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## **Abstract**

In ball milling the rates of breakage vary primarily with the size distribution of powder in the mill. Using an approximate solution to the batch-grinding equation, the acceleration and deceleration of breakage rates of all individual size classes are determined when the grinding environment is varied. Experimental results with limestone and copper ore show time-dependent breakage rates under both dry and wet grinding conditions. The effect of grinding additives on breakage rates is also studied. In general, breakage rates increase for coarse sizes and decrease for fine sizes with an increase in the fines present in the mill. Such variations have strong implications in closed-circuit grinding.

## **Keywords**

breakage rates, milling, wet grinding, dry grinding

## **Disciplines**

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## **Comments**

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# Chapter 19

## EFFECT OF MILLING ENVIRONMENT ON THE BREAKAGE RATES IN DRY AND WET GRINDING

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### ABSTRACT

In ball milling the rates of breakage vary primarily with the size distribution of powder in the mill. Using an approximate solution to the batch-grinding equation, the acceleration and deceleration of breakage rates of all individual size classes are determined when the grinding environment is varied. Experimental results with limestone and copper ore show time-dependent breakage rates under both dry and wet grinding conditions. The effect of grinding additives on breakage rates is also studied. In general, breakage rates increase for coarse sizes and decrease for fine sizes with an increase in the fines present in the mill. Such variations have strong implications in closed-circuit grinding.

### INTRODUCTION

The minerals and metals industry considers energy consumption in the size-reduction unit operation as an important variable in determining the economic viability of the process. Dating back to the last century, energy-size reduction laws have been in use for this analysis. The most promising one among them, which continues to be used today, is the Bond's Law. But for various reasons these laws are not of much use in process modeling and simulation. Hence in the past thirty years, more detailed mathematical models were developed for the analysis of comminution processes.

During grinding coarse and intermediate size particles are broken and rebroken a number of times, and as a result, the entire assembly of particles becomes finer and finer. It is possible to describe the evolution of product size distribution with parameters that characterize the breakage property of the particle, feed size distribution and operating conditions of the mill. This phenomenological approach provides a formal and quantitative description of the size-reduction process. These models are divided into three broad categories (Kapur, 1988). Of the three, the linear size-discretized population-balance model is the most developed for tumbling-mill grinding processes. In this paper, we critically analyzed the breakage parameters of such a model.

In the formulation of the size discretized model for batch ball mills, the particulate assembly undergoing breakage was divided into several narrowly sized intervals. A mass balance of material entering and leaving the *i*th size interval yields the well-known batch grinding equation:

$$\frac{dm_i(t)}{dt} = -K_i m_i(t) + \sum_{j=1}^{i-1} b_{ij} K_j m_j(t) \quad (1)$$

For a total of  $n$  size intervals, the model uses  $(n-1)$  breakage rate parameters ( $K_i$ 's) and  $(n-1)(n-2)/2$  breakage distribution parameters. Such a large set of parameters presents problems in determining the values of these parameters from grinding data. Hence, functional forms for breakage rates and breakage distributions have been proposed. One such family of functional form (Rajamani and Herbst, 1984) is given as:

$$K_i = K_1 \exp \left( \sum_{j=1}^L \zeta_j \left[ 1n \frac{\sqrt{x_j x_{j+1}}}{\sqrt{x_1 x_2}} \right]^j \right) \quad L = 1, 2 \text{ or } 3 \quad (2)$$

$$B_{ij} = \Phi_1 \left( \frac{x_i}{x_{j+1}} \right)^{\Phi_2} + (1 - \Phi_1) \left( \frac{x_i}{x_{j+1}} \right)^{\Phi_3} \quad (3)$$

These two functional forms reduce the parameter set to the utmost seven unknown values. Equations (2) and (3) correlate breakage rates and cumulative breakage functions with the size of the intervals, respectively. There is no explicit dependence on either time or size distribution of the particles. Hence these functional forms can be applied only for a short duration of grinding time during which breakage rates are presumed constant. Herbst et al. (1981) recognized this aspect in their "similar fineness" hypothesis for scaling up ball mills. As the grinding process proceeds, more and more fines are produced in the mill. Therefore the size distribution within the mill changes continually, which in turn, affects the kinetics of breakage. In such a case the use of functional forms in parameter estimation may "force fit" the data and produce unrealistic breakage rates which are far different from the real values. Therefore, in the application of the grinding model, the breakage rate parameter should be allowed to take on any value without applying any constraint.

The subject of this paper is to study the effect of mill environment (particle size distribution within the mill) on the breakage rates in batch grinding. An approximate solution to the batch-grinding equation will be used for the estimation of breakage rates without imposing any functional form. Experimental results for homogeneous limestone and heterogeneous copper ore under dry and wet grinding conditions are discussed. Also, the nature of breakage-rate variations due to grinding additives is discussed.

### BREAKAGE-RATE FUNCTION ESTIMATION

The exact analytical solution of the batch grinding equation (Reid, 1965) is non-linear in  $K_i$  and  $b_{ij}$  parameters. However, upon recasting Equation (1) in terms of a cumulative mass fraction retained over the bottom size interval  $i$  as:

$$\frac{dR_i(t)}{dt} = -K_i R_i(t) + \sum_{j=1}^{i-1} (K_{j+1} B_{i+1,j+1} - K_j B_{i+1,j}) R_j(t) \quad (4)$$

a simpler approximate solution can be obtained. Then the parameters are determined easily by graphical means with this solution (Kapur, 1970, 1982; Purker et al., 1986). The solution known as the G-H solution is given as:

$$\frac{1}{t} \ln \frac{R_i(t)}{R_i(0)} = G_i + H_i \frac{t}{2} \quad (5)$$

The attractive feature of this solution is that the plot of the expression on the left-hand side of Equation (5) versus  $t$ , known as the G-H plot gives a straight line, if the breakage rates are constant. In other words, just by examining the G-H plot of the experimental data, one can verify whether the grinding mill behavior follows the linear population-balance model set forth in Equations (1) and (4). Alternatively, knowing the breakage distribution functions ( $B_{i,j}$ ) and the product size distributions, the breakage rates for all sizes can be estimated easily by applying the G-H solution on successive time intervals. Details of this estimation scheme are given by Rajamani and Guo (1991). The estimation scheme has been carefully verified with both error-free computer-generated batch-grinding data (constant or time-dependent breakage rates) and with actual experimental data.

## EXPERIMENTAL WORK AND ANALYSIS

All of the experimental work was done in a 25-cm x 29-cm batch ball mill fitted with eight rectangular lifters. The operating conditions were: 50 percent ball filling with a maximum ball size of 3.7 cm and 60 percent critical speed. The mill torque did not change appreciably in the entire duration of the test in each of the experiments reported here. Therefore, breakage rates expressed in units of  $\text{time}^{-1}$  are consistent within each experiment.

### Dry Grinding Results

Limestone was used in the dry grinding tests. First, 10 x 14 mesh monosize feed was used to determine the breakage distribution function. Two batch grinding experiments were conducted with a natural size feed (Feed A) and a coarser feed (Feed B). The purpose of these tests is to check the dependence of breakage rates on feed-size distributions. Figure 1a shows the respective feed size distributions. If these particle size distributions did not influence breakage rates, the estimation done in the context of the linear batch-grinding equation should give the same set of breakage rates. The ESTIMILL (Herbst et al., 1988) computer program, based on the linear model, was used to back calculate the breakage rates, and not surprisingly as seen in Figure 1b, different breakage rates were obtained. The coarse feed shows consistently lower breakage rates compared to the natural size feed. If such a homogeneous and free-flowing dry powder should exhibit breakage rate variations, there is no doubt that the variations would be more pronounced in the wet grinding of heterogenous ore.

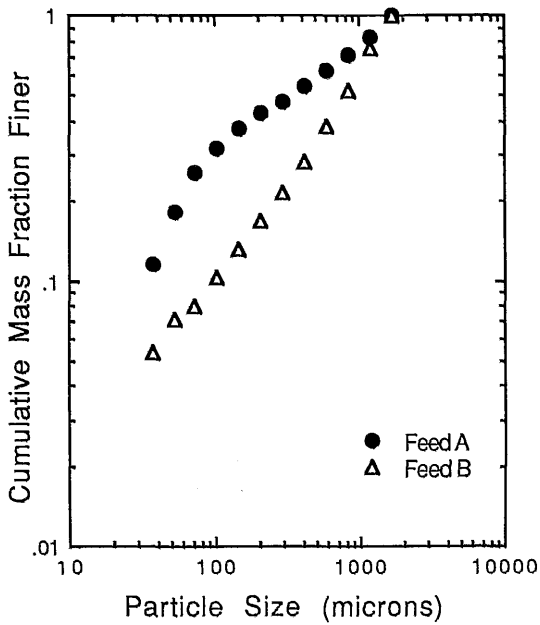


FIGURE 1a. Feed size distribution for limestone dry-grinding experiment.

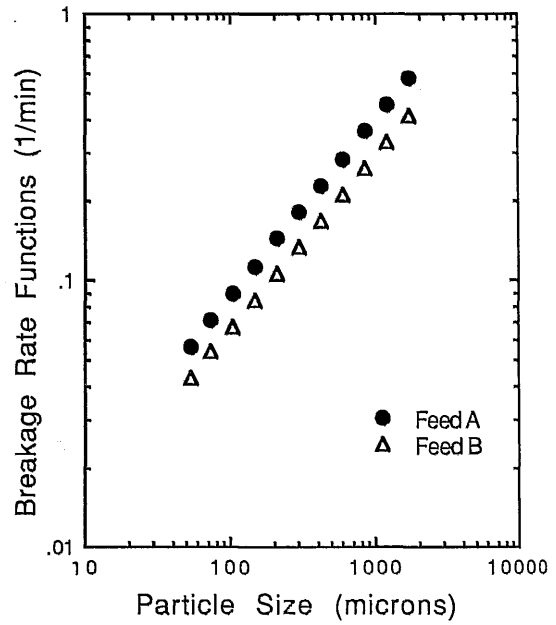


FIGURE 1b. Breakage rates estimated by a linear model for limestone dry-grinding experiments with two different feeds.

Next, the breakage-rate variations analyzed with the G-H Scheme for the natural-size feed (Feed A) are shown in Figure 2. It is noted that there is an acceleration followed by deceleration and again acceleration of the breakage rates for 10 x 14 mesh particles. Mesh sizes 14 x 20 and 20 x 28 exhibit acceleration in the first two minutes but there is little change after that. The breakage rates estimated for the coarser size feed (Feed B) are shown in Figure 3. The breakage rate for 10 x 14 mesh increases in the first three minutes and then it decreases rapidly. All other sizes show much less variation except when the rate for the top size decreases sharply. This experiment was repeated with the same feed to check the sharp decrease in the breakage rate. Again, the same results were obtained.

A number of factors determine the breakage rate of particles. Foremost, fine particles, present in the mill charge, influence the breakage rate significantly. Fine particles, being too numerous, surround the coarse particles and so the ball collision forces are transmitted via the fine particles to the coarse particle. Therefore the breakage of coarse particles depend on the number of contact points with the surrounding fines. Hence, an increase of fines in the mill increases the breakage rate of coarse sizes, but too high an increase can cushion the breakage stress transmitted and therefore, the rate of breakage can decrease. It is also possible that weaker particles in a size interval break in the first few minutes and relatively stronger particles are broken subsequently. In this situation data analysis with the linear model would show a deceleration of rates in the beginning. In any case, it is impossible to pinpoint which mechanism is active at a given time based on the ball mill grinding data alone.

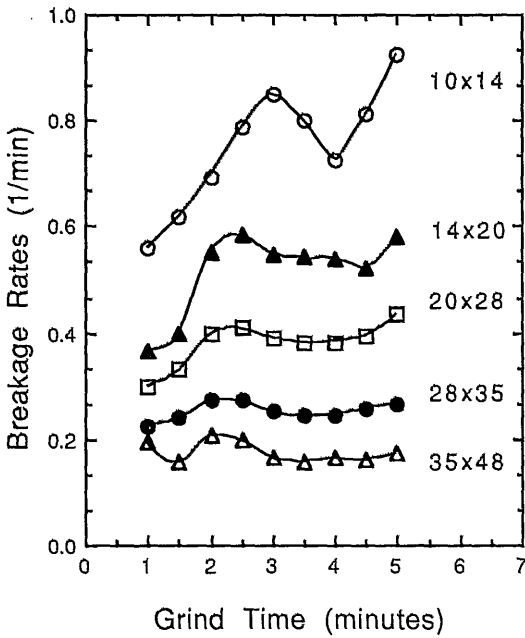


FIGURE 2. Time dependence of breakage rate for a limestone dry-grinding experiment (natural-size feed).

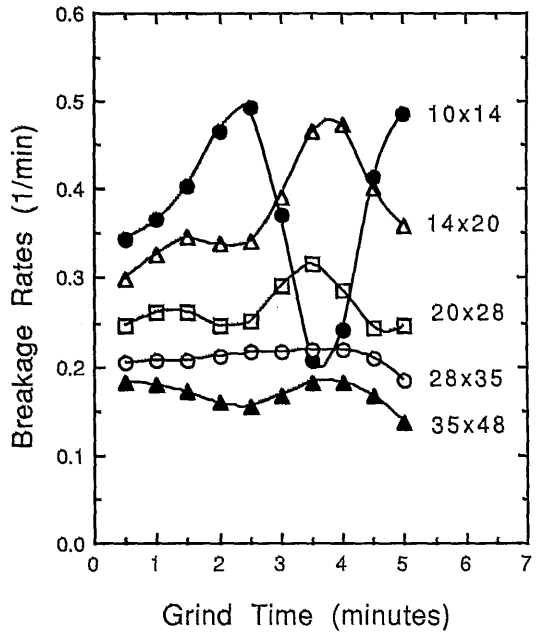


FIGURE 3. Time dependence of breakage rate for a limestone dry-grinding experiment (coarse-size feed).

Wet Grinding Results

In general, wet ball milling gives higher mill capacities than dry grinding, providing the slurry density is not so high that the mill charge becomes highly viscous. It is well-known that wet-batch milling exhibits time-dependent breakage rates. In the least, differential settling of particles in the slurry causes preferential breakage of coarser particles. Based on detailed experimental work Austin et al. (1984) and Tangsathikulchai and Austin (1989), concluded that coarser particle-breakage rates can accelerate or decelerate depending on loading conditions, slurry density and feed size distribution. Siddique and Herbst (1977) used the functional forms shown in Equations (2) and (3) and estimated the breakage rates of limestone ground in a wet batch mill. They concluded that with time breakage rates increase for coarser sizes and decrease for finer sizes. In other words, the breakage rate versus size curve pivots around a critical size. Recently Klimpel (1990) used a direct tracer technique to provide evidence for preferential breakage of coarse coal particles in wet grinding.

Wet-batch grinding experiments were done with limestone and copper ore in the same 25-cm x 29-cm mill. Different feed size distributions and slurry density conditions were used in the tests. First, monosize grinding experiments were done to determine the breakage-distribution function. In the case of copper ore, four different monosize grinding experiments were done to determine the set of non-normalizable breakage functions.

The variations in breakage rate with time is easily examined with the G-H plot. Straight lines on this plot indicate constant breakage rates provided that the same plot for the top size interval exhibits

a slope of zero. Such a G-H plot for wet grinding (60 percent solids) of limestone is shown in Figure 4. For comparison, a set of simulated data, for which the breakage rate was held constant, is also shown. In fact the marked deviation of the experimental data from a straight line confirms that the rates are changing with time.

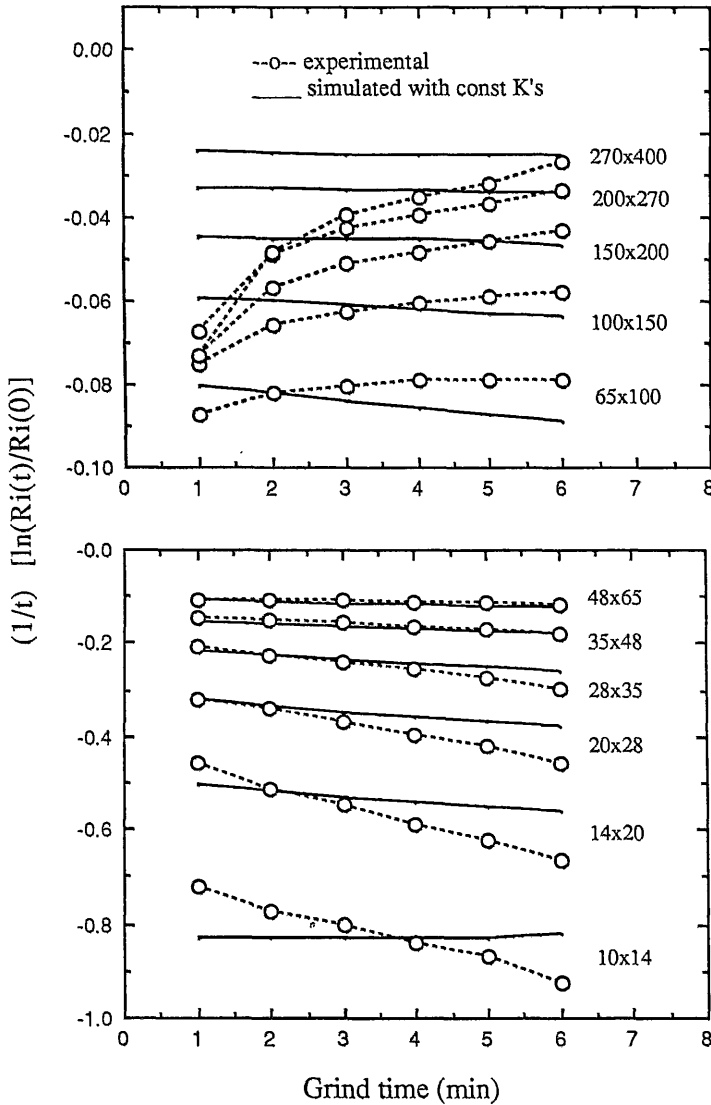


FIGURE 4. G-H plot for limestone wet-grinding experiment at 60 percent solids.

The time dependence of the breakage rate determined from the G-H plot for copper ore grinding (natural size feed and 60 percent solids) is shown in Figure 5. Consistent with the argument that coarser particles settle faster, and hence are broken preferentially, the breakage rate of 10 x 14 mesh size increases at first and stays at the higher value. However the breakage rate for all other sizes



decreases first, then increases and finally reaches a steady value. The same trend was seen for all smaller size intervals with the exception that the variations are much less in magnitude. In contrast, the breakage rates for a coarser feed copper ore ground at 60 percent solids shows the opposite effect. As shown in Figure 6, the 10 x 14 mesh particles show a nearly similar trend as before, but other size intervals exhibit a continual acceleration in rates.

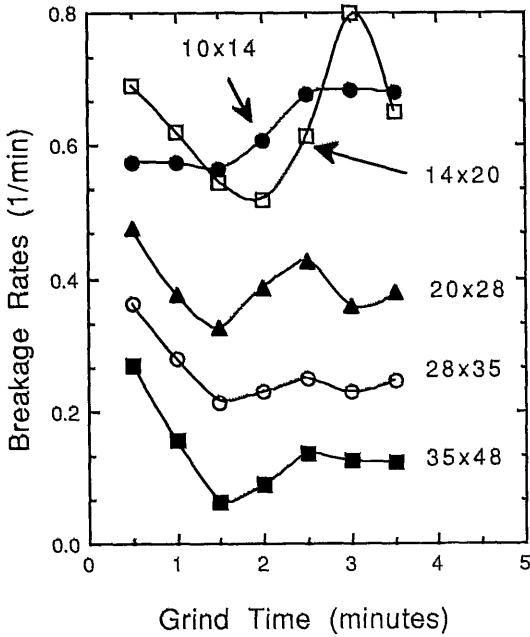


FIGURE 5. Time dependence of breakage rates for copper ore wet-grinding experiment at 60 percent solids (natural-size feed).

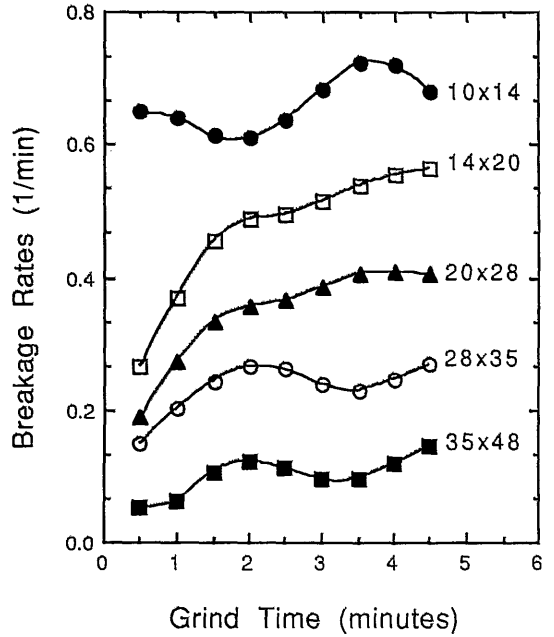


FIGURE 6. Time dependence of breakage rates for copper ore wet-grinding experiment at 60 percent solids (coarse-size feed).

At higher slurry densities the trends are completely different. Figures 7 and 8 show the breakage rates for 65 percent solid and 75 percent solid grinding tests, respectively. In both tests the trends are the same—a decrease in rate followed by an increase. On the contrary, the trends are completely different from that shown for 60 percent solid tests. Thus the breakage rates are dependent on mill environment. The motion of ball charge imposes a constant compressive force regime on the intervening layers of particles. How the particles flow through the ball charge depends on the size distribution and slurry viscosity. Consequently, it is impossible to deduce from first principles the breakage rates from particle size distribution alone.

Grinding-Aid Experiments

Numerous laboratory and industrial grinding studies have shown that the process of size reduction can be significantly influenced by chemicals added to the slurry being ground (Rule et al., 1985; Somasundaran and Lin, 1972; Klimpel and Manfrey, 1978; El-Shall and Somasundaran, 1984; Fuerstenau et al., 1985).

Recently Klimpel and co-workers (1982) have established, in a series of papers, that a patented chemical additive known as XFS-4272 is effective in increasing mill throughput at constant fineness of grind or in producing a finer product at constant mill throughput. The chemical additive XFS 4272 is a low-molecular weight water-soluble anionic polymer, and is representative of a family of

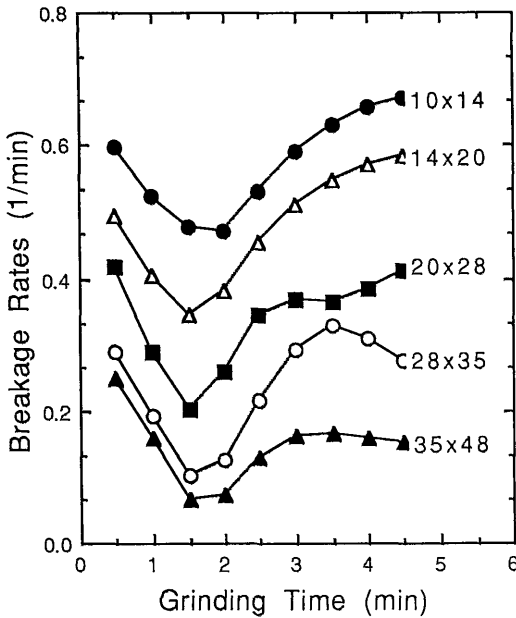


FIGURE 7. Time dependence of breakage rates for copper ore wet-grinding experiment at 65 percent solids (natural-size feed).

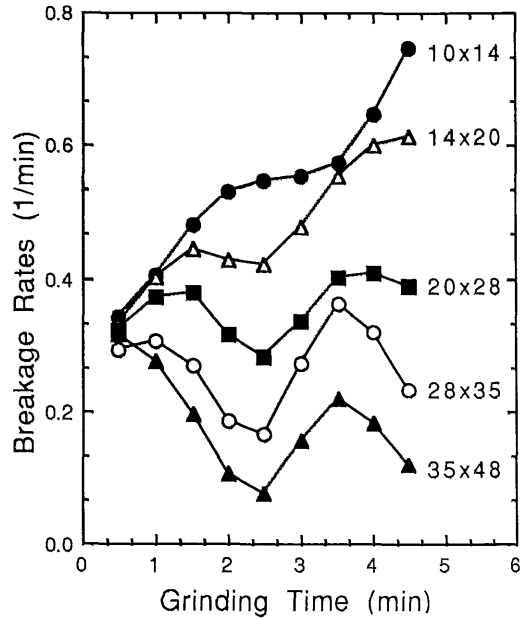


FIGURE 8. Time dependence of breakage rate for copper ore wet-grinding experiment at 75 percent solids (natural-size feed).

compounds that operate as a selective dispersant in ore grinding systems. Fuerstenau et al. (1984) did a detailed study of the effect of grinding additives on mill capacity, power draft and fineness of the product. However, the effect on the breakage rates of different size intervals has not been studied.

The use of additive XFS 4272 is recommended at high-percent solids. Experiments were done with limestone at 80 percent solids in the presence and absence of the additive. The additive dosage was 0.03 weight percent on the basis of dry solids. Again monosize (10 x 14 mesh) grinding tests were done to determine the breakage distribution function. Then natural-size feed tests were done to estimate the time dependence of breakage rates.

Once again we revoke the argument that the ball charge motion imposes a constant force regime on particles but only the flow of particles through the ball charge determines the breakage rate. Thus, at 80 percent solids without a grinding aid, the slurry is so thick that it behaves like separate lumps. In fact the entire particle may not be wetted at all at such a low addition of water. Hence, it is difficult for this material to flow through the ball mass. As seen in Figure 9, the breakage rate variations are

erratic. A definite pattern cannot be deduced at all. However, the addition of a grinding additive makes the slurry very fluid. In fact the sample flows out of the mill freely when the mill was opened. Hence the breakage rate of all sizes, shown in Figure 10, shows a deceleration followed by an acceleration. A few other tests, not reported here, point to the same free-flow phenomenon.

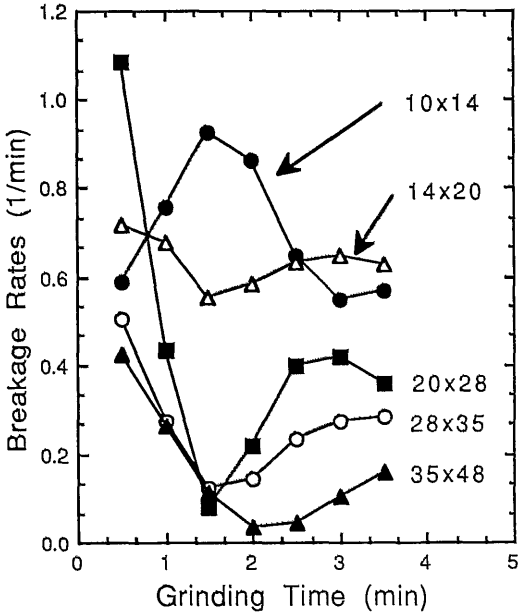


FIGURE 9. Time dependence of breakage rates for limestone wet-grinding experiments at 80 percent solids (natural-size feed).

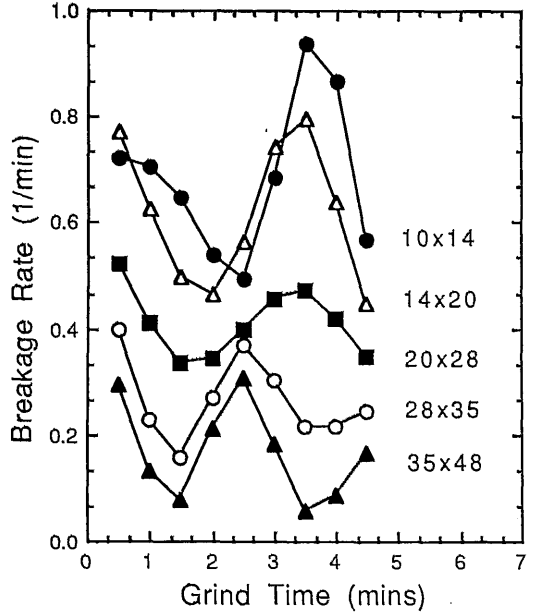


FIGURE 10. Time dependence of breakage rates for limestone wet-grinding experiment at 80 percent solids with grinding additive XFS 4272 (natural-size feed).

CONCLUSION

The variation in breakage rates is very useful in both mill scale-up and closed-circuit simulation. In scale-up, one should be careful about the breakage rates estimated in the laboratory mill—the same rates, even if they are energy normalized, may not apply in the large mill if the latter processes a different feed size distribution. In closed-circuit simulation, a single set of breakage rates may not apply in the calculations. As the ore advances through the mill, the size distribution becomes finer and as a result breakage rates change. Therefore, a position-dependent breakage-rate scheme must be used in the simulation calculations.

Here, the variations in breakage rates are demonstrated with experimental data. Although a general trend cannot be seen, the breakage rate of coarse size increases but all other sizes exhibit a deceleration followed by an acceleration of rates. These trends depend on the homogeneity of the ore as well as the feed size distribution. The addition of grinding additives, especially at very high percent solids, causes the slurry to flow freely through the ball charge, and hence, all size fractions exhibit the same trend.

A number of causes and reasons can be advanced to explain this phenomenon. However, it is difficult to separate the effect due to particle size distribution from the rest, because the particle size distribution and breakage rate are so intimately related.

Even though the breakage rates are changing, the size-discretized population-balance model is still valid. The model uses constant parameters, hence, it is valid for short intervals of time during which the breakage rate can be presumed constant.

#### ACKNOWLEDGEMENTS

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