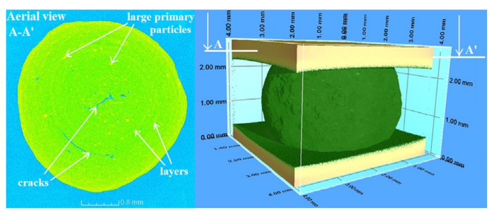
HIGHLIGHTS

- Energetic coefficient of restitution is independent of the granule size.
- Energetic coefficient of restitution decreases with increasing moisture contents.
- Larger wet granules exhibit a higher breakage probability than smaller dry ones.
- Granules harden due to accumulation of plastic dislocations when repeatedly loaded.
- Moisture lubricates inter-particulate contacts and significantly softens granules.

GRAPHICAL ABSTRACT



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ABSTRACT

Comminution processes have traditionally been considered as empirical endeavors, with great difficulties in analyzing, predicting and controlling the observed behavior. Process industries have faced serious problems, ranging from poor product quality control up to managing product quantity losses due to unexpected attrition and breakage events. After a decade of ardent research, there has been a notable advancement in our understanding of granular behavior under mechanical stresses. However, far less is known about the energetic aspects occurring at such conditions.

In this article, we present critical information from an energetic perspective concerning the deformation and breakage behavior of characteristic elastic–plastic granules under quasi-static compressive forces, studied using single granule diametrical compression tests at a constant strain controlled loading velocity. The force–displacement behavior has been approximated using the Hertz model (Hertz, 1882) for elastic loading, the Tomas model (Tomas, 2007a) for elastic–plastic loading and the Stronge–Antonyuk correlations (Stronge, 2000; Antonyuk, 2006) incorporated Hertz model (Hertz, 1882) for elastic unloading with additional displacements due to apparent viscous effects. The rate independent specific energy characteristics have been studied and a corresponding energetic coefficient of restitution has been derived. A comparison of the energetic characteristics at primary breakage of fresh and pre-loaded granules has been presented using breakage probability functions. The phenomenon of strain hardening during localized repetitive compressive loadings has also been analyzed. Furthermore, the influences of granule size, moisture content and stressing intensity have been considered in each of the investigated entities.

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1. Introduction

Different kinds of useful as well as hazardous granular materials are encountered in daily life such as chemicals, detergents,

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minerals, pigments, pharmaceuticals, building materials, food materials, power related materials, accessories, bio materials, waste materials, fertilizers, pesticides, plastics, electronics, mechanical and automotive fittings. In analogy with their mechanical nature, several physical deteriorative processes may advance, resulting in significant quality degradation, due to prolonged exposure to stressing forces during their processing, handling, transportation and storage. In most cases, the stressing forces are dominantly compressive in nature, especially during transportation and storage operations, where underlying granules are subjected to sustained compressive forces resulting from the mass of granules accumulating above. The magnitude of deformation and the intensity of breakage is defined by the nature, characteristics, intensities, number and frequency of the stressing forces. Therefore, granulation techniques should be optimized to produce "designer" products, that withstand the deteriorative effects of incident compressive forces and undergo a negligible deformation, while concurrently retaining their optimum desired qualities to ensure best applications. In this analogy, it is necessary to investigate the mechanical behavior of granular materials under primal and repetitive compressive loadings of different magnitudes, velocities and frequencies at unique and random locations.

The past two decades have seen a remarkable progress in the study of the compression behavior of different kinds of granules and agglomerates. Johansson et al. (1998) suggested that the degree of deformation of microcrystalline cellulose pellets depend upon the re-arrangement of primary particles and de-localization of structural inhomogeneities. Similar conclusions and further evaluations regarding cracking and fragmentation mechanisms were furnished from the investigations of Khanal et al. (2005), on the breakage behavior of coarse agglomerates (concrete spheres) by numerical simulations using a two dimensional discrete element method. Subero and Ghadiri (2001) observed the effects of breakage of solid bridges between primary particles on the crack propagation velocity during overall breakage of glass ballotini agglomerates. Procopio et al. (2003) presented excellent results illustrating the effect of contact flattening on the breakage behavior of elastic and elastic–plastic granules. The energetic aspects occurring during compression of elastic–plastic granules under primal loading until primary breakage have been adequately studied by Antonyuk et al. (2005) and Müller and Tomas (2012). However, far less knowledge of the energetic aspects have been established with respect to repetitive compressive loadings, at unique and random locations. In this article, we present the micromechanical properties and the energetic aspects during repetitive compressive loadings of model elastic–plastic granules.

It is important to consider the effects of moisture as granules are often processed under moist or wet conditions depending upon their application. The works of Iveson et al. (2001, 2002), Iveson and Page (2004, 2005) and Smith (2008) give a comprehensive picture of the influence of moisture content on the deformation and breakage behavior of granules during granulation. From their pioneering works, the transition from the brittle to the plastic deformation regime of moisture laden granules is well understood. Similarly, Müller et al. (2011a) furnished an in-depth understanding of the influence of moisture on the deformation and breakage behavior of dominant elastic, elastic–plastic and dominant plastic granules subjected to compressive forces during post-granulation operations. The undesirable effects of moisture on advancing the statistically distributed breakage probability, is well understood from their work. In this article, we present analogical evaluations on the effects of moisture from an energetic perspective.

Due to the contrasting energy contributions by elastic wave propagations, inelastic deformations, heat dissipations, crack resistances, etc., observed in granules under quasi-static compressive forces and dynamic impact velocities, the relationship between them appears to be highly complex (Tavares and King, 1998). However, Chau et al. (2000) suggested that the dynamic impact breakage energy is equivalent to one and a half times the static or quasi-static compressive breakage energy for isotropic brittle spheres. Later, Han et al. (2006) expressed the relationship for a uniform sized particle population using a power function, which includes certain constants based on material and process parameters. Rozenblat et al. (2013) expressed a simple empirical equivalence function to calculate the equivalent dynamic impact velocity which would cause the same breakage probability as the incident quasi-static compressive force, independent of the size. In this article, an attempt to compare the results of primal and repetitive compressive loadings has been made using the specific compressive breakage energy and its energetically equivalent impact breakage velocity distributions. Further concepts and evaluations are also presented.

2. Compression mechanics

2.1. Non-linear non-adhesive elastic loading

Hertz (1882) expressed the contact pressure during a perfectly elastic non-adhesive collision between two homogeneous isotropic spherical solids by means of an elliptical distribution. In analogy with the Hertzian approach, the non-linear non-adhesive elastic force–displacement behavior of a spherical granule during quasi-static diametrical loading between two flat and stiff contacts can be expressed as

$$F_{el} = \frac{1}{6}E^{*}\sqrt{ds^{3}} \tag{1}$$

where F_{el} is the elastic contact force, s the displacement, d the diameter of the granule and E^{*} the effective Young's modulus, which can be related to the Young's modulus E and the Poisson's ratio ν of the granule according to the following equation (Johnson, 1985; Tomas, 2007b):

$$E^{*} = \frac{2}{(1-\nu^{2})}E \tag{2}$$

The elastic contact stiffness k_{el} results from the first derivative of the contact force with respect to the displacement as

$$k_{el} = \frac{d}{ds}F_{el} = \frac{1}{4}E^{*}\sqrt{ds} \tag{3}$$

The elastic strain energy absorption W_{el} results from the integral of the contact force over the displacement as

$$W_{el} = \int_{0}^{s\,\le\,s_y} F_{el}\,ds = \frac{1}{15}E^{*}\sqrt{ds^{5}} \tag{4}$$

where s_y is the displacement corresponding to the contact force F_y at yield point, i.e. at origin of incipient plastic yielding of the contact zone.

The stiffness–force–strain energy relationship can be expressed as

$$\frac{3}{2}F_{el}\frac{1}{s} = \frac{d}{ds}F_{el} = \frac{d^{2}}{ds^{2}}\frac{2}{5}F_{el}s \tag{5}$$

2.2. Non-linear non-adhesive elastic–plastic loading

The approach of Schubert et al. (1976) to model the elastic–plastic contact behavior, was the earliest known approach from a particle technology perspective. The authors expressed the contact pressure increase of a spherical body compressed against a rigid plate, as a function of the contact radius. Li et al. (2002) presented

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