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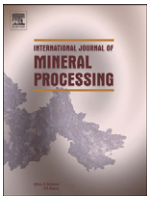

# Energy dissipation in particle bed comminution

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ABSTRACT

In particle bed comminution energy is dissipated by several microprocesses which accompany the flow of particles, their compaction, and breakage. It is unknown how much energy is associated with each microprocess and what the ratios are between the energies dissipated by the different microprocesses. Based on an experimental study, a model has been developed to calculate a critical compaction velocity and the energy dissipated by flow losses. The critical compaction velocity describes the probability of the deaeration of a particle bed. Since the flow losses consume less than 0.1% of the total energy input, this microprocess can be considered negligible compared to others.

## 1. Introduction

The stressing of particle beds aims at forming a compact body or breaking the constituent parts into finer pieces. Both results are achieved by an initial flow of individual particles followed by their deformation and breakage. On this basis the total energy input (energy absorption) has been divided amongst several microprocesses (Schubert, 1967):

- energy loss due to friction between the particles as well as between the particles and the confinements of the particle bed (friction losses),
- energy absorption till breakage (breakage energy),
- energy loss due to irreversible structural changes of particles (plastic deformation work),
- energy loss due to friction occurring while displacing the fluid in the pores (flow losses),
- energy loss caused by the wear of the confinements of the particle bed, and
- energy loss due to thermoplastic effects, sound wave propagation and oscillation of elastically deformed fragments.

Unfortunately, it is unknown how much energy is associated with each microprocess. Even the ratio between the energies, which are consumed by the individual microprocesses, is often estimated without any real knowledge. The breakage energy is assumed to make up only a small part of the energy absorption (1.5…12% (Schubert, 1967)). The plastic deformation work is, like the breakage energy, a very material dependent process reaching the same order of magnitude as the breakage energy for limestone (Heegn, 1986). The plastic deformation work in the case of quartz is important only at high stress intensities due to the higher strength of the material and its lower tendency to agglomerate. Overall the friction losses are estimated to be the most energy intensive microprocess (Müller, 1989).

An experimental study was used to derive a model for calculating flow losses and evaluating their relevance in particle bed comminution.

## 2. Material and methods

The flow through a packed particle bed is influenced mainly by the external dimensions of the bed and its internal porosity, the fluid inside the pores, and the fineness of particles. Therefore the porosity and the fineness had to be investigated very carefully since both parameters change during stressing. A range of particle sizes between 1 and 1000 μm was used to vary the granulometry of the feed materials (limestone, quartz, silicon carbide, and glass beads). All together the feeds were manufactured mainly by grinding and size classification as broad fractions ($x_{90}/x_{10} \approx 40$), ten narrow fractions ($x_{90}/x_{10} \approx 3$), and 23 bimodal mixtures ($x_{90}/x_{10} = 10…1000$). An example of these particle size distributions is given in Fig. 1. It is obvious that a bimodal mixture of two narrow size fractions does not produce the particle size distribution of a “natural” grinding product, but is considered to give an acceptable approximation of it.

Prior to each experiment the materials were dried for more than 10 h at 120 °C to assure an ignorable humidity. Confined particle beds were compressed in a hydraulic press (DP 1600/1, Hegewald & Peschke) at low stress velocity ($v_s = 0.05$ cm/s) and in an energy-controlled spindle press (Müller, 1989) at high stress velocities (10 cm/s). The

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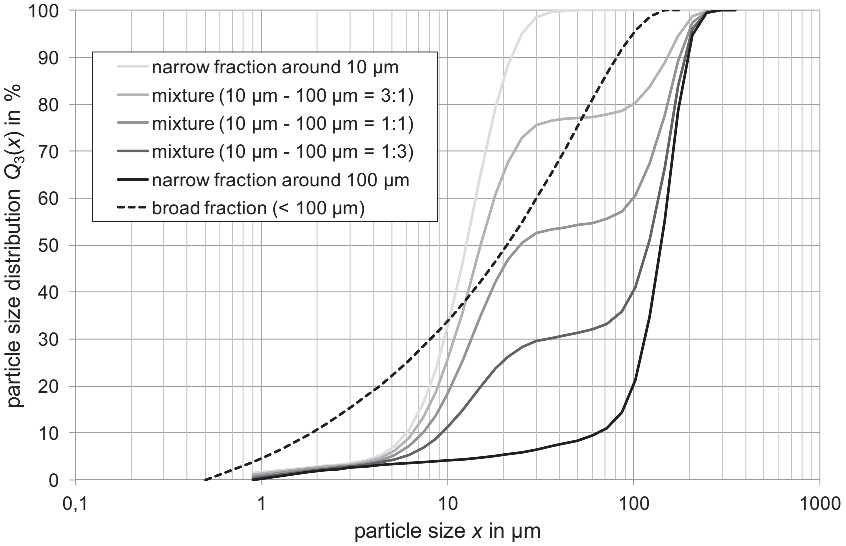

**Fig. 1.** Particle size distributions of the feed (limestone): narrow fractions (10 µm, 100 µm), mixtures of narrow fractions (mass ratio 1:3, 1:1, 3:1), a broad fraction < 100 µm.

dimensions of the confined particle beds resulted from the requirements of an ideal particle bed (Mütze et al., 2011):

- height 10 mm
- diameter 30…70 mm

The annular gap between the piston and the die was around 200 µm in order to release excess air which was pressed out of the particle bed by the compaction. Each test was repeated up to five times; the arithmetic mean was used for further calculations. The coefficient of variation was mostly below 2% or is noted otherwise.

The particle size distributions of the products were measured by sieving and laser diffraction after sufficient dispersion. The size distributions were used to describe the grinding kinetics and changes in fineness. This focused on the volume-specific surface area $S_V$ which is one of the main influencing variables in fluid flow through packed beds.

The energy absorption $E_m$ was calculated as the area enclosed by the stress and the relief curves and divided with the mass of the stressed particles. The stress and the relief curves were also used to describe the elastic–plastic compaction behaviour dependent on material and process conditions (Mütze, 2012, 2014).

## 3. Modelling and results

Initially the model development focused on an appropriate description of the changes in the porosity of the particle bed as a result of compaction. Furthermore an evaluation was necessary to which extend the fluid is trapped inside the pore volume. Finally the energy consumption due to flow losses was calculated.

### 3.1. Compaction behaviour

As known from literature, the important parameters in uniaxial compaction are the pressure, the material type, the particle size, the particle size distribution, and the stress velocity (Cooper and Eaton, 1962; Heckel, 1961; Kawakita and Lüdde, 1971; Mütze, 2012, 2014; Walker, 1923). Changes in the porosity are closely connected with the deformation of the particle bed. The plastic deformation of the particle bed can be described by the normalized compression $\Theta_{\text{plast}}$ (Eq. (1)). This compression correlates the actual change of the bulk density $\rho_{\text{b,plast}}$ due to the compaction pressure $p$ with a maximum possible change indicated by the solid density $\rho_{\text{s}}$ (Mütze, 2012, 2014):

$$\Theta_{\text{plast}}(p) = \frac{\rho_{\text{b,plast}}(p) - \rho_{\text{b,plast,0}}}{\rho_{\text{s}} - \rho_{\text{b,plast,0}}}. \tag{1}$$

The correlation between plastic deformation and pressure on the particle bed is often approximated by an equation with two parameters (Heckel, 1961; Kawakita and Lüdde, 1971; Walker, 1923). The influences of the mean particle size, the particle size distribution, and the stress velocity on the compaction behaviour have been studied recently by using Eq. (2) (Mütze, 2012, 2014):

$$\Theta_{\text{plast}}(p) = \Theta^* \ln\left(1 + \frac{p}{p^*}\right) \tag{2}$$

| | |
|---|---|
| $\Theta^*$ | model parameter 1: reference compression |
| $p^*$ | model parameter 2: reference pressure |

Due to its mathematical form, Eq. (2) reflects the $\Theta_{\text{plast}}(p)$-plot of narrow size fractions as well as bimodal mixtures and broad size distributions with adequate accuracy (Fig. 2). The deviation between the measured and the calculated values of $\Theta_{\text{plast}}$ is below $\pm 0.02$ for most of the examined size fractions. The two model parameters describe opposite effects of compaction. While the reference pressure describes the resistance against the uniaxial compaction of a powder, the reference compression describes the aptitude of a powder to compaction. These contrary trends allow an exemplified displaying of only one parameter in order to show the effect of for instance the particle size and the stress velocity.

The reference pressure and thus the resistance against compaction increases significantly with decreasing mean particle size and increasing stress velocity for narrow size fractions (Fig. 3). This correlates with the predominant compaction mechanism of breakage for coarse-grained materials and the increasing probability of breakage with increasing particle size. This effect is superimposed by the micro-plasticity of fine fractions at which the high strength of particles <10 µm leads to plastic deformation at the contact points when the yield stress is reached (Rumpf, 1965). Due to this