Abstract

This paper evaluates fragmentation behaviour, particle size distribution and liberation degree during bed comminution of particles. Three different cases of bed comminution are modelled through discrete element simulations. The role of stressing velocities on breakage, effects of crushing walls on fragmentation and influence of crushing gaps on liberation and particle size distribution are considered. The discrete element sample is modelled to represent the concrete specimens of B35 strength category.

It has been observed that the particles around the stressing walls fail differently than the inner particles during bed comminution. The stressing velocity and the crushing walls have been found to affect the cracking mechanism of the particles. The liberation degree in bed comminution is less as compared to single particle crushing. The results presented in this paper can be used to model the liberation and recycling of valuable aggregates from cheaper matrices.

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1. Introduction

Bed comminution is defined as the crushing of a large number of particles at a time. Generally, it is performed under compressive loading. The deformation behaviour of a particle bed is not affected by boundary walls if the diameter is at least twice the height and the height is five times the size of the particle to be crushed (Aziz and Schönert, 1980). Hanisch (1983) investigated non-side limited quartz particle beds (initial height of the particle bed was five times the mean size of the initial particle size) under compressive stressing, which exist in many mills (Schubert, 1993). Mostly inter-particle breakage occurs in the bed crushing of particles (Evertsson and Bearman, 1997).

Particles on the confining surface are stressed differently than internal particles. An increase in bed height reduces the energy absorption because a fraction of an applied energy will be used in repositioning the particles, and clusters of densified material move outwards the stressed zone. The increase in bed height also increases the stiffness of the system. A fraction of broken particles decreases sharply from a one particle layer to a two particle layer but differs only little between 4 and 8 layered bed (Schönert, 1996). The stressing of a single particle or even of one particle layer achieves a higher size reduction than stressing the particle bed. Better size reduction can be achieved by inserting steel balls in the particle bed which concentrate the force and the energy in their neighbourhood and increase the inhomogeneity of the stress field (Schönert, 1996).

The confined and non-confined particle bed comminutions were modelled with the compressive load to study the comminution behaviour of limestone particles (Oettel and Husemann, 2004). During compressive stressing of a non-confined particle bed, Nguyen et al. (2002) observed breakage and compaction of the particles, which stayed in the stressing zone until the end of the compression. This is due to the fact that the material directly under the stressed zone is not able to escape. Gutsche and Fuerstenau (1999) examined the retardation of breakage kinetics...
during the compressive loading of narrowly sized mineral feeds in confined particle beds.

The energy utilization in size reduction (to generate new surfaces) of a single particle is better than particles in a bed (Aziz and Schönert, 1980). This is due to the fact that during bed crushing some input energies will be used by repositioning (internal arrangements) of particles in the bed. After stressing the material, loosening and mixing and again re-stressing provide better energy utilization in terms of new surface generation (Hanisch, 1983). On adopting this method, Schubert (1993) mentioned that the energy utilization could be improved up to 50% which was verified by experiments. The specific energy to produce the crushed products increases with a decrease in the feed size (Kanda et al., 1996).

Liu (1994) investigated the particle size distribution during bed crushing of particles and observed that with the increase in stressing energy finer particles are generated. Herbst et al. (1974) applied mass balances to describe the liberation process more in general. The liberation and comminution of minerals are presented by King (1994).

Discrete element method has proved to be a good solution for researchers who want to study the bulk breakage of particles. Researchers have used the properties of a single particle and tried to relate the properties on a large scale comminution. During bed crushing of agglomerates, Couroyer et al. (2000) compared a pressure–displacement relationship between experiments and simulations. They observed some minute fluctuations (due to particle breakage) in experiments (with particle sizes 1.7–2.0 mm) in contrast to simulations (with particle sizes 0.9–1.0 mm) where large fluctuations can be seen.

Similarly, Ouwerkerk (1991) showed that the discrete element method can be used as a tool to couple single particle and bulk particle tests. On crushing of particle beds by a single grinding ball, Potapov and Campbell (2000) showed that the deeper the bed the lesser the breakage, and observed the dual properties of the friction. From a study of Couroyer et al. (2000) and Potapov and Campbell (2000), it can be inferred that the friction has a large effect on bulk crushing. According to Potapov and Campbell (2000), friction causes a loss in impact energy and in contrast to this the same friction influences a flow of particles around the grinding ball. In other words, with the increasing friction the grinding ball has more contact time to crush the particles around it and produces more breakage, but on the other hand more energy is lost by frictional dissipation.

It can be noted from the above discussion that the particles around the stressing walls fail in different way than the inner particles inside the bed. In this case, the objective of the research is to investigate the fundamental issues, like, failure behaviour of particles around the stressing walls and inter-particle breakage, effects of crushing walls on liberation degrees and effects of crushing walls and velocities on fragmentation of particles during bed comminution. These issues should be understood in order to design an efficient mineral processing machine and to achieve the desired outputs like, particle shapes, particle sizes and liberation degrees. Also, this work is an extension of a single particle comminution (Tomas et al., 1999; Khanal, 2005; Schubert et al., 2005) to a bed comminution. The research results can also be used to model the liberation and recycling of valuable aggregates from cheaper matrixes. The understanding of the particle failure during bed crushing helps to select the suitable process (like, the type of crushing bed, Section 2.2) and parameters (like, wall velocities, crushing wall gap, etc.) to achieve the desired liberation degrees and the particle size distribution. For example, during mineral processing and recycling, we want to liberate the valuable products in the same shape and strength as they were before from the cheaper fine matrixes (hardened cement paste) for further use (Tomas et al., 1999).

In this research, the discrete element simulation has been adopted to study the comminution behaviour of particles during bed crushing. The bonded particles are chosen to represent the valuable aggregates embedded inside the cheaper matrixes. In reality, this is similar to processing and recycling of concrete where the valuable gravels are embedded inside the cheaper sand particles.

1.1. Particle–wall contact

During particle–wall contact particle deforms once it touches the stressing wall. When the generated tensile stress is equal to the strength of the material, crack initiates (Schubert et al., 2005). The contact deformation initiates a small circular crack along the radius of the contact circle (Tomas et al., 1999). The crack follows this path and forms a wedge like fragment showing a sharp cutting edge effect. This sharp tip of the fragment penetrates the remaining part (parent specimen). In this process, shear stresses are generated on the opposite side of the enhancement of the crack at the interface between the wedge like region and the parent specimen. During propagation of the circular crack, meridian cracks propagate and unbalanced stresses introduce secondary cracks. The amount of occurrence of this phenomenon depends on the stress generated inside the particle during impact (Schubert et al., 2005).

1.2. Particle–particle contact

At the contact zone of two particles (see Fig. 1), the compressive zones are obtained. When the generated tensile stress on the periphery of the contact deformation is equal to the material strength then crack initiates from the boundary of the contact deformation. After initiation of the cracks, the weakest interface of the aggregates and the hardened cement paste propagates the cracks (in case of aggregate–matrix composites). Around the impact site, the fragments are smaller and they are surrounded by larger fragments.
2. Discrete element modelling

Discrete element simulation (DEM) of a bed crushing has been performed by modelling three layers consisting of nine specimens in a container. The compression loading sketch is shown in Fig. 2. The upper wall moves against the specimens while three other walls are kept fixed. Schubert et al. (2005) has already given the breakage behaviour of individual specimen.

The two-dimensional DEM model (disc) is considered to have constituents of gravel as large primary particles and sand as small primary particles and bonded with hardened cement paste. Since the program needs the specification of micromechanical properties and contact parameters such as stiffness and bond strength rather than classical macro-mechanical properties such as Young’s modulus, the numerical model, so, has to be calibrated. So the micro-properties of the model have to be changed until the simulated properties match the real ones. A maximum utilization of the real concrete properties gives a good start for a successful simulation. The detail of the calibration procedure adopted in this simulation is given by Schubert et al. (2005).

Small particles (962) having 1 mm radius are mixed with 38 large particles, radii of 4–6 mm with gaussian distributions of large particles. The larger particles have normal and shear stiffness of $1 \times 10^{10} \text{N/m}$ and density of 2870 kg/m$^3$ whereas the smaller particles have the stiffness of $1 \times 10^7 \text{N/m}$ with density 1790 kg/m$^3$. The normal strength and shear strength of the model are 4.1 MPa. The parallel bond normal stiffness and shear stiffness are $1 \times 10^{11} \text{N/m}^3$ and $6.3 \times 10^{10} \text{N/m}^3$, respectively. The required number and diameter of particles are randomly generated within the defined area and assigned the bonding properties to the particles. An explicit-time-marching calculation scheme is adopted. The following features are applied to the model:

- A stiffness model, providing a linear elastic relation between the contact forces and the relative particle displacement.
- A slip model, so that two entities in contact may slip relative to each other.
- A bond model, limiting the total normal and shear forces that the contact can carry.

The arrangement of the particles in the individual specimen is shown in Fig. 3. The bigger balls represent gravels and the smaller represent sand. Three different cases are simulated to study the fracture behaviour and fragmentation of the specimens. The discrete element simulations are carried out by using commercially available software PFC2D (2002).
2.1. Effects of crushing velocities on fragmentation

The effect of crushing velocities on fragmentation has been investigated with three different velocities – 1 m/s, 5 m/s and 10 m/s. The sketch of the crusher is shown in Fig. 2 where the upper wall is moving against the specimens at a predefined velocity and other walls are fixed. In one case, 5 m/s, the stressing wall is allowed to move farther than others to observe the effects of loading distance on liberation and particle size distribution of the particles.

2.2. Effects of crushing walls on fragmentation

The geometry of the crushing wall also effects the comminution (Oettel and Husemann, 2004). Four different types of bed crushing (Fig. 4) are performed to understand the effects of side and stressing walls on cracking, liberation and particle size distribution. In closed wall, the particles cannot escape from the bed during stressing whereas in open wall the particles can escape from the open section of the bed.

1. One side wall and the base wall are fixed, and the remaining two walls are in motion (two fixed closed moving).
2. One side wall and the base wall are fixed, and the remaining two walls are in motion but the upper wall does not cover the whole opening (two fixed open moving).
3. Two side walls and the base wall are fixed, and the stressing wall is in motion (three fixed closed moving).
4. Two side walls and the base wall are fixed, and the upper wall is in motion but does not cover the whole opening (three fixed open moving).

2.3. Influence of crushing gap on liberation degree

The effect of a distance between impactor and fixed wall is investigated by modelling the crushing system as shown in Fig. 5. This situation is similar to the rotary crusher where the specimen is impacted by a hammer.

2.4. Liberation degree evaluation

Liberation degree is a parameter that explains the extent to which aggregates are freed from matrixes. In simulations, the number of larger particles is freed from the matrix of smaller particles, which in reality is the extent to which aggregates, gravel particles, are freed from the cement and sand matrix after stressing. If aggregates are totally freed (no adherence) from hardened cement paste, then these aggregates are called totally liberated aggregates. These products deliver a skeleton material (Tomas et al., 1999) for high strength construction purposes. Liberation degree depends on the bonding strength of the material.

In the simulation, the liberation degree is defined in terms of contact existing between primary particles and is evaluated on a number basis. The liberation degree is calculated by detecting the contacts, which aggregates have with surrounding hardened cement particles. The fragmented parts obtained are scanned to determine the liberation degree. During this process each aggregate particle is checked for adhered neighbour particles and divided into two categories, liberated and non-liberated. An aggregate particle is considered to be non-liberated when the number of adhered hardened cement paste particles is higher than seven, which corresponds to an average rate of 5% of impurities often occurring in recycling practice (Schubert et al., 2005). Similarly, if the particle has less than or equal to seven contacts then it is considered as fully liberated. The value of seven contacts which are permitted for full liberation is obtained from a comparison with experiments. The flow chart for evaluating the liberation degree is shown in Fig. 6. The trend of the liberation degree provides a method to find the optimum velocities and optimum conditions for better recycling. From the recycling point of view, the liberation degree analysis is very important. Similarly,
the particle size distribution is also evaluated through contact existing between primary particles in a cluster.

2.5. Particle size distribution evaluation

Particle size distribution is a parameter that gives an idea about the extent to which particles of different sizes are formed after crushing. In other words, it is calculated to understand the distribution of fragments after crushing. In experiments, particle size distributions are calculated on mass basis and obtained through the sieving procedure, but in the simulation it is number basis. Different authors (Clearly and Sawley, 2002; Schubert et al., 2005) have developed different techniques to evaluate the particle size distributions during simulations. In this research the particle size distributions are evaluated by detecting the contacts which exist between particles (Schubert et al., 2005; Khanal, 2005). In brief, the number basis is converted to the mass basis with a known density. The mass of the primary particles are added to form the theoretical mass of the clusters.

3. Results and discussion

3.1. Effects of crushing velocity on fragmentation

Different stages during crushing at a velocity of 1 m/s are shown in Fig. 7a. From the figure it can be noticed that during such crushing there exists a complicated failure of material comprising of particle to wall (Schubert et al., 2005) and particle to particle (Khanal, 2005) crushing. When there is a particle to wall impact, wedge like region (for example in Fig. 7a, 2 column 1 row – middle particle; Fig. 7b, 1 column 1 row – left two particles; Fig. 7c, 2 column 1 row – three particles) can be seen at the contact side, and thus, has sharp cutting edge effect (Tomas et al., 1999; Schubert et al., 2005) inside the parent specimen. When there is a particle to particle contact, there exists pure crushing failure. This is characterised by production of finer (smaller) fragments (in the beginning of the crushing) and they are surrounded by larger fragments around the impact site. It can be observed that at higher crushing...
velocities, the top layered particles break first and then next layer of particles and so on. This can be verified by Figs. 7b and 7c at 5 m/s and 10 m/s crushing velocities, respectively, where the top layered particles are broken first with the increasing velocities. At 1 m/s, every layer is affected during crushing. At 5 m/s, when the top layered particles are broken, some amount (less than at 1 m/s) of the lower particles are also affected, whereas at 10 m/s first all the top layered particles are crushed, then only the next layers are affected and broken. This maybe a dynamic effect during high velocity crushing but the research work is to study the comminution behaviour of the material. Hence, from a practical point of view, we apply higher stressing velocities for the comminution.

The liberation degrees are 9.3%, 9.9% and 9.3% for the crushing velocities 1, 5 and 10 m/s, respectively. As mentioned above, the 5 m/s was allowed to move farther than others, therefore it has produced more liberated particles than others (this is an effect of time-dependent stressing). In general, it can be seen that the liberation degrees for the bed crushing are almost similar and in the range of 9–10% in such crushing simulations.

3.2. Effects of crushing walls on fragmentation

Crack patterns obtained for different types of simulation are shown in Fig. 9. Four corners clearly indicate the effect of circumferential walls on fracturing of the specimen. All particles are fragmented at the corners during closed moving whereas in open moving the particles are not completely fractured on lower left corner. This is due to the fact the crushed particles are escaping from the open section as a result the particles at the left corner (side of the open wall) do not get sufficient energy for the complete comminution. In the closed moving cases the moving wall covers the complete opening of the container, as a result, all fragmented particles are pushed inside. The fragments are escaping in both open moving cases, and the material is not completely crushed at the open end side. From the figure, it can be observed that, given the same condition, the closed moving cases are more efficient than the open moving cases in generating fragments. At the crushing velocity of 20 m/s, the top layered particles are completely destroyed before the next layer of particles are affected, as explained in Section 3.1.

Fig. 10 shows the effect of crushing walls on particle size distributions at 20 m/s. From the figure it can be observed that the two fixed close moving produces finer fragments as compared to others. The left hand distribution shows the generation of fine particles. The three fixed open moving produces coarse particles. In general, the liberation degrees are in the range of 4–10%, Fig. 11.

3.3. Influence of crushing gap on liberation degree

Fig. 12 shows the effect of distance between the impactor and the fixed wall during fracture of a particle. During such crushing, the impactor hits and sweeps a part of the specimen. In these cases, particles fail in a shear mode. A small gap between impactor and fixed wall causes more fractures as compared to a large gap, because the smaller gaps have higher impactor material contact and transfers high energy to the specimen.

Particle size distributions and liberation degrees obtained at various gaps are shown in Figs. 13 and 14, respectively. The ideal distribution is that distribution where all the constituent (primary) particles are disintegrated from the sample. It represents the aggregates and the hardened cement paste particles with a step function. The figure illustrates that 1 mm gap produces finer fragments, whereas 30 mm gap produces coarser fragments.

![Fig. 7c. Different stages of the bed crushing at 10 m/s.](image)

![Fig. 8. Particle size distributions during bed crushing.](image)
Fig. 9. Effect of walls during crushing, $v = 20$ m/s.

Fig. 10. Effect of walls on particle size distributions, $v = 20$ m/s.

Fig. 11. Effect of walls on liberation degrees, $v = 20$ m/s.
The Fig. 14 shows that the effect of the gap (till 10 mm) in liberation degree is almost the same, but it reduces suddenly when the gap reaches 30 mm, which is due to an inefficient crushing, where the rotor hits much less material of the specimen.

4. Conclusions

The particle bed comminution was simulated to understand the crushing mechanism of multiple particles at a time. It was observed that in bed comminution both the particle–wall and particle–particle stressing conditions are active (for fracturing). It was noted that the stressing velocity affects the cracking mechanism of the particles in the bed comminution. At higher crushing velocities, the top layered particles break first and then next layer of particles and so on. The liberation degree in bed comminution is less as compared to single particle crushing (Schubert et al., 2005). In case of closed crushings, the liberation degrees are in the range of 9–10%. Under the identical condition, the closed moving cases are more efficient than the open moving cases in generating fragments. The two fixed close moving simulation produces fine fragments as compared to other three cases (Section 3.2). On the study of influence of crushing gap on liberation degrees, the 1 mm crushing gap produces fine fragments. In general, it can be concluded that the discrete element simulation can be a useful tool to investigate the failure behaviour of particles around the stressing walls and inter-particle breakage, and effects of crushing walls and velocities on fragmentation of particles during bed comminution.

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References


