

# Modelling and simulation of large diameter autogeneous and semi-autogeneous mills

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## Abstract

In recent years there has been an increasing trend within Australia to instal large diameter (> 9.0 m) AG/SAG mills. A number of these mills have been extensively surveyed by the JKMRC under a wide range of operating conditions. Using the JKMRC's AG/SAG mill model, the results from these surveys together with those from a large data base of pilot scale mills were analysed in terms of their breakage rate distributions. The variations in these distributions were found to be similar at both the pilot scale and in mills up to 9.6 m in diameter and were related to operating conditions such as mill speed, ball charge volume, ball size and ore feed size. The data indicated that the effect of increasing speed, ball charge or ball size in SAG mills was to increase the degree of coarse particle breakage, often with an associated reduction in the degree of fine particle breakage. The effect of increasing the feed size was found to be dependent upon the mode of mill operation ie AG or SAG, with AG mill throughput increasing as the feed  $F_{80}$  was increased. The opposite was true for SAG mills providing the ball charge was in excess of about 5% by volume.

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## 1. Introduction

The continued popularity of autogeneous (AG) and semi-autogeneous (SAG) mills has resulted in increasing demands for techniques to predict the performance of these machines under a wide range of conditions. The need for such techniques is apparent at all stages of the development of a comminution circuit, from the conceptual design stage to scale-up from pilot test work and finally optimisation of the full scale circuit.

Mathematical modelling and simulation can play a crucial role at each of these stages. Over the last 20 years, the Julius Kruttschnitt Mineral Research Centre (JKMRC) has been developing mathematical models of AG and SAG mills, which when incorporated into their process simulator, JKSImMet, have been successfully used in a variety of applications. To be useful these models need to have been tested using industrial data.

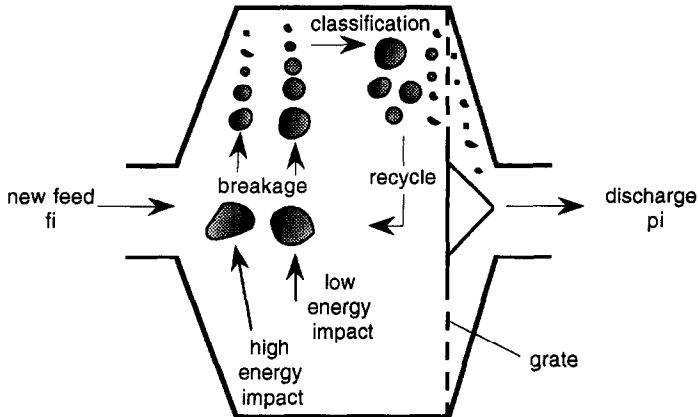


Fig. 1. Schematic of AG/SAG mill operation.

To this end the JKMRC has accumulated over 150 pilot and full scale AG/SAG mill data sets with which to develop, test and refine its mathematical models.

This paper presents the variations in model performance observed in the JKMRC's pilot mill data base together with those of a number of large diameter units. The variations are related to changes in operating conditions and are explained by the behaviour of the grinding charge and the various breakage mechanisms that occur within AG/SAG mills. The work forms part of a much larger effort of developing robust models and scale-up procedures that can be reliably used over the complete range of design and operating conditions found in the minerals processing industry.

## 2. Model structure

The following section presents a summary of the main components of the current JKMRC AG/SAG mill model. A full description of the model can be found elsewhere (Leung et al., 1987; Leung, 1987).

The size reduction processes inside an AG/SAG mill can be represented in a simplified manner as shown in Fig. 1. Feed enters the mill and is subjected to breakage from collision with other particles and/or the mill shell. The products from breakage either exit via the grate or remain to undergo further collisions.

This process has essentially 3 components, namely

- collision frequency (breakage rate),
- description of ore size distribution after collision (appearance function),
- description of particle transport out of the mill (discharge rate).

At steady state these components are combined in the perfect mixing model (Whiten, 1974) as follows:

$$f_i - p_i + \sum_{j=1}^{i-1} r_j s_j a_{ij} - (1 - a_{ii}) r_i s_i = 0 \quad (1)$$

and

$$p_i = d_i s_i \quad (2)$$

where  $f_i$  = feed rate of particles of size  $i$  (tonnes/hr),  $p_i$  = product rate of particles of size  $i$  (tonnes/hr),  $r_i$  = breakage rate of particles of size  $i$  (1/hr),  $s_i$  = mill contents of particles of size  $i$  (tonnes),  $d_i$  = discharge rate of particles of size  $i$  (1/hr), and  $a_{ij}$  = appearance or breakage distribution function.

### 2.1. Appearance function

The appearance or breakage distribution function is a description of how an ore particle breaks when energy is imparted to it. In AG/SAG milling both crushing (high energy) and abrasion/chipping (low energy) size reduction are believed to occur. Laboratory techniques have been developed at the JKMRM which are used to characterise an ore with respect to both these forms of comminution. In the case of high energy breakage a twin pendulum device is used (Narayanan and Whiten, 1988), whilst for low energy breakage a tumbling test is used (Leung, 1987).

### 2.2. Discharge rate

The discharge rate is considered to be the product of two mechanisms:

1. transport to the grate, and
2. classification by the grate.

It can be modelled using the following equation:

$$d_i = d c_i \quad (3)$$

where  $d_i$  = discharge rate of size  $i$ ,  $c_i$  = classification function value for size  $i$ , and  $d$  = maximum discharge rate.

The maximum discharge rate ( $d$ ) is determined iteratively within the model using an empirical relationship which relates the slurry hold-up to the volumetric flowrate of slurry which is discharged from the mill. The classification function ( $c_i$ ) at the grate is based on a simple classifier model as shown in Fig. 2.

The value of  $X_g$  is the effective grate aperture, whilst  $X_m$  is the maximum particle size which behaves "like water", i.e. is not subject to classification.

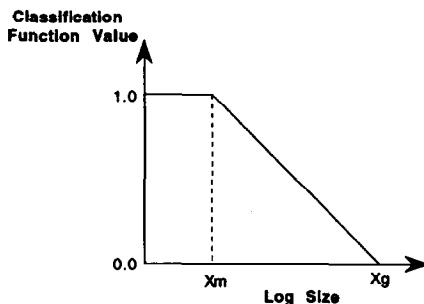


Fig. 2. Grate classification function.

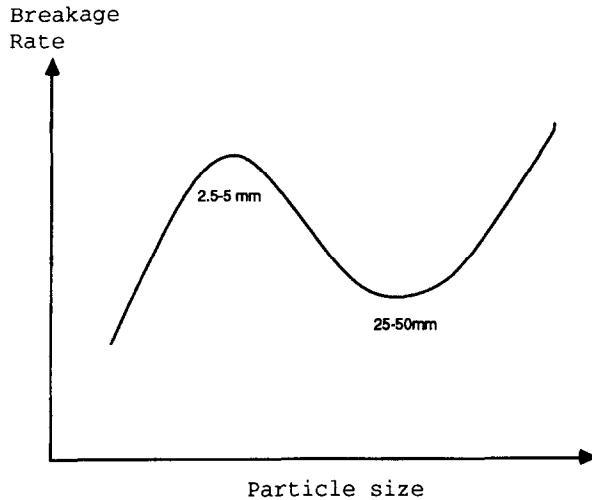


Fig. 3. Example of an AG/SAG mill breakage rate function.

### 2.3. Breakage rate

Given a feed and product size distribution from an AG/SAG mill and an appearance function of the ore being treated, the breakage rate distribution can be back-calculated using Eqs. 1 and 2. The distribution is represented using cubic splines (Ahlberg et al., 1967). Five spline knots, typically situated at the following sizes, are used to represent the distribution: 0.25, 4, 16, 44, 128 mm.

The breakage rate is related to particle size and typically takes the form shown in Fig. 3. The shape of the breakage rate distribution is largely governed by the charge particle size distribution and the frequency with which the charge is turned over. It will hence be dependent on the ball charge, feed size distribution and mill speed.

Fig. 3 shows the characteristic breakage rate curve usually observed in AG/SAG mills. Of particular relevance are the maximum and minimum points on the curve. These points are believed to indicate the limits, with respect to size, of the various breakage mechanisms that occur within the mill. By studying how the shape of the breakage rate curve changes the effect of process variables can be evaluated and explained.

### 3. AG/SAG mill data base

The JKMRC has accumulated data from a wide range of industrial mills as well as substantial numbers of pilot scale surveys using standard (6' × 2') mills. The pilot mill data base now numbers over 60 surveys using a range of feed sizes, ball charge volumes and ore types.

The JKMRC data base of full scale AG/SAG mills numbers well over 100 data sets. Recently it has been extended to cover mills with diameters up to 9.6 m which were operated under a range of autogenous and semi-autogenous conditions. In addition data on large diameter mills running at different speeds were also collected.

Table 1  
Summary of mill operating conditions

Operation	Mill dia × length (m)	Power (MW)	New feed		Mill operation		
			$F_{80}$ (mm)	Feed (tph)	AG/SAG	Ball size (mm)	% critical speed
Wagerup	7.93 × 3.64	2.45–2.63	90–95	196–343	SAG	92	55.0–70.0
OK Tedi	9.60 × 4.27	6.7–7.9	26–100	1300–2100	SAG	94; 120	74.0
Leinster	9.40 × 5.65	2.2–3.4	131–187	173–242	AG	–	76.5

These more recent data sets have been particularly interesting in that they represent installations at the extreme end of the design and operating spectra. When compared with the pilot mill data they provide a valuable contrast with which to develop and test scale-up procedures as well as assisting with our understanding of AG/SAG milling.

In this paper some of the results from modelling 3 large diameter mills will be described. These are Alcoa's Wagerup SAG mill, Ok Tedi Mining's SAG mill and Western Mining's Leinster AG mill. Table 1 lists a summary of the operating conditions for each mill.

#### 4. Performance trends

##### 4.1. Effect of mill speed

The effect of mill speed was investigated at Alcoa's Wagerup mill. Three surveys were conducted at speeds ranging from 55% to 70% of critical. Fig. 4 illustrates the breakage rate curves obtained from fitting the SAG mill model to the survey data.

From Fig. 4 a clear systematic change in the shape of the breakage rate distribution is

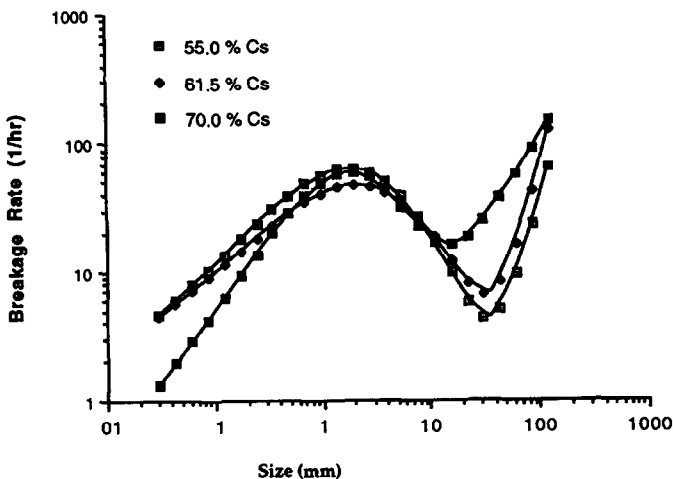


Fig. 4. Effect of mill speed on breakage rates.

apparent. As the mill speed increases, the rate of breakage of coarser particles in the range 10–100 mm increases. At the same time the rate of breakage of finer particles reduces.

The maximum occurring at approximately 2.0 mm is believed to mark the effective limit for impact breakage. Below this size attrition breakage is thought to predominate and is associated with a cascading motion of the grinding media. It can be clearly seen from Fig. 4 that this type of breakage is enhanced at the lower speeds and in practice gives rise to a finer product size. It is thought to be further enhanced by the presence of increased quantities of rock grinding media in the size range 25–75 mm. These are a result of the lower breakage rates of this size of material which occur at lower speeds.

At the coarse end of the size distribution impact and abrasion breakage predominate and are associated with the cataracting motion of the grinding media. As a result the higher mill speeds are seen to produce higher breakage rates at these sizes. In operational terms higher breakage rates at coarser particle sizes give rise to higher throughputs. This effect is reflected in the performance of the Wagerup mill, the throughput of which increased by 150% as the speed increased from 50% to 70% of critical.

The predominance of attrition breakage at the lower speed and impact breakage at the higher speed is a direct reflection of the changes in mill charge motion that are observed to occur as the mill speed changes (Morrell, 1993). It can be concluded that for the range of speeds studied higher mill speeds tend to provide a higher mill throughput though at the expense of a coarser mill product. It is not expected that this trend would continue indefinitely as the mill speed is further increased. As centrifuging speeds are approached a point will be reached where the breakage rates of the coarser particles are expected to reduce.

#### 4.2. *Effect of ball size*

The effect of ball size was investigated at the Ok Tedi Mining operation. A total of eleven surveys were conducted in two separate campaigns. Between campaigns the new ball size was increased from 94 to 120 mm. Several months elapsed between the the time of the ball size change and the second campaign, thus allowing the ball charge to reach equilibrium. The average breakage rates from each of the survey periods are shown in Fig. 5. The volumetric ball charge, feed size distribution and ore hardness were similar for both.

Fig. 5 again shows the characteristic cubic form. The two curves exhibit a marked difference, however, particularly above and below about 75–80 mm.

The increase in breakage rates at the coarser sizes which is evident from the larger ball size is explained by the additional kinetic energy that they provide for breakage. The number of larger balls in a given volume, however, is less than that with smaller diameter balls. Charging with larger diameter balls therefore results in a higher kinetic energy but less frequent breakage impacts. The net result is that as the ore particle size decreases the effect of increased kinetic energy that larger balls provide becomes less pronounced and becomes overshadowed by the effect of a reduction in ball numbers. This is particularly noticeable in the so-called critical size range of 25–50 mm where the smaller ball size provides a much higher breakage rate.

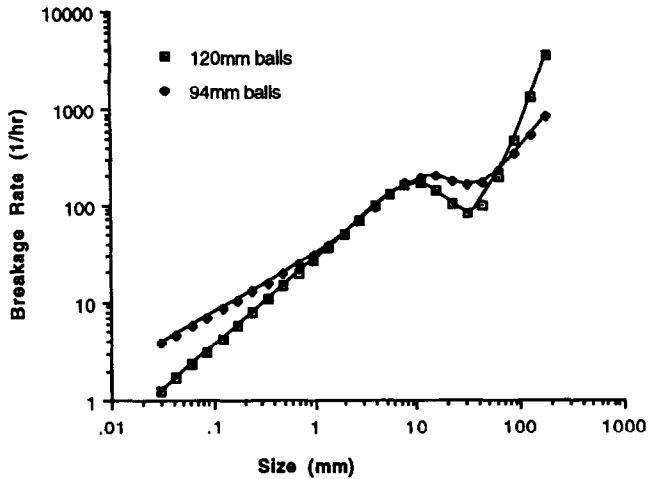


Fig. 5. Effect of ball size on breakage rates.

On the basis of the arguments provided in the previous section it might be expected that the reduction of critical size material that would result when using the smaller ball size would result in a reduction in the breakage rates at the fine end of the particle size range. It should be noted, however, that the Ok Tedi mills run with a relatively high ball charge (up to 18% by volume). The rock contribution to the grinding media is therefore minimal and hence the breakage rate distribution is dominated by the size distribution of the ball charge. The increased numbers (and their correspondingly higher surface area) that the 94 mm balls provide are hence thought to explain the enhanced breakage rates at finer sizes.

#### 4.3. Effect of feed size

The surveys at Leinster Nickel Operations provided an opportunity for investigating feed size effects on a large diameter fully autogenous mill. Five surveys in autogenous mode were conducted during which the feed size  $F_{80}$  ranged from 135 mm to 187 mm. The breakage rate trends from these data are illustrated in Fig. 6.

In fully autogenous mills the grinding media is provided exclusively by the feed ore. Thus any change in the feed ore size distribution will directly affect the grinding media size distribution and hence the breakage rates. This contrasts with ball mills whose grinding media charge is largely independent of the feed ore and whose breakage rates are therefore relatively insensitive to feed ore size distribution.

It is clear from Fig. 6 that as the feed size  $F_{80}$  increases the breakage rates in the +5 mm size range also increase. The pattern in the -5 mm size fraction, however, is not clear.

Ideally the feed size distribution to an AG mill should provide large enough rocks to generate sufficiently high kinetic energy to break smaller rocks. At the same time sufficient numbers of larger rocks need to be provided to ensure that a high enough

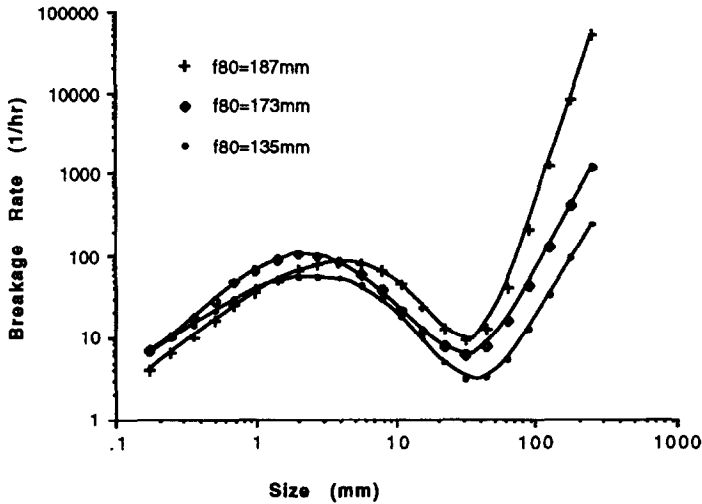


Fig. 6. Effect of  $F_{80}$  on breakage rates for the Leinster AG mill.

frequency of breakage is maintained. Clearly the number of rocks and the feed size distribution are interrelated and a balance must be maintained between the two factors to achieve optimum performance.

In the Leinster case, where the mill was operated in AG mode, the trend was for higher breakage rates, and hence higher throughput, to result from a coarser feed.

However in some SAG milling installations (Morrell, 1992) the reverse is seen. Analysis of the pilot mill data base indicates the same phenomenon. The breakage rate distribution variations observed in the pilot mill data base were empirically related to operating conditions. This was done by regressing variables such as ball charge volume and  $F_{80}$  to the breakage rate values at each of the 5 spline knots. Using these relationships Figs. 7 and 8 show the predictions of the changes in the breakage rate curve resulting from increasing the  $F_{80}$  for an AG and a SAG mill running with a 10% ball charge.

The similarity in the pattern for the pilot AG mill data and the Leinster mill data is apparent is an increase in  $F_{80}$  causes an increase in the breakage rates in the coarser size fractions. In the case of the pilot SAG mill data, however, the trend is for the coarse breakage rates to decrease as the  $F_{80}$  increases. This can be explained by the dominant role that a relatively large ball charge has in dictating the nature of the grinding media charge. As the volume of ball grinding media increases the contribution of rock grinding media will lessen. The coarser feed rocks will hence provide less of a role in providing grinding media and will instead simply provide a rock burden which requires to be ground. By reducing the  $F_{80}$  in these circumstances the grinding burden will therefore be lessened.

This latter situation is reflected in the performance of ball mills where a decrease in the feed size will invariably result in an increase in throughput. If it is considered that a

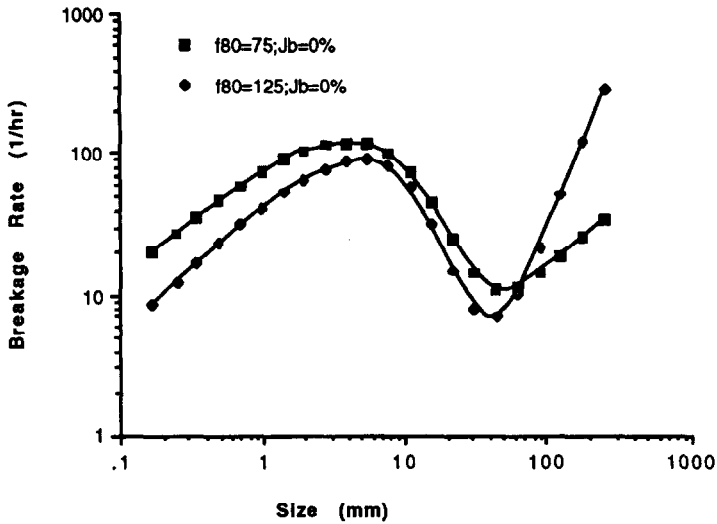


Fig. 7. Effect of  $F_{80}$  on breakage rates for AG mill operation — pilot mill data base.

ball mill is a limiting case of a SAG mill, it is to be expected that as the ball charge in a SAG mill increases the effect of changing the feed  $F_{80}$  will tend to that experienced with a ball mill. It is clear from this result that there should exist a specific ball charge at

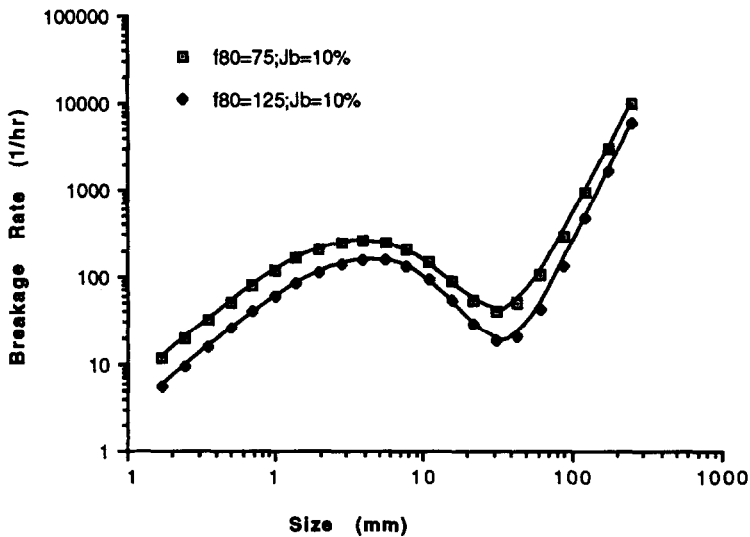


Fig. 8. Effect of  $F_{80}$  on breakage rates for SAG mill operation — pilot mill data base.

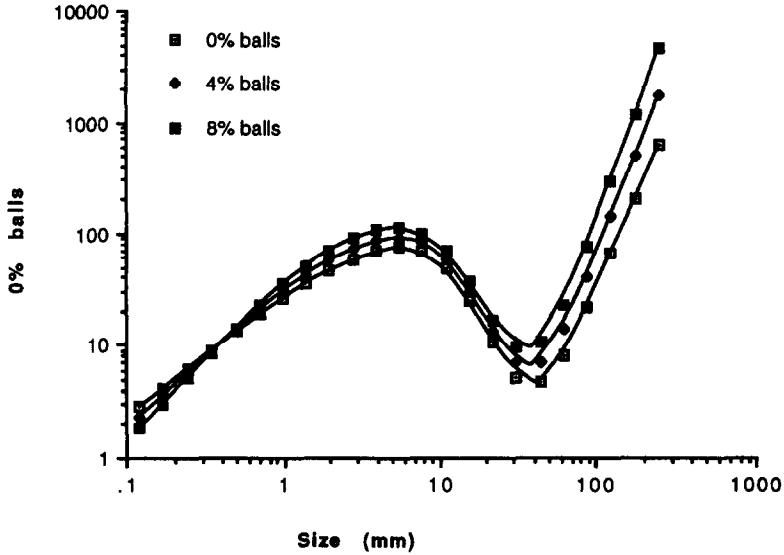


Fig. 9. Effect of ball charge volume on breakage rates for AG mill operation — pilot mill data base.

which changing the  $F_{80}$  will have a negligible effect, as the mill will respond neither as a fully autogenous machine nor as a well loaded SAG mill. The pilot mill data suggest that this point occurs at a ball charge of about 5% by volume.

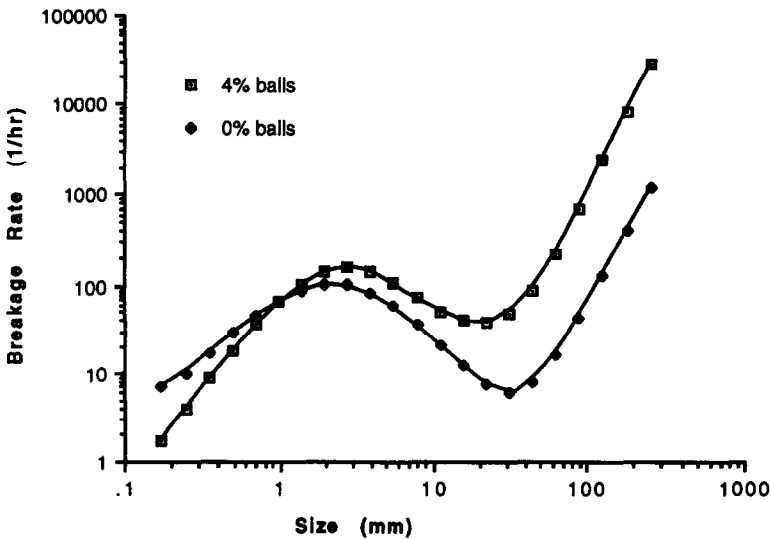


Fig. 10. Effect of ball charge volume on breakage rates for AG mill operation — Leinster mill.

## 5. Effect of ball charge volume

One of the principal operating variables in the pilot mill data base is the ball charge volume, with values varying in the range 0–10%. Analysis of these data has provided the relationship illustrated in Fig. 9. In addition a comparison of the results of running the Leister AG mill with 4% of balls is shown in Fig. 10.

The effect of adding balls to both the pilot and full scale mill is seen to be an increase in the rates over most of the size range, which in practice results in increased mill throughput. Below about 1 mm, however, the effect becomes less pronounced and eventually reverses i.e. the higher the ball charge is the lower the rate. This results in the observed coarser product size distribution. This latter effect is consistent with the argument put forward earlier that the reduction in the 25–75 mm rock charge that results from higher ball charges is detrimental to the finer grinding performance of the mill. It should be noted that as the ball charge reaches the levels used at Ok Tedi Mining (up to 18%), the reduction in breakage rates at the fine end of the size distribution may not occur due to the dominance of the balls in the grinding charge.

## 6. Conclusions

The JKMRG AG/SAG mill model has been fitted to a number of pilot and full scale data sets. Using the resultant breakage rate distributions the effects of a number of operational variables were investigated. Analysis of the changes in the breakage rate distributions indicated that the effect of increasing speed, ball charge or increasing ball size in SAG mills is to increase the degree of coarse breakage, often with an associated reduction in the degree of fine particle breakage. These effects were found to be similar at both the pilot scale and in mills up to 9.6 m in diameter. The effect of increasing the feed size was found to be dependent upon the mode of mill operation ie AG or SAG. The tendency was for the throughput of AG mills to increase as the feed  $F_{80}$  was increased, whilst the opposite was true for SAG mills with ball charges in excess of about 5% by volume. SAG mills with ball charges < 5% exhibited an increasingly weaker AG mill type response as the ball charge approached 5%.

## Acknowledgements

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