Modelling and Scale-up of High Pressure Grinding Rolls

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INTRODUCTION

The high pressure grinding rolls (HPGR) is a relatively new technology which offers potential benefits in energy savings, circuit simplicity and improved product characteristics in mineral processing applications. To date the modelling of HPGR performance has been largely restricted to describing size distribution curves from laboratory machines using the self-similarity principle (Kapur [1]; Fuerstenau *et al*. [2]). For plant designers and operators interested in how HPGR technology can be incorporated in comminution circuits, such descriptions are of limited value. What is required is a performance model which is able to describe the throughput, size reduction and power draw of an HPGR given its dimensions, speed and a representative ore sample. A new HPGR model has been developed, which meets these objectives.

In this paper a fundamental model describing the HPGR throughput and a phenomenological model for the size reduction and power draw are given. Using laboratory test data the models are calibrated, after which they are able to scale-up to pilot and industrial size units. Details of the scale-up procedure are illustrated and examples of the scale-up are included.

MODELLING OF HPGR THROUGHPUT

Rolls throughput can be theoretically expressed as follows:

$$Q \quad = \quad 3600 \, U \, L \, x_g \, \rho_g \qquad\qquad (1)$$

where
|		
Q	=	mass throughput (tph)
U	=	circumferential velocity of the rolls (m/s)
L	=	length of rolls (m)
x_g	=	working gap (m)
ρ_g	=	flake density (t/m^3)

However equation 1 assumes that there is no slip between the rolls surface and the ore. Figure 1 shows the deviation between the measured throughput and the calculated one using equation 1 for a diamondiferous ore treated through a 100 mm Polysius laboratory scale HPGR. It is clear that the equation progressively over-predicts the HPGR throughput as rolls speed is increased, indicating that slip at the rolls face is occurring.

To correct for the slip effect it is considered that for a specific feed the slip is a function of the rolls speed and the dimensionless working gap which is defined as

x_g /D, where D is the rolls diameter. Figure 2 plots the correction factor c (c = $\dfrac{Q_m}{Q_c}$, where Q_m is the measured throughput and Q_c is that calculated by equation 1) versus the product of the speed and the dimensionless gap (U*$\dfrac{x_g}{D}$) diamondiferous ore. A linear regression of the plot was obtained and equation 1 was accordingly modified as follows:

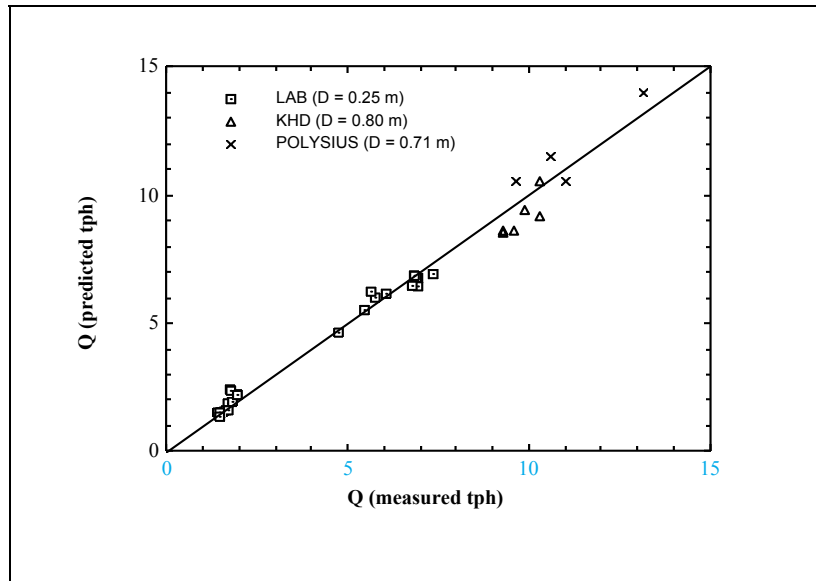$$Q \qquad = \qquad 3600\ U\ L\ x_g\ \rho_g\ c \qquad\qquad\qquad (2)$$

where c is the correction factor determined from Figure 2.
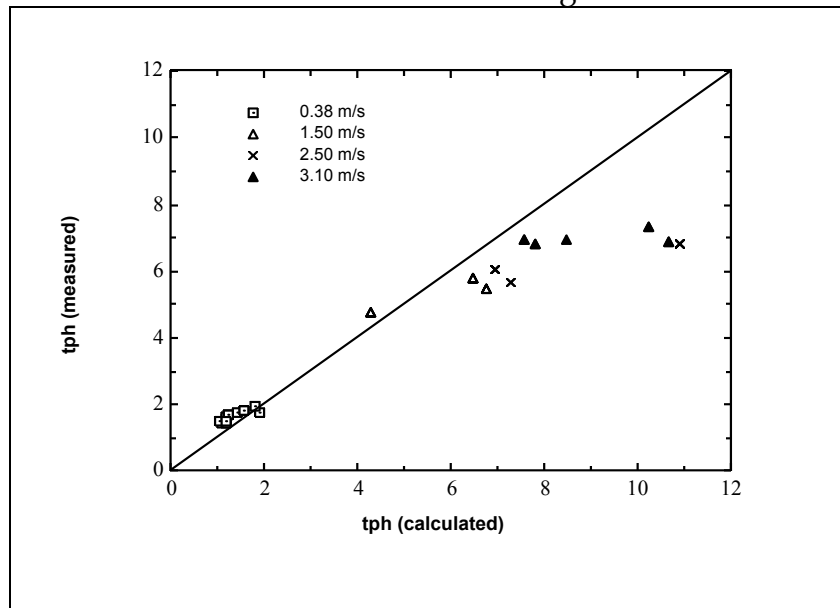
Figure 1: Deviation of the Throughput Calculated from Equation 1 for Diamondiferous Ore Treated through a Laboratory HPGR at Various Speeds
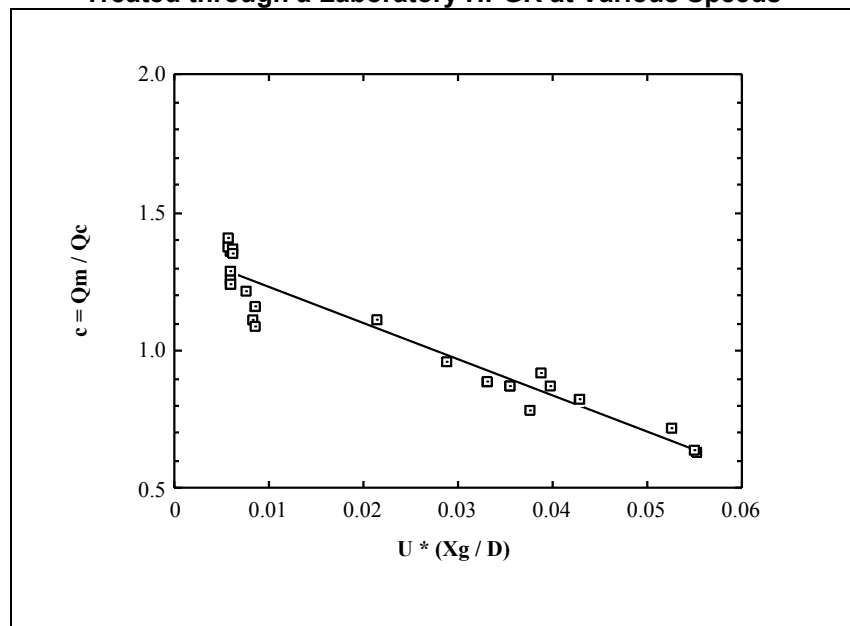
Figure 2: Throughput Correction Factor for Diamondiferous Ore Treated through a Laboratory Scale HPGR

Figure 3: Prediction of Throughput for Two Pilot Scale HPGRs from Equation 2 with Model Parameter c Calibrated Using Laboratory Scale HPGR data

Using equation 2 with c determined from Figure 2, the throughput of a laboratory scale HPGR (D = 0.25 m) and two pilot scale HPGRs (KHD, D = 0.8 m; Krupp Polysius, D = 0.71 m) was predicted. A comparison between the calculated and the measured throughputs is given in Figure 3. The rolls speeds varied from 0.29 m/s to 3.1 m/s, rolls length from 0.1 m to 0.21 m, rolls diameters from 0.25 m to 0.80 m, and working gaps from 3 mm to 23 mm. The throughput model prediction is seen to be good.

## MODELLING OF SIZE REDUCTION

Model structure

Underlying the structure of the size reduction model are three assumptions about the inherent breakage mechanisms that occur in HPGRs (Morrell *et al*,[3]),viz.

i. If particles are bigger than a certain critical size they will be broken directly by the roll faces as would occur in a conventional rolls crusher. The breakage in this zone can be considered as analogous to a 'pre-crusher', the products from which may subsequently pass to a region where a bed under compression has formed (Figure 4). The boundary between the pre-crusher and bed compression regions is defined by a critical gap (x_c).
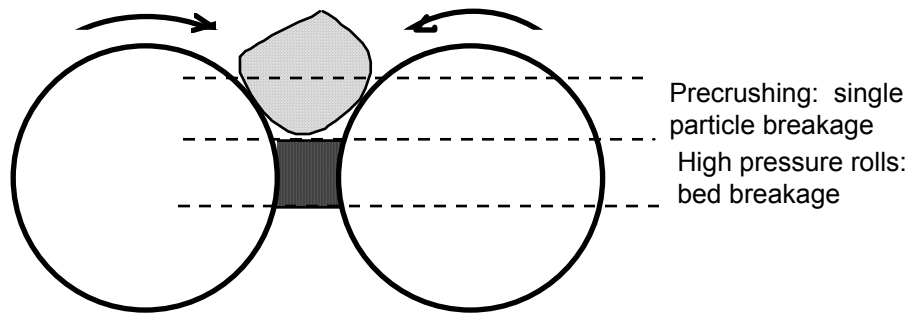
Figure 4: Schematic of Size Reduction Zones

ii. Breakage at the edge of the rolls is different to that at the centre and conforms more to that experienced in a conventional rolls crusher (Figure 5). This is the so-called 'edge effect' which defines the proportion of relatively coarse particles usually seen in HPGR products. Its existence has been explained by the pressure gradient across the width of the roll and the static confinement of the ore at the edges of the rolls which the cheek-plates provide.
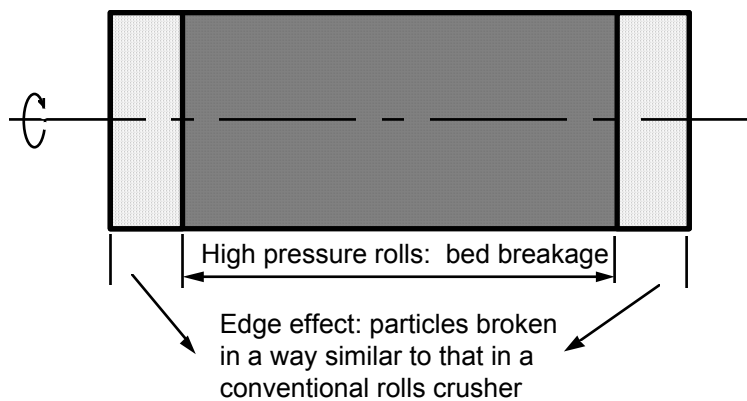
Figure 5: Schematic of the Edge Effect Zone

iii. At some point away from the edges of the rolls, and extending upwards from the area of minimum gap (x_g) to an area bounded by the critical gap (x_c), is a compression zone where breakage conditions are those experienced in a compressed packed bed.

From a modelling viewpoint these assumptions can be accommodated in the conceptual structure shown in Figure 6. Feed firstly passes to the 'pre-crusher'. Particles greater in diameter than the critical gap (x_c) are crushed below this size in a single particle breakage mode. The products from this breakage then combine with feed particles which are smaller than x_c. A proportion is then diverted to another single particle crusher stage where all particles greater than the minimum gap (x_g) are crushed to below this size. The remainder are diverted to a compression stage where all particles greater than x_g are crushed below this size but in a compressed bed mode. All products then combine to produce the final HPGR product.
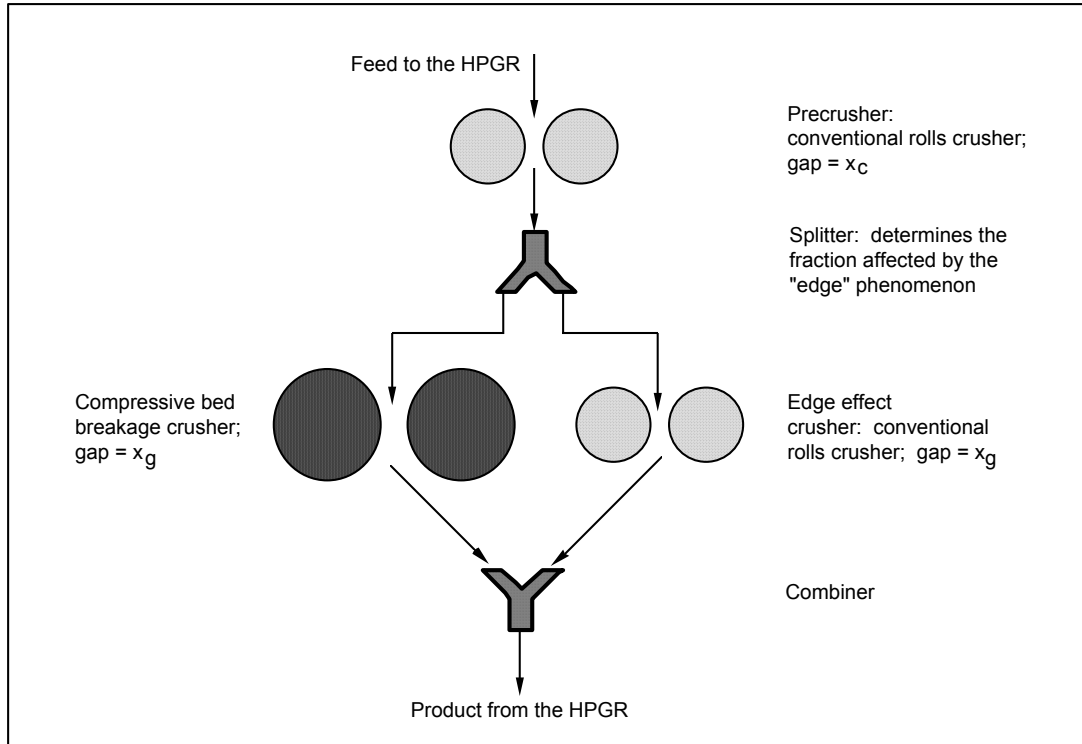
Figure 6: Schematic Structure of the HPGR Model

Using the model

The model contains three breakage processes and one splitting process between the edge and compressed bed zones. For the breakage processes a conventional crushing model (Andersen [4]; Whiten [5]) is employed to describe the size reduction.

For the pre-crushing process, breakage of particles is assumed to be in single particle mode in which rocks are nipped directly by the faces of the rolls, similar to a conventional rolls crusher. The parameters used to describe crushing in this zone are determined from tests conducted in a conventional (non-HPGR) laboratory rolls crusher and single particle breakage tests. The effective gap of the crusher is represented as follows:

$$x_c = 0.5 \left\{ (D + x_g) - \left[(D + x_g)^2 - \frac{4 \rho_g D x_g}{\rho_c} \right]^{0.5} \right\} \tag{3}$$

where x_g is the working gap, ρ_c is bulk density of feed and ρ_g is flake density.

In the edge zones rock breakage is also assumed to take place in single particle mode. The parameters used to describe crushing in this zone are the same as that for pre-crushing, except that the effective gap is set to that of the working gap (x_g).

In the compressed bed crushing zone size reduction is assumed to be similar to that experienced by a bed of particles in a piston press. The parameters used to describe size reduction are determined from tests in a laboratory or pilot scale HPGR machine combined with breakage tests in a piston press. The piston press tests provide information on the relationship between size reduction and energy input in a compressed bed. They also provide a description of the characteristic shape of the product size distribution. This part of the model contains 2 parameters which are fitted to the laboratory scale HPGR test data

The last sub-process in the model is the split between the edge and compressed bed zones. The edge zones are associated with the drop in pressure that is experienced towards the edge of the rolls. Their extent is assumed to be a function of the working gap. The fraction of feed which is crushed in the edge zones (f) can therefore be expressed as:

$$
f \quad = \quad \gamma \frac{x_g}{L} \tag{4}
$$

where γ is split factor. Using the KHD pilot scale HPGR test results where sizing data of both pure flake and total product were available, the split factor γ was found to be approximately constant with a value of 3.4. In physical terms this means that the edge effect zone extended from the edge of the roll a distance equivalent to 1.7 times that of the working gap.

MODELLING OF POWER DRAW

The size reduction model contains an energy balance equation (Andersen and Napier-Munn [6]) which ensures that the energy for size reduction is compatible with that provided by the motor. In the size reduction model two are fitted to the laboratory scale HPGR data. One of these, the T_{10} parameter, is related to the specific energy imparted by the HPGR. To illustrate this the T10 - Ecs plot from 24 sets of diamondiferous ore tests under various rolls speeds and feed size conditions are shown in Figure 7.
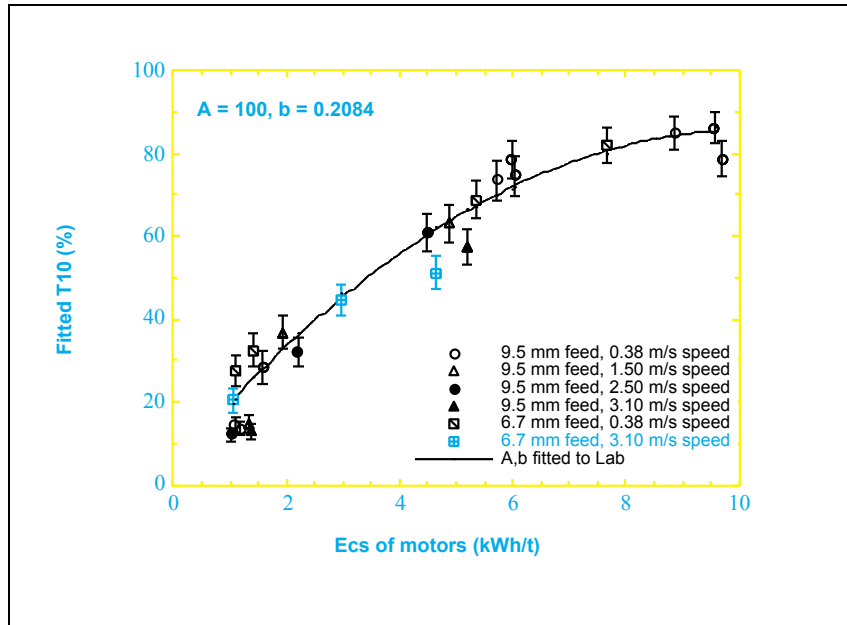
**Figure 7: The Fitted T$_{10}$ vs Specific Energy E$_{CS}$
for Diamondiferous Ore Treated through a Laboratory HPGR**

A power coefficient k_p is required which relates the measured power to that derived from the model for size reduction. This model uses the specific energy (kWh/t) and associated T values from the piston press breakage experiments. From these it calculates the overall specific energy in a piston press. The difference between this value and that observed from the motor is accommodated by k_p, ie. k_p is the ratio of the observed to the theoretical piston press specific energy. This coefficient has been found to be reasonably constant over a range of specific energies but increases rapidly beyond a certain limiting value. This is shown in Figure 8 for the 24 sets of diamondiferous ore data.
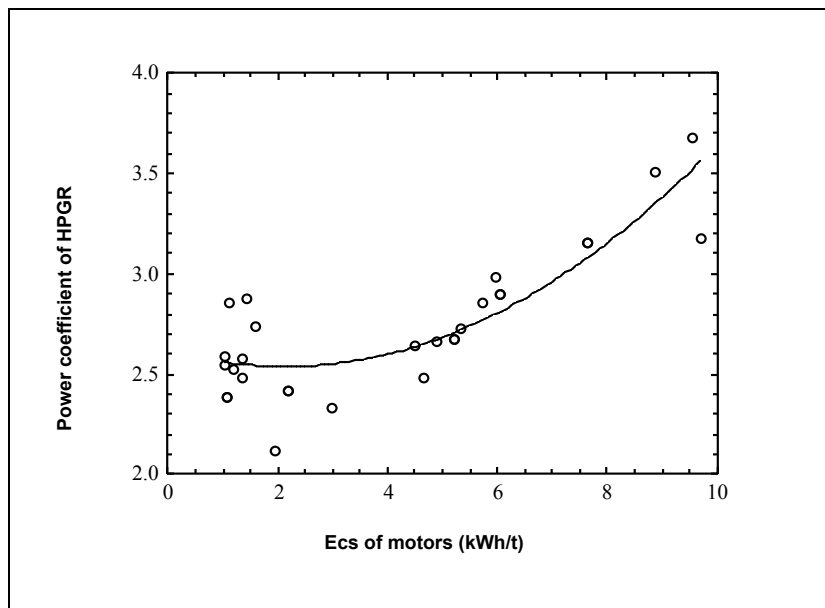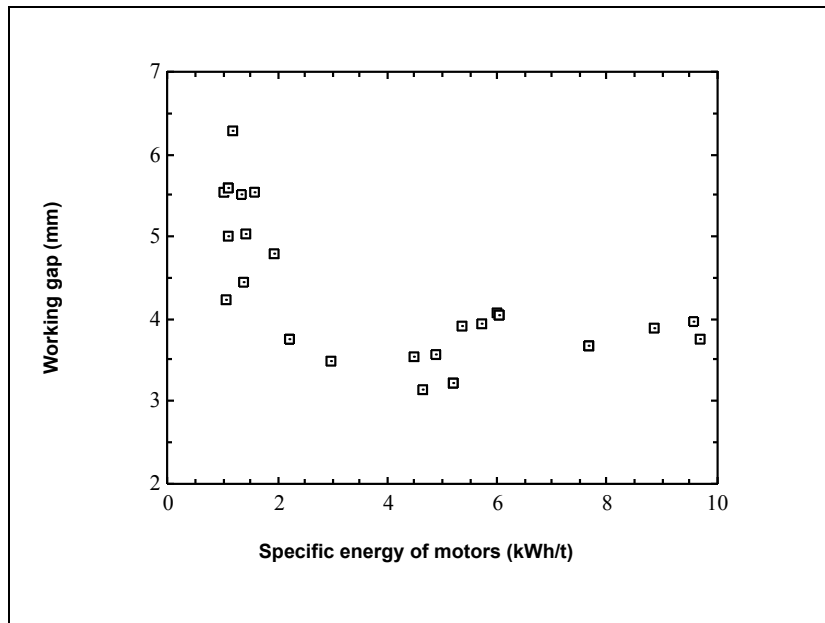

**Figure 8: Relationship between Power Coefficient (k_p) and Specific Energy
for diamondiferous Ore Treated Through a Laboratory Machine**

Scale-up procedure

The parameters ρ_c and ρ_g in Equation 3 will all be functions of feed type, operating conditions (eg working pressure) and the roll surface (eg smooth, chevroned, studded). Therefore, providing the pilot scale or the full scale machines are operating under similar conditions to the laboratory unit, then x_g will be proportional to the diameter of the rolls. The principal dependence of the working gap will be on the working pressure, with the gap reducing as the pressure increases. As working pressure is directly related to specific energy, then it will be found that as the specific energy increases the gap will decrease. An example of this is shown in Figure 9 for diamondiferous ore treated through the laboratory machine.

Figure 9: Relationship between Working Gap and Specific Energy for diamondiferous Ore Treated Through a Laboratory Machine

To predict the performance of pilot scale and full scale HPGRs the model is firstly calibrated using the results from the laboratory, conventional rolls, single particle breakage and piston bed breakage test. Figure 10 illustrates the scale-up procedures. Also shown in Figure 10 are the values of the parameters obtained from the calibration, which are now used to predict the two pilot scale units and one full size machines treating the diamondiferous ore.
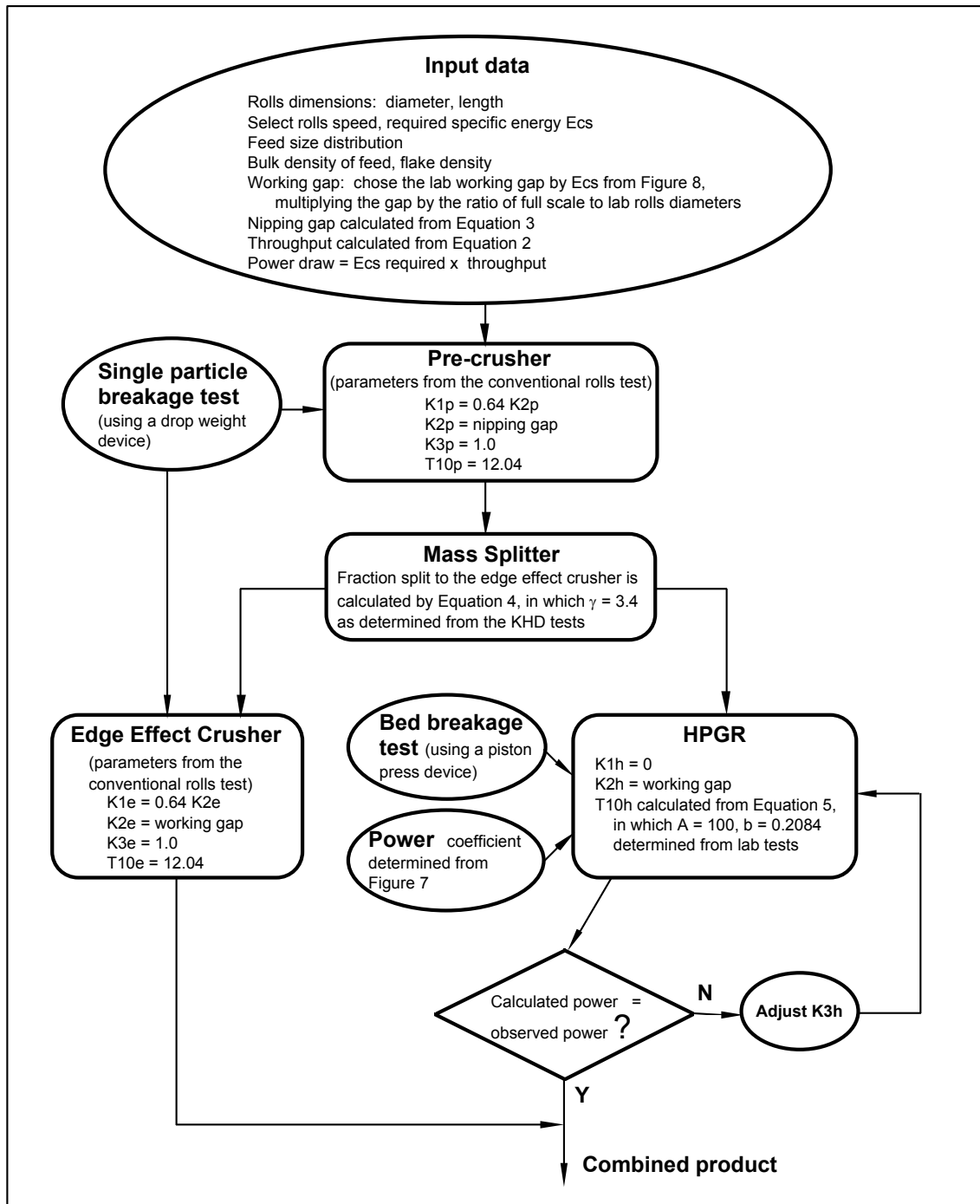
Input data

Rolls dimensions: diameter, length
Select rolls speed, required specific energy Ecs
Feed size distribution
Bulk density of feed, flake density
Working gap: chose the lab working gap by Ecs from Figure 8,
        multiplying the gap by the ratio of full scale to lab rolls diameters
Nipping gap calculated from Equation 3
Throughput calculated from Equation 2
Power draw = Ecs required x throughput

Single particle breakage test
(using a drop weight device)

Pre-crusher
(parameters from the conventional rolls test)
K1p = 0.64 K2p
K2p = nipping gap
K3p = 1.0
T10p = 12.04

Mass Splitter
Fraction split to the edge effect crusher is calculated by Equation 4, in which γ = 3.4 as determined from the KHD tests

Edge Effect Crusher
(parameters from the conventional rolls test)
K1e = 0.64 K2e
K2e = working gap
K3e = 1.0
T10e = 12.04

Bed breakage test (using a piston press device)

Power coefficient determined from Figure 7

HPGR
K1h = 0
K2h = working gap
T10h calculated from Equation 5, in which A = 100, b = 0.2084 determined from lab tests

Calculated power = observed power **?**

N Adjust K3h

Y

Combined product

**Figure 10:**   **Schematic of the Model Algorithm and Scale-up Procedure**

Examples of scale-up

The full scale-up procedure has now been implemented in the comminution simulator JKSimMet. When running the simulations of pilot scale or the full scale machines the parameter K_3 for the compressed bed crushing zone is automatically adjusted until the model predicts the same power draw as was originally chosen for the simulation. As a the resultant product size distribution is based on this power consumption.
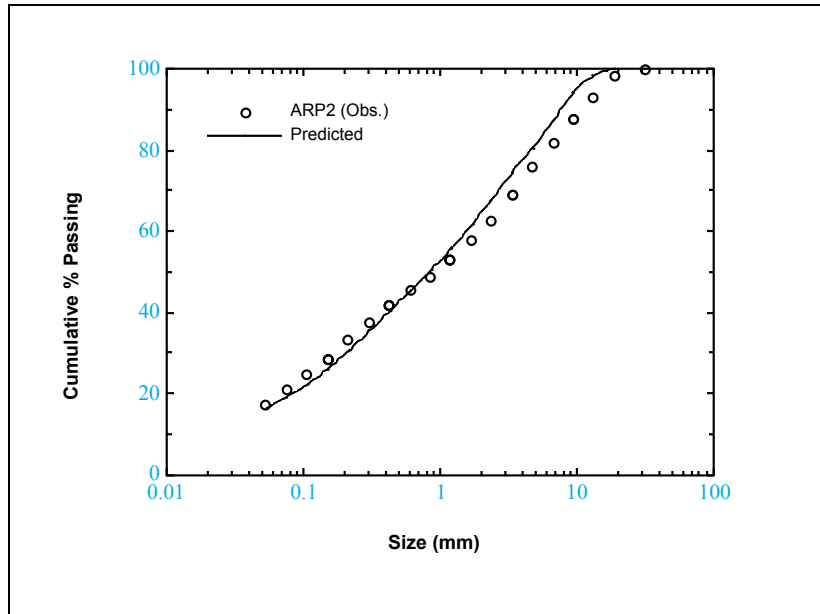
Pilot scale

In the case of the KHD tests the rolls diameter was scaled up to 0.8m from 0.25m of the laboratory machine, with smooth roll surface as that for the laboratory test.

The model prediction and actual data for this test are shown in Figure 11. The agreement is good.
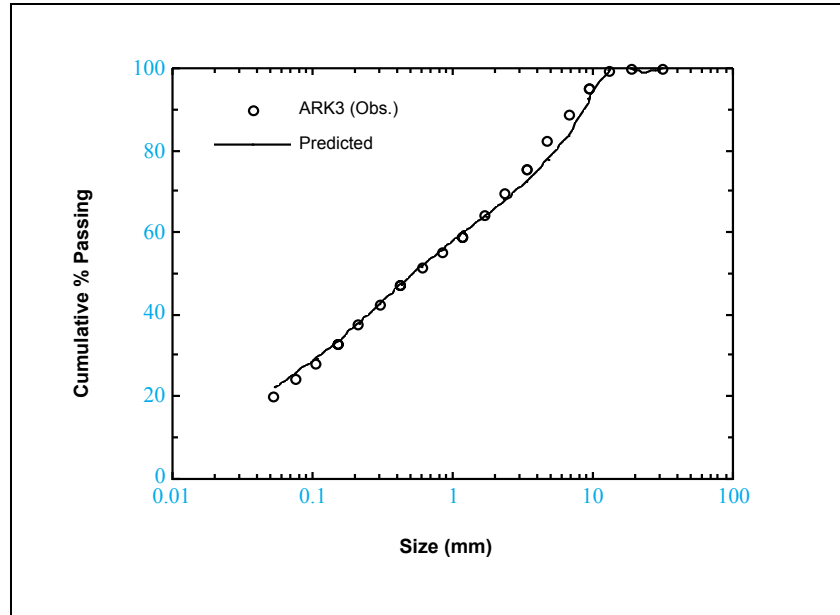
**Figure 11:   Observed vs Predicted Product Size Distributions
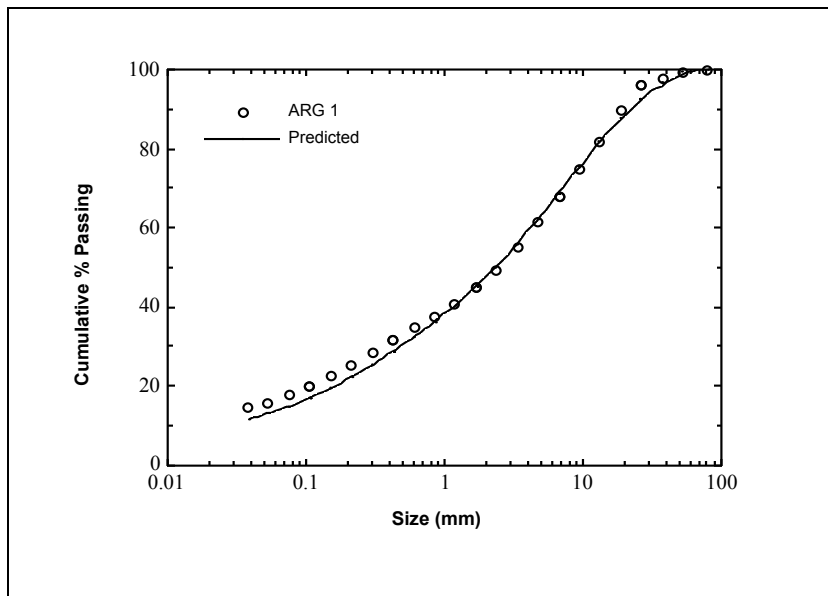for the KHD Pilot Scale Machine Treating Diamondiferous Ore**

In the case of the Krupp Polysius pilot tests (rolls diameter 0.71 m), difficulties were experienced due to the use of 4 mm profiles on the rolls of the machine. These resulted in a considerably larger working gap than was observed for the KHD pilot tests using smooth rolls. It is concluded that laboratory tests must be conducted with a rolls surface similar to that proposed on the full scale machine. To obtain some indication of whether the model could predict the Polysius pilot results it was assumed that as the machine had 4 mm high profiles its working gap would be 8 mm greater than with smooth rolls (ie each roll would drag into the gap an extra amount of material equivalent to the gap increasing by 4 mm). The results from using this assumption are shown in Figure 12. Considering the assumptions that had to be made the predicted results compare favourably with those observed.

Figure 12:   **Observed vs Predicted Product Size Distributions**
for the Krupp Polysius Pilot Scale Machine Treating Diamondiferous Ore

Full scale

Figure 13 shows the results from predicting the product size distribution of a 2.2m diameter machine using the model calibrated from laboratory scale data on the same ore. Again, the agreement between the observed and predicted data is good.

Figure 13:   **Observed vs Predicted Product Size Distributions**
for a 2.2 m Full Scale Machine Treating Diamondiferous Ore

CONCLUSIONS

A fundamental model for HPGR throughput and a phenomenological model for size reduction and power draw have been developed by considering the machine operation as comprising the sub-processes of pre-crushing, compressed bed crushing and edge effect crushing. Parameters for the models can be obtained from simple laboratory breakage tests and a limited testwork programme using a laboratory scale HPGR. After calibration the model is able to scale-up to pilot and industrial size units to predict throughput, size reduction and power draw.

ACKNOWLEDGMENTS

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