

HPGR simulation from piston-die tests with an itabirite ore

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Abstract

The Minas Rio project, owned by Anglo American, has HPGRs in open circuit operated as a tertiary/quaternary crushing stage. Currently this type of equipment is designed from HPGR tests on laboratory scale and pilot scale tests. This paper presents a methodology for simulating HPGR from piston-die tests on laboratory scale and a mathematical model developed in Hacettepe University in Turkey. The parameters determined from the results of the piston-die tests were used to validate the HPGR testing on pilot scale. Finally, the model was used to predict the particle size distribution in the HPGR product on industrial scale.

Keywords: HPGR; modeling; simulation; piston-die; Minas-Rio.

1. Introduction

The Minas-Rio Project is under ramp up phase and the project aims to process itabirite ores. Some studies have been performed to verify the response of HPGR with different operating conditions and different lithologies of itabirite ores (Ribeiro *et al.* 2010, Mazzinghy *et al.* 2013, Russo *et al.* 2013, Turrer *et al.* 2013). Minas-Rio has three HPGR in open circuit supplied by ThyssenKrupp. The HPGRs have 2.40 m diameter by 1.65 m length with 4,800 kW installed power (two motors of 2,400 kW per machine). The motors are equipped with variable speed drives. Anglo American requested the Global Comminution Collaborative (GCC), through the Anglo American Centre for Sustainable Comminution, to critically analyze the HPGR circuit design using modeling and simulation tools, with the aim of identifying areas where minor modifications in the

operating conditions could lead to improved robustness of the plant and greater ability to meet the design criteria. The idea of the GCC work was to use, whenever possible, the latest available mathematical models of the unit operations in simulating the Minas Rio comminution circuit. As such, it became obvious that the commercial mineral processing plant simulators would not be appropriate, due to the unavailability, at the time, of mathematical models of HPGRs that could meet the requirements of the project. Therefore, the simulation platform used was the JKMDK, that is, the Model Developer's Kit, which was developed at the JKMRRC as a tool to aid in developing new mathematical models of unit operations by the center's researchers as well as partner institutions (Hilden *et al.* 2013). The simulator combines Microsoft Excel® with a large database of models and a powerful

solver to enable simulation of complex circuit flow sheets. Although it lacks the convenient circuit drawing capabilities of commercial mineral processing plant simulators, it has the important advantage of allowing rapid implementation of new or different models.

The population balance model was introduced in 1947 by Epstein (Napier-Munn *et al.* 1996). The model 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 in a continuous milling is represented in Figure 1. A simple mass balance for size fraction of *i* in 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; feed in size *i*.

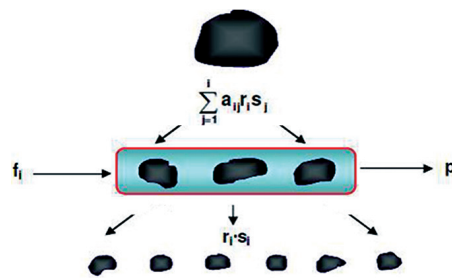


Figure 1 Mechanism in population balance model.

The mass balance equation can be written as follows in the Eq. 1.

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

Where p_i is the product out size *i*; f_i is the feed in size *i*; a_{ij} is the breakage function (appearance of size *i* produced by breakage of size *j*); r_j is the breakage rate of size *j*; s_j is the amount of size *j* material within the mill; r_i is the breakage rate of size *i*; 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 disappearing rate of a specific size after breakage. If the breakage rate of a specific size is equal to one, all the particles in that size fraction are broken out. If it is zero there is no breakage at that size. 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, for a given feed and product size distributions, the breakage rate of the particles is back-calculated using the breakage function of the material. Unlike the population balance model, in a novel approach, the breakage rate is expressed as follows in the Eq. 2.

$$r_i = a x_i^\alpha \tag{2}$$

where r_i is the breakage rate of particles of representative size x_i , *a* is a constant that depends on both the ore and the

machine, and α is a constant, which depends essentially on the ore characteristics. The shape of the breakage rate

is shown in Figure 2 for various *a* and α values.

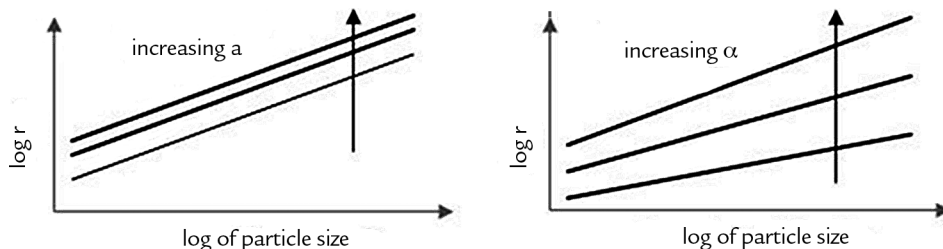


Figure 2 Variation of the breakage rate with increasing *a* and α .

As can be seen from Figure 2, breakage rates increase with a while α determines the slope of the breakage rate and the breakage rate of the particles increase with the size. The parameter a is mainly dependent on operational conditions, such as specific grinding force, which is a function of the applied pressure, as well as roll dimensions, and roll speed. The increase in the applied pressure increases the breakage rate of the particles. In log scale the breakage rate shifts parallel upwards. The slope of the breakage rate is thought to be dependent on the size distribution of the particles in the material bed or in feed to the HPGR. In compressed breakage systems, the fine particles assist the breakage of the relatively coarse particles by enhancing the inter-particle breakage in the material bed. Under compression, the applied load

is transferred to the material by means of the surrounding particles whereby the distribution of the particles in the material bed determines the efficiency of the breakage. In this novel approach, the effect of the size distribution of the material bed is represented with the parameter α . For finer size distributions, the value of α is increasing, which means that the finer size distribution increases the breakage rate of the coarse particles in itself by making the energy transfer more efficient in the system. To represent the whole feed size distribution with a single number, the specific surface area is considered. Hence, the theoretical specific surface area of the material coming into the HPGR is calculated and then correlated with the parameter α . On the other hand, the increase in α lowers the breakage rates of the fine particles below 1 mm. When

more fines are added to the system, the fines in the mill content are increased decreasing the breakage rate of the fines, which is defined as tph broken per tonne in the mill. Increasing tonnage into the mill will decrease the breakage rate. After defining the breakage rate in this novel approach, for a given feed and product size distribution, the mill content (s) and breakage function (a) are required. The mill content is defined as the accumulation in the mill which is the combination of the new feed to the system and partially broken material still within the system. For the HPGR operation, the mill content was considered as the material between the rolls to be crushed. For this purpose, the volume between the rollers, from the nipping gap to the working gap, is calculated geometrically. Figure 3 illustrates the volume between the rolls.

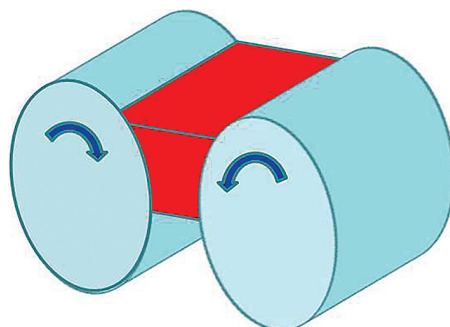


Figure 3
Schematic representation
of the volume between the rolls.

As mentioned previously, the parameter a is a function of the roll speed. In the population balance model, the breakage rate is defined as the amount of the material broken in tph per tonne of the material in the mill (tph broken/tonne in the mill). For increased rolls speed, the mill content will be same while the throughput increases. Regarding the above definition of the breakage rate, for the same

mill content, the amount of the broken material increases with the throughput as a result of the roll speed. In this case, only the amount of the broken material increases; the ratio of the broken or unbroken particles within the system is the same with no more fines being generated, i.e. there is no change in the product size distribution. So the increase in breakage rate depending on the roll speed should

be separated from the disappearing rate of the particles. Hence the parameter a is defined to be a function of the roll speed and applied pressure.

The required breakage distribution function of the material is determined by lab-scale compressed bed breakage tests. The representation of the compressed bed breakage test is given in Figure 4.

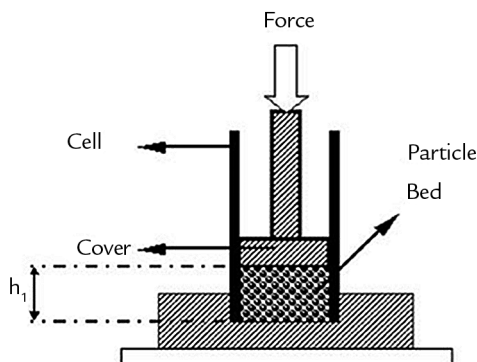


Figure 4
Representation of the
particle bed compression.

In this test, narrow-sized fractions of the material to be tested are prepared. Then they are compressed for different pressure levels. From the force-displacement graph, the corresponding energy

levels are calculated. The size distributions of the compressed materials are determined by sieve analysis. 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 present approach, the breakage distribution function is calculated for 2 kWh/t.

2. Material and method

Samples containing about 50 kg of itabirite ores were received at Laboratório de Tecnologia Mineral (LTM) da Universidade Federal do Rio de Janeiro (UFRJ) for testing. Sample preparation included

crushing and then screening into a number of narrow-size classes, ranging from 11.2-9.5 mm to 0.85-0.60 mm. Tests then consisted of pressing, at different pressures using a hydraulic press, as shown in the

Figure 5, each of the samples contained in narrow-size classes, and recording the resulting force-deformation profile in order to assess the amenability of the samples to compressive crushing.



Figure 5
Piston-die system used in the compression tests.

The piston-die tests were carried out for 5 size fractions (mm) -11.2 +9.5, -6.7 +5.6, -3.35 +2.8, -2.0 +1.7, -0.85 +0.60 and each fraction was tested considering 4 different pressures (kN) 50, 100, 500, 1000. The calculated energy values together with the size distributions were used to calculate: the material hardness parameter; the material softness parameter

(for HPGR model); and the appearance function (for HPGR model). The studies were performed in two stages:

i. In order to validate the model structure of the Hacetepce Model, the pilot plant data gathered from open circuited HPGR, having dimensions of 0.8x0.25m, was used. The studies showed that the model developed by Hacetepce Univer-

sity (HU) could make a close estimation, regarding to the product size distribution of Itabirite ore, under specified operating parameters.

ii. Once the model was fitted, the HPGR commissioned at Minas Rio was simulated and product size distribution, operating pressure, and operating gap parameters were determined.

3. Results and discussion

3.1 Piston-die tests

Particle size distributions of each of the test studies were determined by sieve

analysis. Figures 6 to 10 illustrate the size distribution curves for itabirite ore. It is

evident that the product becomes finer as the force applied on the material increases.

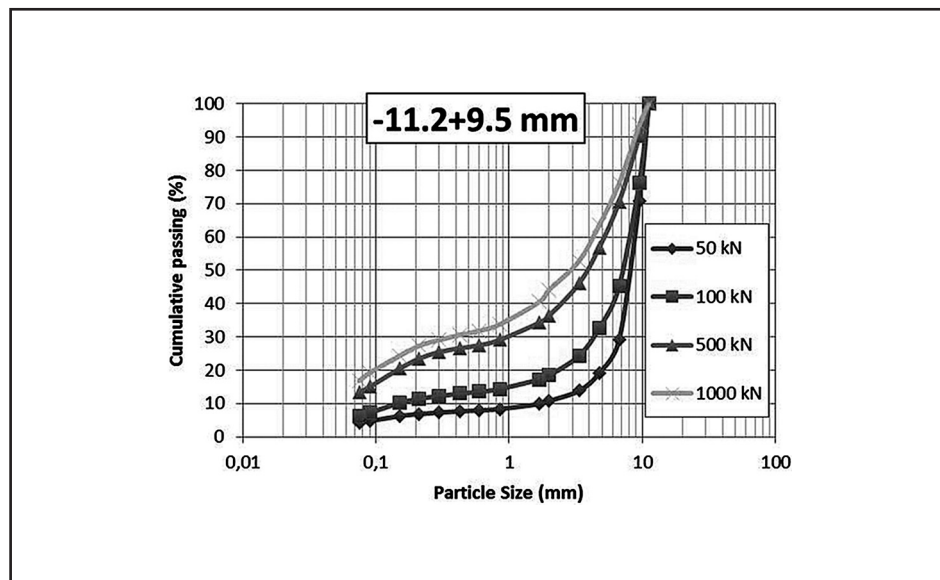


Figure 6
Particle size distributions obtained from piston-die tests carried out with -11.2+9.5 mm fraction.

Figure 7
Particle size distributions
obtained from piston-die
tests carried out with -6.7+5.6 mm fraction.

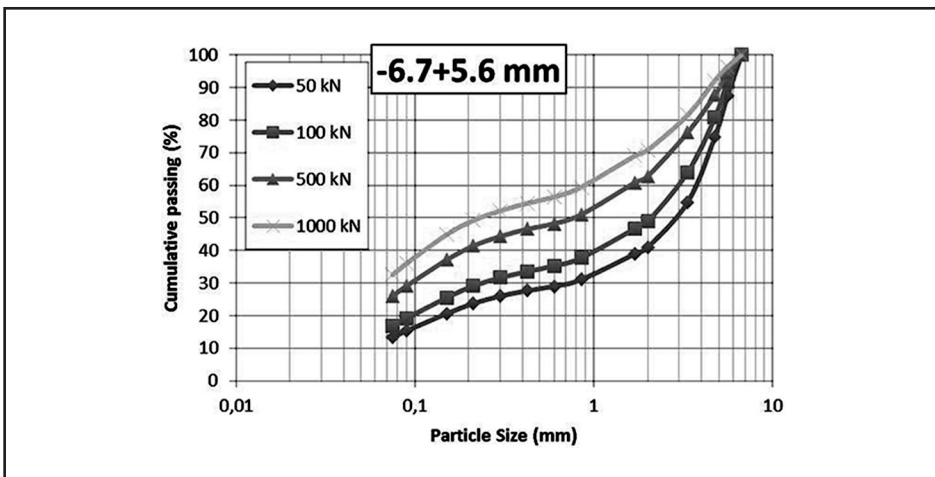


Figure 8
Particle size distributions
obtained from piston-die
tests carried out with -3.35+2.8 mm fraction.

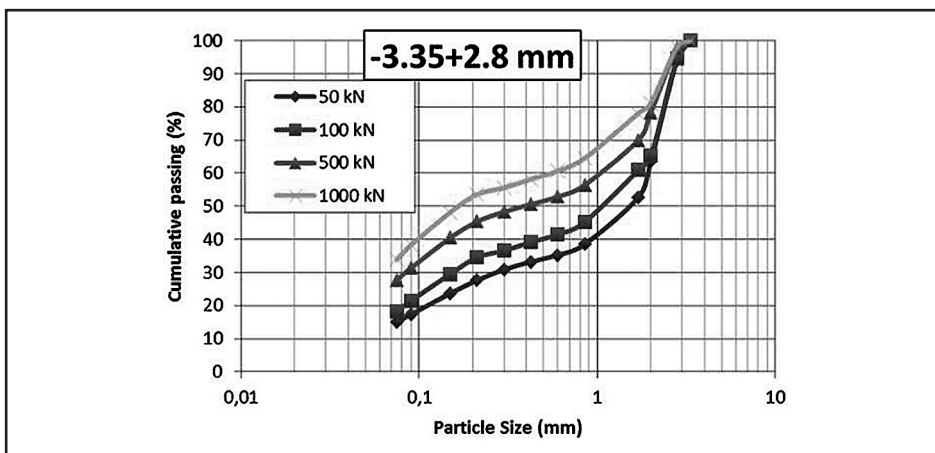


Figure 9
Particle size distributions
obtained from piston-die
tests carried out with -2.0+1.7 mm fraction.

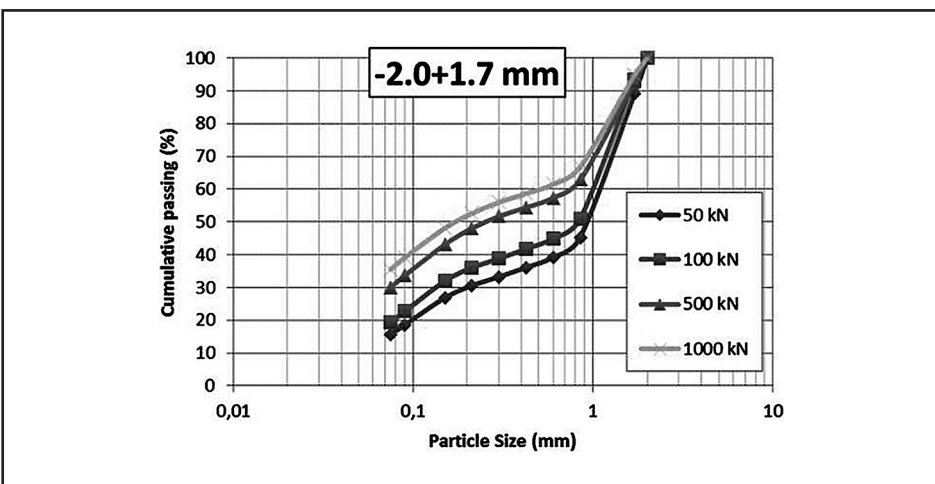
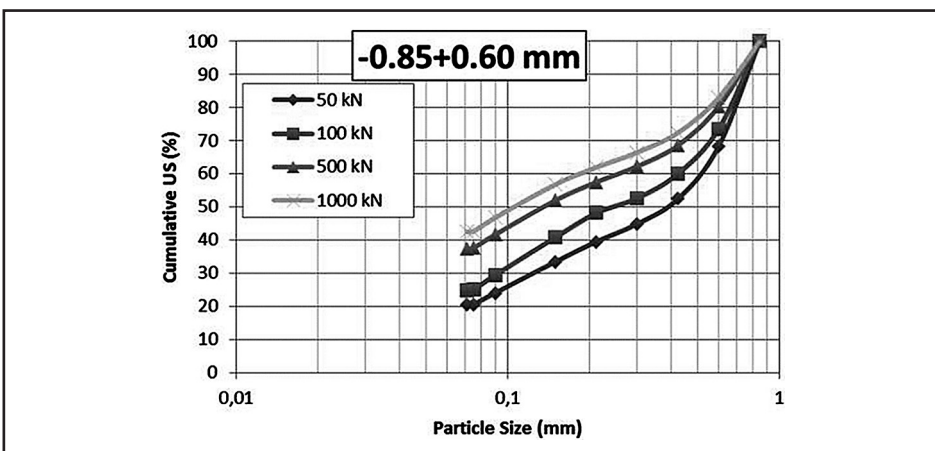


Figure 10
Particle size distributions
obtained from piston-die tests
carried out with -0.85+0.60 mm fraction.



3.2 Parameter estimation

The parameters for material hardness, material softness and ap-

pearance function have been used to characterize breakage on the basis of

the modelling approach used by HU (Dundar *et al.* 2013).

3.2.1 Material hardness parameter

Figure 11 was obtained by plotting the specific comminution energy (E_{cs}) against t_{10} values, which are defined as

the percent passing from one tenth of the original mean particle size. The specific comminution energy parameter was

calculated by dividing the energy found from the force-displacement graph and the sample mass.

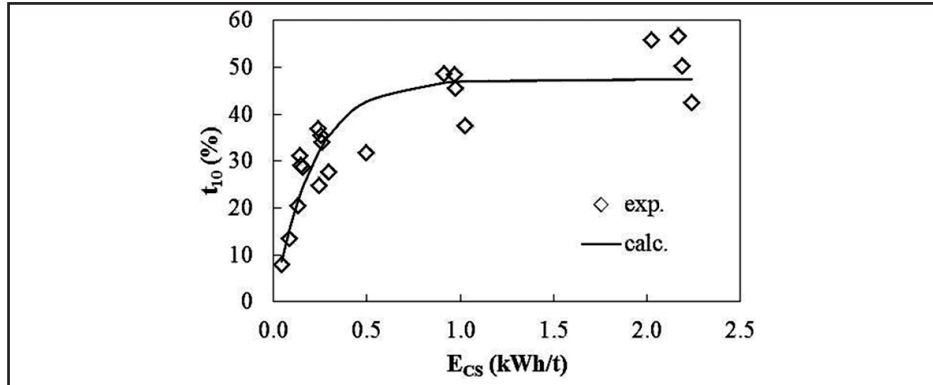


Figure 11
 $E_{CS-t_{10}}$ relationships of itabirite ore.

$E_{CS-t_{10}}$ data of itabirite ore were fitted to the breakage model using Eq.

3 in order to back calculate A_{pd} and b_{pd} model parameters:

$$t_{10} = A_{pd} (1 - \exp (-b_{pd} E_{cs})) \quad (3)$$

where A_{pd} and b_{pd} are parameters that characterize the amenability of the ore to compression breakage (Dundar *et al.* 2013). In analogy to the impact-breakage test (Napier-Munn *et al.*

1996), the product $A_{pd} * b_{pd}$ values may be used as an indicator of ore hardness, so that the higher the $A_{pd} * b_{pd}$, the softer the material. Evidently, the $A_{pd} * b_{pd}$ values obtained from this test cannot be directly

compared to the $A*b$ obtained from Drop Weight Tests, given the different particle sizes and stressing conditions. Calculated parameters are present in Table 1.

A_{pd}	b_{pd}	Hardness ($A_{pd} * b_{pd}$)	B	c	Softness index ($B*c$)
48.2	5.09	245.0	0.92	16.50	15.2

Table 1
Piston-die material parameters.

3.2.2 Material softness parameter

The data obtained from the piston-die tests is also used in calculating the ma-

terial softness parameter put into HPGR model which is estimated by plotting the

disappearing rate of a given size fraction with E_{cs} , as shown in the Figure 12.

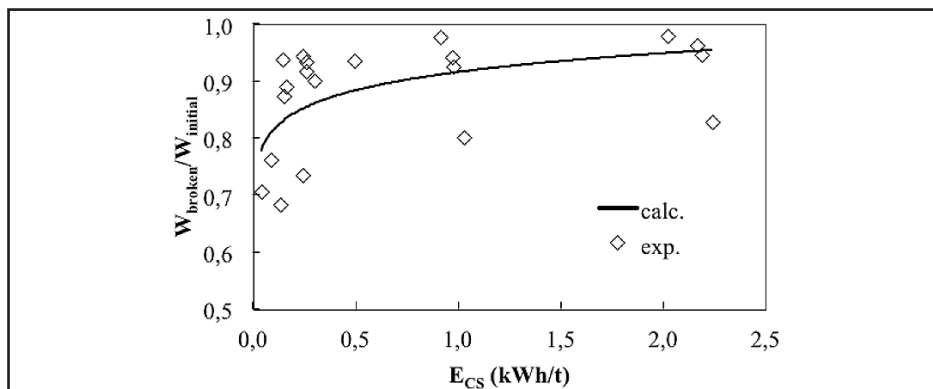


Figure 12
Disappearing rate ($W_{broken}/W_{initial}$) for itabirite ore.

The data is fitted to Eq. 4, where parameters b and c were calculated and shown in Table 1.

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

These parameters were then mul-

tiplied so as to determine the softness

parameter, which increases as the

value increases.

3.2.3 Appearance function

In order to calculate the appearance function of the ores, t-family curves are graphed. The t-family curve is drawn by plotting $t_2, t_4, t_{10}, t_{25}, t_{50}$ and

t_{75} values against t_{10} which is defined as the percentage passing from one tenth of the original mean particle size and $t_2, t_4, t_{10}, t_{25}, t_{50}$ and t_{75} are the percentage

passing from 1/2, 1/4, 1/25, 1/50, 1/75 of the original mean particle size. Figure 13 shows the t-family curves determined for itabirite ore.

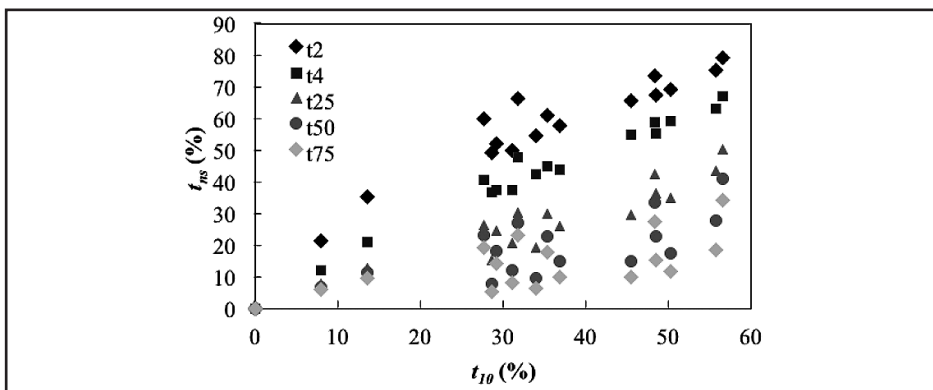


Figure 13
t-family curves of itabirite ore.

From the t_{10} versus t_n values and considering an arbitrary value of

2 kWh/t for the comminution energy E_{cs} , the appearance function for the

itabirite ore was estimated, being given by Figure 14.

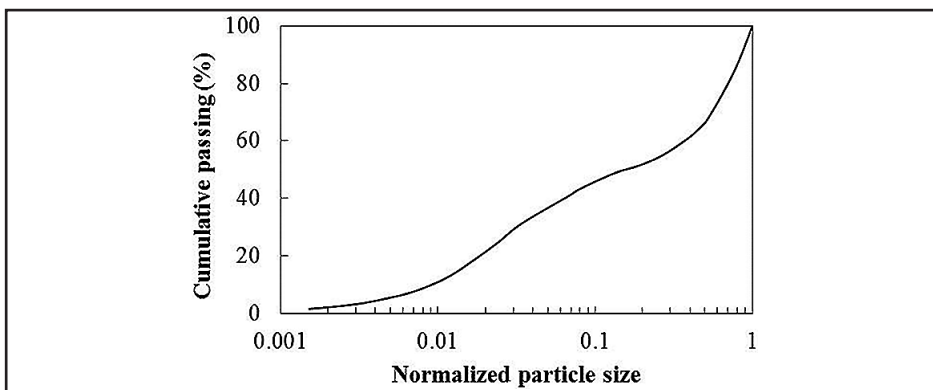


Figure 14
Breakage distribution function.

In summary, as a result of the compressed bed breakage tests, the material

hardness, the material softness and the appearance function parameters were estimat-

ed, showing that the itabirite ore presented marginally lower resistance to breakage.

3.3 Model fitting with HPGR pilot-scale tests

The open circuit HPGR grinding test works for the itabirite ore was fitted to the Hacettepe HPGR model. The

HPGR presented dimensions of 0.8 m roll diameter and 0.25 m width. The surface of rolls was lined with a Stud-Plus® liner. The

test program for the itabirite ore involved four single pass tests at different specific pressures as show in Table 2.

Variable	Test			
	1	2	3	4
Roll speed (RPM)	19.1	19.1	19.1	9.5
Zero gap (mm)	10	10	10	10
Specific pressure (N/mm ²)	2.8	4.7	5.4	4.8
Throughput (t/h)	71	69	71	36
Net specific power (kWh/t)	0.8	1.5	1.6	1.8

Table 2
Test conditions and results.

The operating conditions together

with the material characteristic e.g., ma-

terial softness and appearance function,

were inputted to the open circuit HPGR simulator and the product size distributions were fitted. In order to validate

the Hacettepe HPGR Model structure, the fitted size distributions were then compared with the measured ones (pilot-

scale tests). This is shown in Figure 15, which demonstrates the good agreement between them.

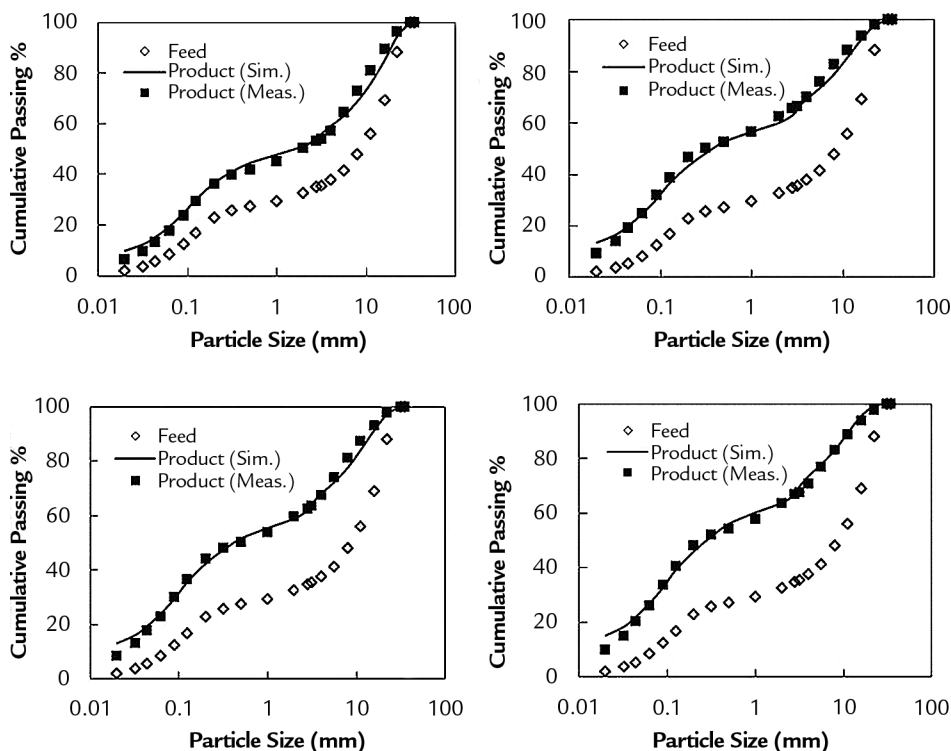


Figure 15
Fitted and measured product size distributions from pilot-scale tests on the itabirite iron ore in four different pressures.

3.4 Simulation of HPGR at Minas Rio

In general, the ratio of cake thickness (GAP) to roll diameter is between 2-3%. Moreover, the largest particle nipped between the rolls in the compression zone would be about 1.5 times the gap. Larger particles would cause the rolls to separate and the compression zone to collapse, re-

ducing grinding efficiency. For Minas Rio HPGR, the largest particle to be nipped is calculated as 75 mm. However, -25 mm material from the secondary crushing circuit will be fed to the HPGR, which is regarded as very fine. It is foreseen that for the itabirite ore, the HPGR of Minas

Rio will reach 3,240 t/h of throughput operating at a GAP of 65 mm, roll speed of 2.4 m/s and 80 bar of pressure to obtain the product size distribution illustrated in Figure 16. This will feed the primary ball mill circuit, comprised of ball mills operating in closed circuit with hydrocyclones.

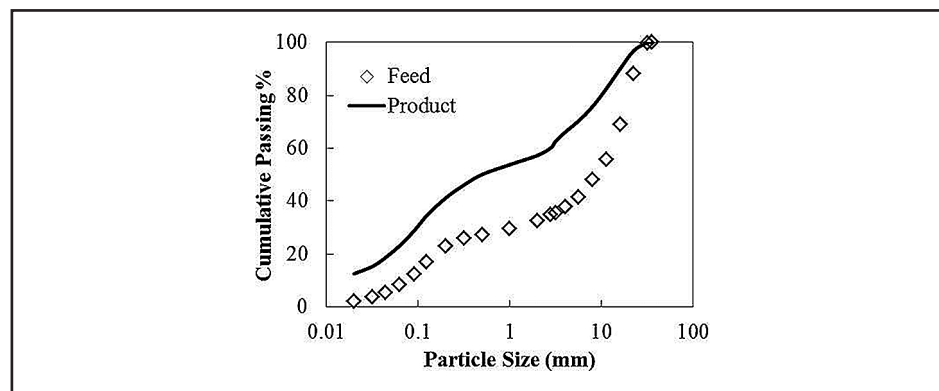


Figure 16
Product size distribution predicted from simulation studies on the industrial-scale HPGRs.

4. Conclusions

The mathematical model for the HPGR, developed by Hacettepe University researchers (Dundar *et al.* 2013), was fitted with pilot-scale data for itabirite ore.

The information obtained through the piston-die tests was used to determine the material hardness and softness parameter and the appearance function. Simulations

were conducted to predict the particle size distribution in the HPGR product in industrial scale using the parameters determined from laboratory tests.

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