

Application of population balance model to HPGR crushing



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ARTICLE INFO

Article history:

Received 3 April 2013

Accepted 4 July 2013

Available online 31 July 2013

Keywords:

High pressure grinding rolls

Modeling

Cement

Mineral

ABSTRACT

Having proved its success in energy efficiency, the High Pressure Grinding Rolls became widespread all over the world in many plants. The first application of the HPGR was in 1985 in a cement plant, mainly for capacity improvement purpose. Then various circuit configurations were derived to achieve reduction in overall specific energy consumption by transferring more of the grinding required to the HPGR. By mid 1990s, HPGR installations have been used in minerals industry. The HPGR was introduced to minerals industry as a replacement for tertiary crushers, SAG mills and rod mills. In some applications it appears as a pebble crusher in AG milling.

HPGR has attracted the attention of many researchers for around two decades, resulting in various modeling approaches for throughput or size reduction of the equipment. This paper will discuss the method of applying population balance model to size reduction of HPGR. Data collected from both cement and minerals industry was used for this study. The breakage rate was defined as a function of the operating pressure and the material characteristics. The material characteristics were determined by compressed bed breakage tests. The relationships between the operating parameters and the model variables lead to predicting the product size distributions of the HPGRs for the given operating conditions.

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1. Introduction

Schönert (1979) stated that the most efficient method to break particles, in terms of the energy utilization, is to compress the particle bed between two plates. Schönert and Knobloch (1984) proposed that particle bed comminution for high throughputs can be achieved by compressing the particles between two counter rotating rolls. By the invention of the High Pressure Grinding Rolls (HPGR) the industrial scale operations for compressed bed breakage was achieved. The first industrial scale operation was implemented in 1985 in the cement industry, mainly for increasing the capacity of the plant (Kellerwessel, 1990; Feige, 1993). The first applications of the HPGR were limited to pre-grinding prior to downstream ball milling. Due to pre-ground material and micro-cracks formed in the particles, the capacity of the downstream ball milling increased while the specific energy consumption decreases (Kellerwessel, 1993). After the initial applications of the HPGR, more of the grinding required has been transferred to the HPGR by introducing various circuit configurations such as pre-grinding mode, hybrid-grinding mode, semi-finish grinding mode and finish grinding mode (Kellerwessel, 1993; 1996).

By mid 1990s, HPGR installations were being used in minerals industry, mainly in iron ore pelletizing and diamond. This was followed by applications in hard rock grinding as copper, gold and platinum ore. The HPGR has been introduced to minerals industry as a replacement for tertiary crushers, SAG mills and rod mills. In some applications it appears as a pebble crusher in AG milling.

Interparticle breakage in the compression zone between the rollers is achieved by choke feeding the material to the HPGR, otherwise the HPGR runs like a conventional roll crusher (Kellerwessel, 1990). During choke feeding a particle bed builds up between the rollers and the applied load is transferred to the material by the surrounding particles. The output of the HPGR mainly depends on the specific energy consumption and the distribution of the applied energy in the material bed according to the composition of the bed in terms of the particle size fractions (Klymowsky and Liu, 1997). Hence, the homogeneity and the uniformity of the feed material of the HPGR are significant parameters in terms of the energy utilization. For best utilization of the comminution energy during the operation of the HPGR, some portion of the HPGR discharge material is recycled back to the HPGR to ensure a uniform material bed and higher pressure gradient along the roller width.

HPGR has attracted the attention of many researchers for around two decades, resulting in various modeling approaches for throughput or size reduction of the equipment (Fuerstenau et al., 1991; Austin et al., 1993; Liu and Schönert, 1996; Klymowsky and Liu, 1997; Lim and Weller, 1997; Morrell et al., 1997;

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Aydogan, 2002; Torres and Casali, 2009). This paper presents the new approach for modeling the HPGR using material characterization together with the existing industrial scale database.

2. Population balance model

The population balance model is referred to as a simple mass balance for the size reduction. The population balance model, introduced by Epstein (1947), is based on the production rate of the material within the mill. The process can be described in terms of transport through the mill and breakage within the mill. For a size fraction of i , transport into a breakage zone, breakage and transport out for continuous milling is represented in Fig. 1. A simple mass balance for size fraction of i in the product is calculated as follows:

- particles coarser than i size are broken into i size fraction,
- particles in i size fraction are broken into smaller sizes,
- new i size is introduced to the system with the fresh feed.

The mass balance equation can be written as follows:

$$p_i = f_i + \sum_{j=1}^i a_{ij} r_j s_j - r_i s_i \quad (1)$$

where p_i is the i size product, f_i the i size feed, a_{ij} the breakage function (appearance of size i produced by breakage of size j), r_j the breakage rate of size j , s_j the amount of size j material within the mill, r_i the breakage rate of size i , and s_i is the amount of size i material within the mill.

In the population balance model two functions are defined; breakage rate function (r) and breakage distribution function (a). The breakage rate is defined as the disappearance rate of a specific size after breakage and expressed as tone per hour broken per tonne in the mill (tph/t = 1/h). The breakage distribution function defines the size distribution of the product formed after the breakage of the parent size fraction. The product size distribution is a function of the energy applied on the parent size. The breakage function defines the material characteristics and is determined by laboratory tests. In the population balance model, the breakage rate of the particles is back-calculated for a given feed and product size distributions using the breakage function of the material.

3. Application of the model

The research on application of the population balance model to HPGR crushing was commenced using cement grinding data and

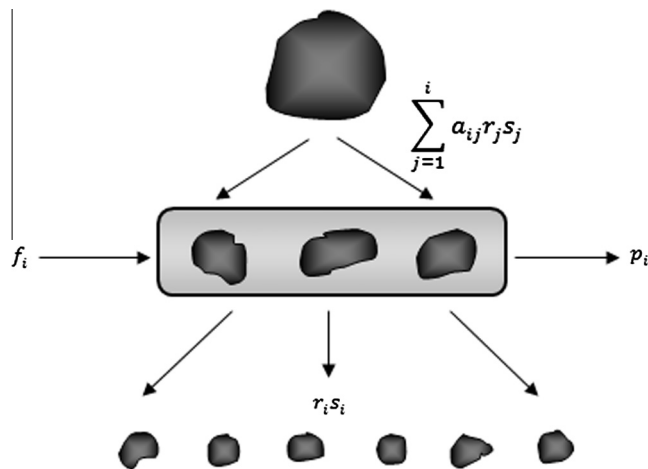


Fig. 1. Product generation in population balance model (Napier-Munn et al., 1996).

gone through mineral data. Dundar (2012) fit the cement grinding data that was acquired by Aydogan (2006) to population balance model. Dundar (2012) back-calculated the breakage rate using Eq. (1). For a given feed and product size distributions of the HPGR, the mill content (s) and the breakage function (a) of the material is required to back-calculate the breakage rate.

Dundar (2012) defined the mill content as roll content which means the amount of the material between the rolls. For this purpose the volume between the rollers, from the nipping gap to the working gap, is calculated geometrically. The content is defined as the accumulation in the rolls bed which is the combination of the HPGR feed to the system and partially broken material still within the system. Since the amount and size distribution of partially broken material is unknown, the feed to HPGR is assumed as mill content. The illustration of the volume between the rolls is shown in Fig. 2.

The required breakage distribution function of the material was determined by lab-scale compressed bed breakage tests. The representation of the compressed bed breakage test is given in Fig. 3. In this test, narrow sized fractions of the material to be tested are prepared then compressed to a fixed range of different pressures. From the force-displacement graph the corresponding energy

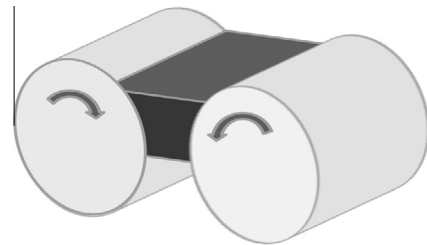


Fig. 2. Schematic representation of the volume between the rolls.

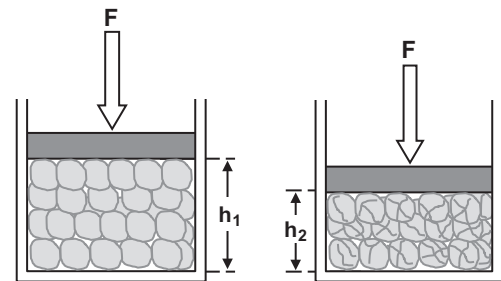


Fig. 3. Representation of the particle bed compression.

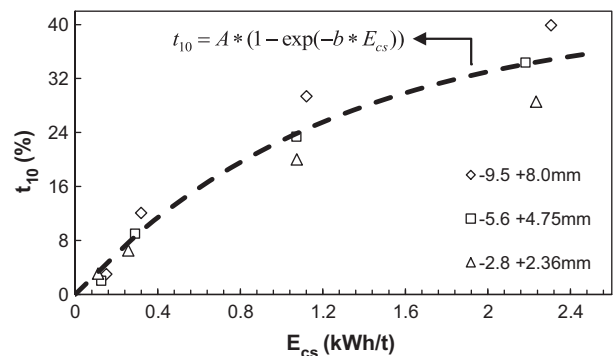


Fig. 4. E_{cs} - t_{10} relationship.

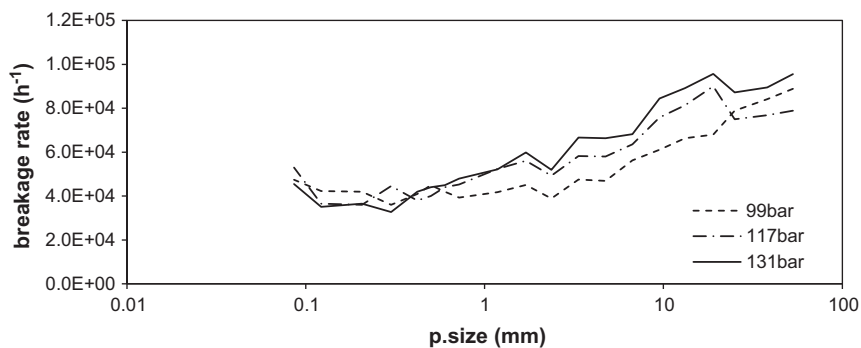


Fig. 5. Back-calculated breakage rates for different operating pressures for cement data.

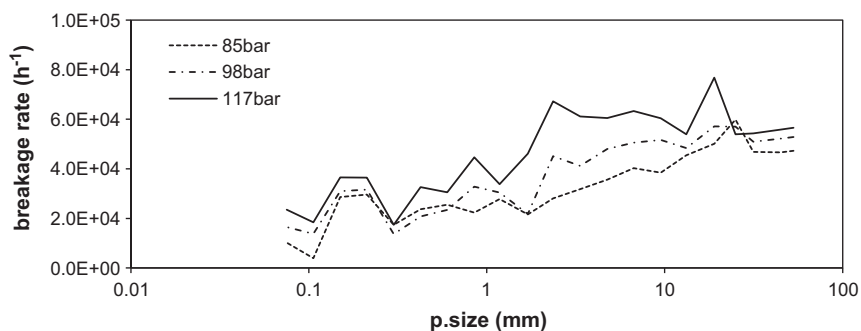


Fig. 6. Back-calculated breakage rates for different operating pressures for gold ore data.

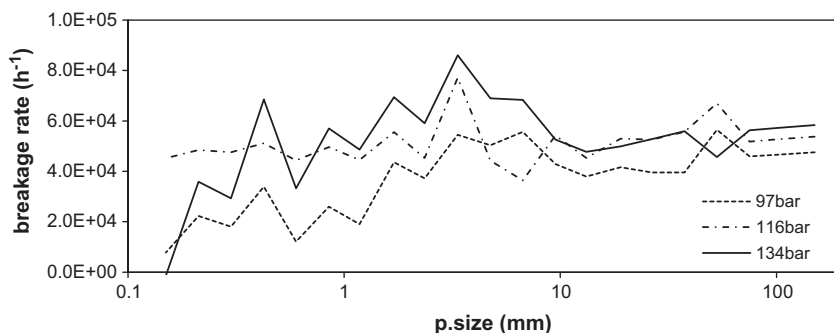


Fig. 7. Back-calculated breakage rates for different operating pressures for platinum ore data.

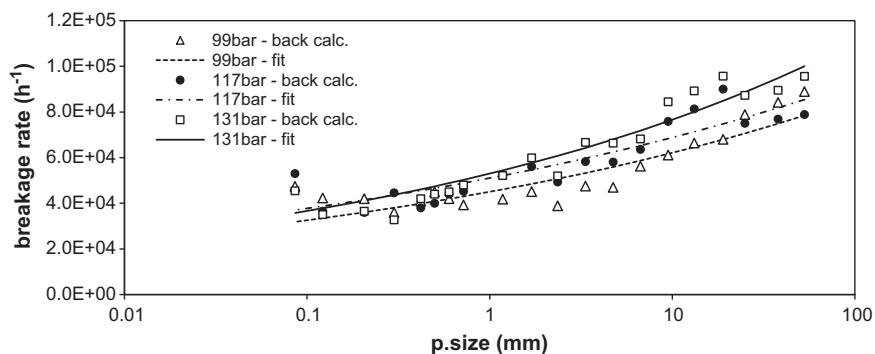


Fig. 8. Back-calculated and fitted breakage rates for cement data.

levels are calculated. The size distributions of the compressed materials are determined by sieve analysis.

The data evaluation for the compression breakage results is carried out using an evaluation method developed for single particle

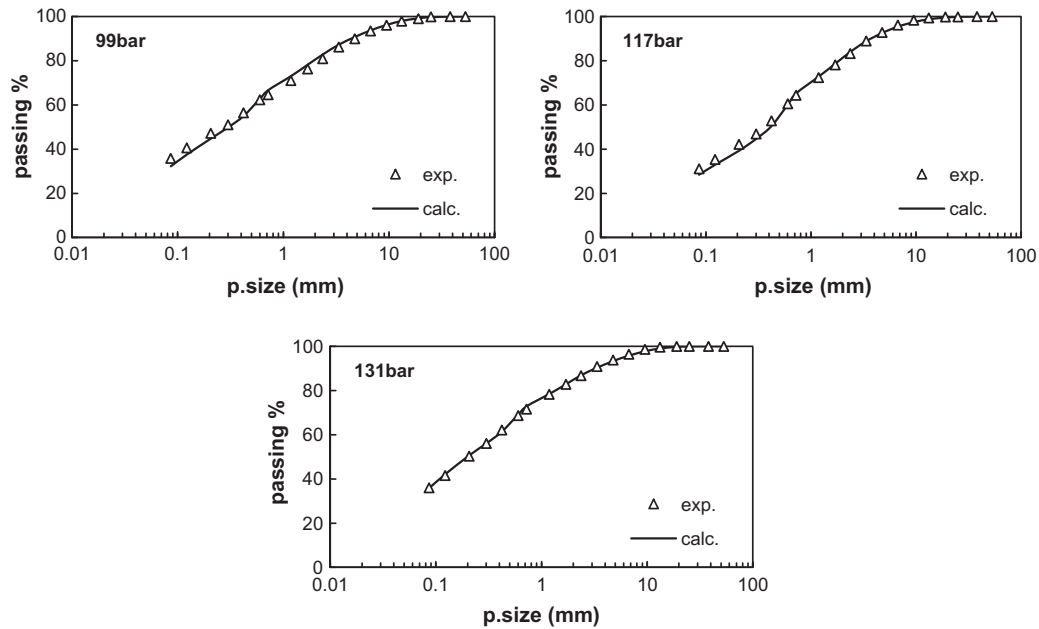


Fig. 9. Calculated size distributions of the HPGR product for cement data.

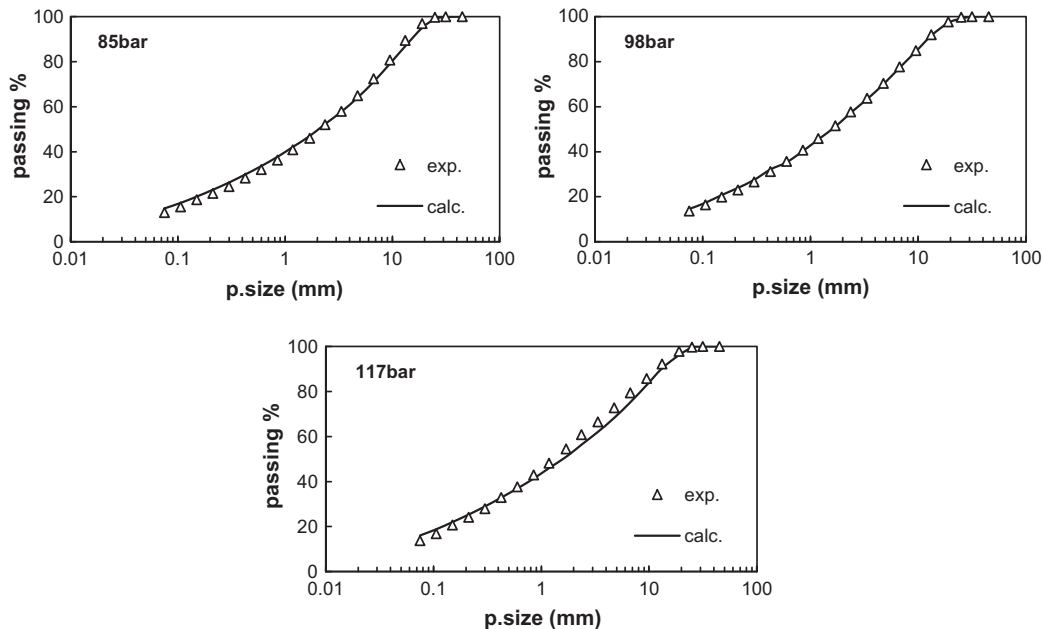


Fig. 10. Calculated product PSDs for gold ore grinding.

impact breakage tests by Narayanan (1986). Since the product size is a function of the energy applied onto the parent size, Narayanan (1986) defined a relationship between the specific comminution energy and product fineness for impact breakage data.

$$t_{10} = A * (1 - \exp(-b * E_{cs})) \quad (2)$$

where A and b are the material constants, E_{cs} is the specific comminution energy and t_{10} is the percent passing 1/10th of the parent size in progeny. A typical E_{cs} – t_{10} relationship obtained from compressed bed breakage test is given in Fig. 4. In Fig. 4, the experimental results for three different size classes were fitted to Eq. (2) and then the relationship between the energy level and the product size

distribution is obtained. By using this relationship the breakage distribution is calculated for a given energy level. In the modeling approach presented here the breakage distribution function is calculated for an input energy of 2 kW h/t.

Fig. 5 gives the back-calculated breakage rates of the cement data for different operating pressures for the same machine. As can be seen from figure the breakage rate increases with the particle size and shift upwards with the increased operating pressure. Applying higher pressure values resulted in more fines generation, therefore the breakage rate of the particles is increased.

Dundar (2012) applied the same methodology to mineral data to calculate the breakage rate. Fig. 6 gives the back-calculated

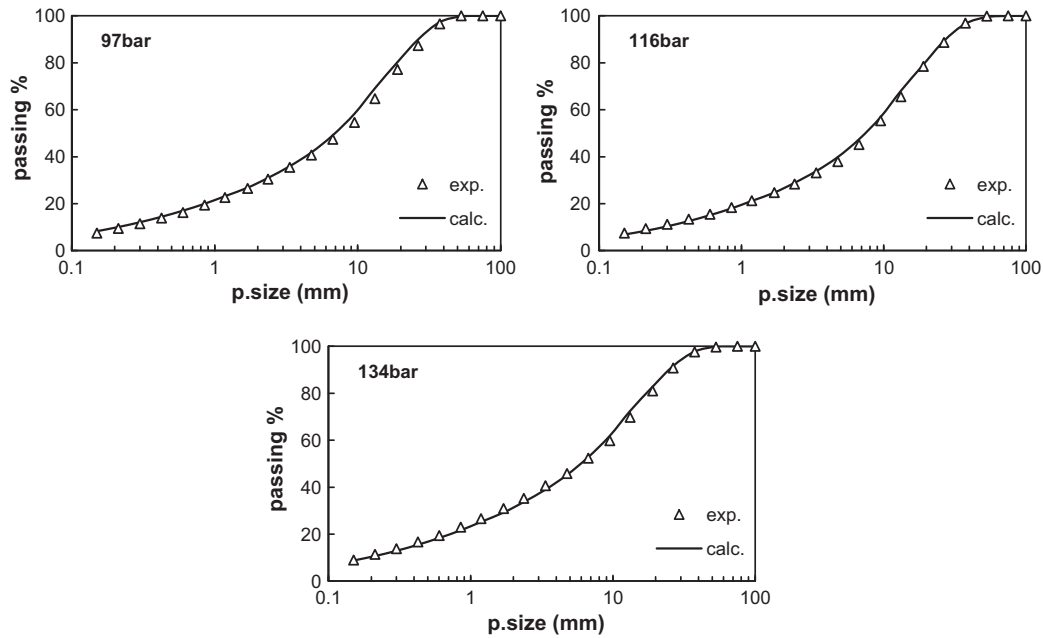


Fig. 11. Calculated product PSDs for platinum ore grinding.

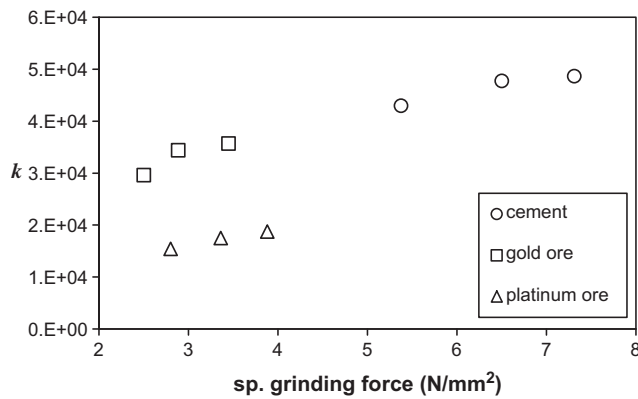


Fig. 12. Relationship between the specific grinding force and parameter k .

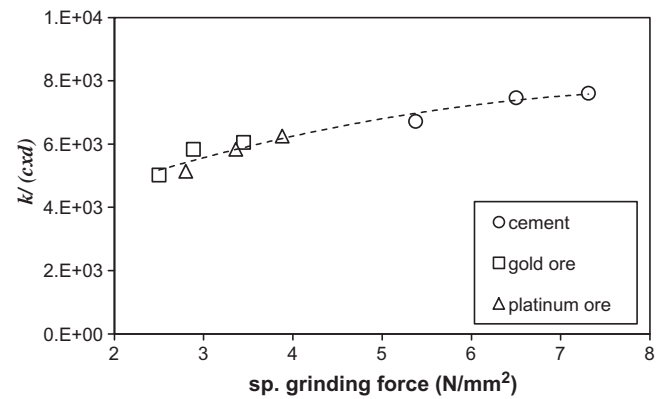


Fig. 14. Relationship between the specific grinding force and normalized k .

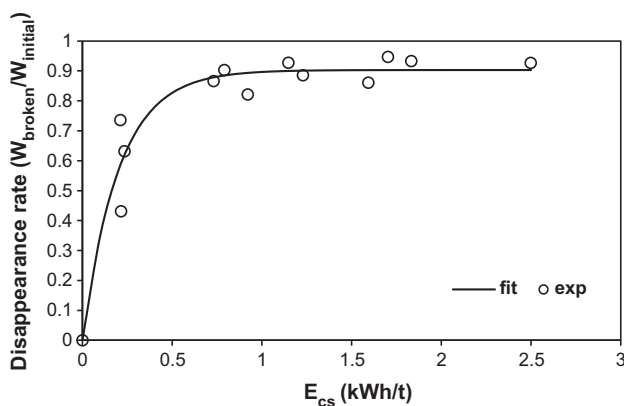


Fig. 13. E_{cs} vs. disappearance rate ($W_{broken}/W_{initial}$).

breakage rates for the gold ore data that was presented by Dunder et al. (2011a). Dunder (2012) also achieved similar relationships for the platinum ore data (Fig. 7).

After achieving such relationships represented in Figs. 5–7, Dunder (2012) expressed the breakage rate as a function of pressure and particle size by using the equation below which was defined by Austin et al. (1976)

$$r = k \cdot x^\alpha \quad (3)$$

where r is the breakage rate, k is the machine constant, α is the material constant and x is the particle size. The back-calculated breakage rates were then fitted to Eq. (3) for cement data (Fig. 8).

A smooth breakage rates were obtained by fitting the k and α parameters, as expected. Regarding the fitted rates, the product size distributions of the HPGR was calculated and compared with the experimental ones to assess the prediction capability of the model (Fig. 9).

From Fig. 9 the calculated product PSDs are in quite good agreement with the experimental results. Same calculations were also carried out by Dunder (2012) for the industrial scale mineral data including gold ore and platinum ore. The calculated product size distributions for the mineral data are given in Figs. 10 and 11 together with the experimental ones.

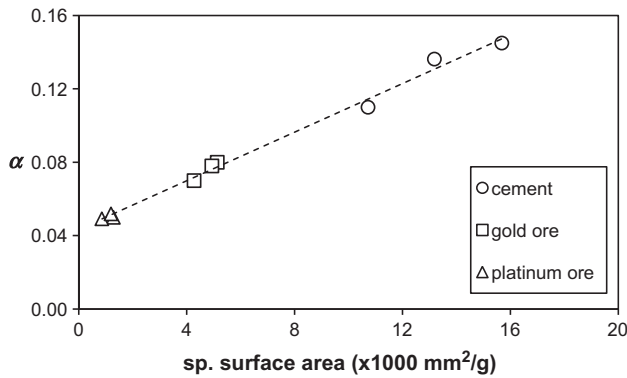


Fig. 15. Specific surface area vs. α .

4. Discussion

By using the feed and product size distributions with the breakage distribution function obtained by compressed bed breakage test, the breakage rate was back-calculated using the mass balance equation of the population balance model. For each data set the k and α parameters were fitted to get the best fit of the product size distribution.

The parameter k mainly depends on the operating pressure, as the breakage rate shifts upwards with the increased pressure. Fig. 12 gives the relationship between the specific grinding force and the parameter k . The specific grinding force is a function of the applied pressure and the rolls dimensions; defined as the force divided by projected area of the rolls. Considering the specific grinding force instead of pressure leads to making a comparison of rolls with different dimensions.

As can be seen from Fig. 12 the value of k increases with the specific grinding force and the highest specific grinding forces were achieved in cement grinding. The specific grinding forces applied in minerals industry are rather low due to the wear issues in hard rock grinding. Above relationship does not include the effect of material characteristics, therefore a research was conducted to input a material parameter that is appropriate to definition of breakage rate. The compression test results were used for this purpose. During the laboratory compressed bed breakage tests, the disappearance rate of the narrow sized fractions was calculated for various energy levels. The disappearance rate of the fractions was calculated according to the mass fraction broken out of that size fraction. The disappearance rate for different size fractions are given in Fig. 13 for various energy levels.

The relationship between E_{cs} and disappearance rate is then fitted to below equation:

$$\frac{W_{broken}}{W_{initial}} = c * (1 - \exp(-d * E_{cs})) \quad (4)$$

After fitting the c and d parameters, the multiplication of those ($c * d$) is regarded as the material softness in this modeling approach. Higher values of this multiplication mean that the disappearance rate is high, so the material has relatively low resistance to compressed breakage. Thus, the breakage rate increases with this value. The equation is structurally equivalent to the t_{10} equation (Narayanan, 1986) used in impact breakage characterization to provide the well known A by b parameters.

The k values for each data set was then normalized according to ($c * d$) parameter and re-plotted against specific grinding force (Fig. 14).

Dunder et al. (2009, 2011b) proposed that the efficiency of the HPGR crushing is improved with relatively finer feed to the HPGR. In HPGR, the finer feed leads to more stabilized material bed

between the rollers, hence, efficient breakage occurs as the inter-particle breakage is enhanced. Regarding Eq. (3), parameter α defines the slope of the breakage rate in this modeling approach. In this approach, the effect of the size distribution of the material bed is represented by the parameter α . The feed size distribution was introduced to the model as in correlation with the α . As a preliminary research, the specific surface area of the feed calculated theoretically by assuming all the particles are spherical, was correlated with the fitted values of α . Fig. 15 gives the correlation between the specific surface area of the HPGR feed and α .

5. Conclusion

The new modeling approach for HPGR crushing is based on population balance model. The breakage rate of the particles was defined as a function of specific grinding force and material characteristics. The model was developed for a wide range of data acquired from hard rock and cement grinding but only a few data was presented in the paper. The data used for the modeling study includes the rolls ranging from 1 m to 2.4 m in diameter. Various feed size distributions were also experienced for different rolls.

Narrow sized compression tests create data for the breakage function and the disappearance rate of the materials. The breakage function used for the modeling is not size specific for now, but a research on size specific breakage function is in progress to make the model more comprehensive.

The parameter α was correlated with the specific surface area of the material that is calculated theoretically. Since there is no technique to determine the specific surface area of relatively coarser particles, theoretical approach was used. In theoretical approach, the sieve aperture size has a big effect on the value of specific surface area i.e. for the same size distribution different values are obtained for different sieve series. Therefore, more accurate parameter to identify the feed size distribution of the HPGR, rather specific surface area, is under research.

Acknowledgements

The authors wish to thank AMIRA International and the sponsors for permission to publish the work done in minerals industry. The authors also acknowledge the funding for this work through AMIRA International's Project P90.

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