AGH Journal of Mining and Geoengineering • vol. 36 • No. 4 • 2012

Yakup Umucu[*], *Vedat Deniz*[**], *Volkan Bozkurt*[***]

THE EVALUATION OF GRINDING PROCESS USING MODSIM©***

1. Introduction

Grinding process mathematical modeling and computer simulation particularly, in mineral industry have been a very intensive research field for several past decades. This is due to the high consumption of electrical energy in comminution circuits and low efficiency of operating mills especially in fine size range.

There are a lot of programs for the computer design of mineral processing circuits, and these programs contain computer simulation models for ball mill design. These models need the input of characteristic breakage parameters for the mineral of interest and that these are often determined in a small size laboratory ball mill and scaled up by the program to the conditions of a full-scale ball mill [1].

MODSIM© is based on the population balance method and is therefore capable of accounting accurately for variations in particle size and mineral liberation characteristics together with other critical properties such as density, mineralogical texture, elemental composition, magnetic susceptibility, energy content, etc. Data structures incorporate mineral and coal processing flow sheets. MODSIM© simulates integrated flow sheets that can include varied types grinding (AG, SAG, Rod and Ball mills) [2].

The grindability properties at different powder filling ratio of calcite samples belongs to Afyonkarahisar region (Turkey) were investigated at batch grinding conditions based on

[*] Suleyman Demirel University, Department of Mining Engineering, Isparta, Turkey
[**] Hitit University, Department of Chemical Engineering, Çorum, Turkey
[***] Osmangazi University, Department of Mining Engineering, Eskişehir, Turkey

a kinetic model. For this purpose, firstly, five different mono-sized fractions were prepared between 1.7 mm and 0.106 mm formed by a 2 sieve series. S_i and $B_{i,j}$ (selection and breakage distribution functions) equations were determined from the size distributions at different grinding times and the model parameters (S_i, a_t, α, γ, β and ϕ_J) for different powder filling ratios. Experimentally determined data were statistically compared with data obtained using model parameter from MODSIM© simulator program.

2. Background

In the analysis of the breakage materials, it is useful to make the initial assumption that the breakage of each size fraction is first order in nature. That is, the rate of disappearance of size 1 due to breakage is proportional to the amount of size 1 material in the mill hold up [3].

$$-\frac{d\left[w_1(t)W\right]}{dt} \infty w_1(t)W \tag{1}$$

Since the mill hold up, W, is constant, this becomes:

$$dw_i = \frac{(t)}{dt} = -S_1 w_1(t) \tag{2}$$

where S_1 is proportionality constant and it is called the specific rate of breakage, with units of time –1. If S_1 does not vary with time [4]

$$w_1(t) = w_1(0)\exp(-S_1 t) \tag{3}$$

that is,

$$\log\left[w_1(t)\right] = \log\left[w_1(0)\right] - \frac{S_1 t}{2.3} \tag{4}$$

where $w_1(t)$ is the weight fraction of mill hold up that is of size 1 at time t [5]. The formula proposed by Austin et al [4] for the variation of the specific rate of breakage *Si* with particle size is

$$S_i = a_T \left(\frac{X_i}{X_0}\right)^{\alpha} Q \tag{5}$$

where:

X_i — is the upper limits of the size interval indexed by i,
X_0 — is 1 mm,

a_T and α — are model parameters that depend on the properties of the material and the grinding conditions,

Q_i — is a correction factor which is 1 for smaller sizes (normal breakage) and less than 1 (abnormal breakage) for particles too large to be nipped and fractured properly by the ball size in the mill.

In abnormal breakage region, each size behaves as if it has some fraction of weak material and the remaining fraction of stronger material. Using a mean value for S_i in this region, values of Q_i are empirically described by

$$Q_i = \frac{1}{1+\left(X_i \diagup \mu\right)^{\wedge}}, \wedge \geq 0 \tag{6}$$

where μ is the particle size at which correction factor is 0.5 and λ a positive number which an index of how rapidly the rates of breakage fall as size increases that is the higher the value of the more rapidly the values decrease. The cumulative breakage distribution, $B_{i,j}$, is defined as "The weight fraction of material broken from size j which falls less than the upper size of size interval *i*" is commonly used to characterize the size distribution resulting from breakage of material from a particular size interval to a smaller size [3, 6].

The $B_{i,j}$ values can be calculated using the BII method which is described by [7].

$$B_{i,j} = \phi_j \left(\frac{X_{i-1}}{X_j}\right)^{\gamma} + (1-\phi_j)\left(\frac{X_{i-1}}{X_j}\right)^{\beta} \tag{7}$$

The parameter is the intercept at $(X_{i-1}/X_j) = 1$, γ is the slope of the lower section of the $B_{i,j}$ curve and β is the slope of the steeper section of the $B_{i,j}$ curve as in Figure 1 [8].

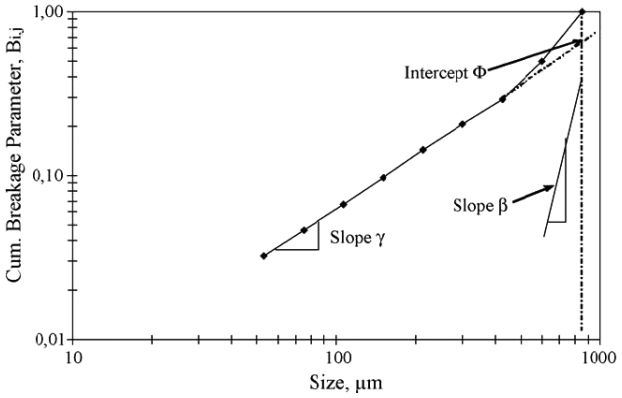

Fig. 1. Obtaining the primary breakage distribution function parameters for any single size fraction feed ground in the mill [8]

3. EXPERIMENTAL STUDIES

3.1. Materials

Calcite was chosen as the feed mineral for this study, because this mineral is major raw materials of industrial paints. The density of these raw materials, measured by a pycnometer, is averaged as 2.68 g/cm^3 over thirteen measurements and Bond Work Index (W_i) of this material is 7.18 kWh/t. The Bond work index is determined by using the standard Bond test procedure [4]. Chemical analyses of this material is also given in Table 1.

TABLE 1
Chemical composition of material

Oxides, [%]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LOI
Calcite	0.27	0.07	0.03	55.72	0.22	42.13

Feed size distributions of test material are given in Table 2, respectively.

TABLE 2
Feed size distributions of material

Sieve size, [mm]	
–1.700 + 1.180	14.80
–1.180 + 0.850	10.30
–0.850 + 0.600	12.59
–0.600 + 0.425	10.86
–0.425 + 0.300	9.04
–0.300 + 0.212	16.81
–0.212 + 0.150	9.76
–0.150 + 0.106	6.89
–0.106	8.95

3.2. Grinding tests

The breakage parameters were determined experimentally using one size fraction technique [8].

The size fractions chosen for tests were, –1700 + 1180, –1180 + 850, –600 + 425, –300 + 212 and –150 + 106 mm, where for example, –1700 + 1180 mm denotes that 100% of the particles are passing by weight at 1700 mm size and 100% of particles are remaining at 1180 mm. The standard set of grinding conditions used is shown in Table 3 for a laboratory mill with a 6283 cm^3 volume.

TABLE 3
Ball mill characteristics and test conditions

Mill	Diameter, D, [mm]	200
	Length, L, [mm]	200
	Volume, [cm^3]	6283
	Mill speed Critical, Nc, [rpm]	101
	Operational speed	76
Media (Balls)	Grinding Diameter, d, [mm]	25.4
	Media [balls] Specific gravity, [g/cm^3]	7.8
	Quality Alloy	Alloy steel
	Assumed porosity	(%) 40
	Ball-filling volume fraction, J_b, [%]	0.30
Material	Specific gravity, [g/cm^3]	2.68
	Powder-filling volume fraction f_c, [%]	0.072-0.096-0.120-0.144
	Interstitial filling U, [%]	0.60-0.80 1.00-1.20

4. Results and discussion

4.1. Determination of S parameters

The results indicated that breakage generally follows the first order relation, and values of S_i could be determined from the slope of straight line of first-order plots. In addition, Figs. 5 and 6 show the S_i in relation to the fraction of powder-filling volume fraction f_c (%) and particle size for calcite, respectively.

Figure 5 also shows the variations of the specific rates of breakage, S_i, values with the particle feed sizes ground in the mill for calcite. It is clearly seen that S_i values increase up to a maximum particle size (0.850 mm), then start decreasing at around 0.850 mm for all materials as illustrated Figure 2. This was due to the in efficiency of the largest feed sizes that were not nipped properly by the balls in the mill.

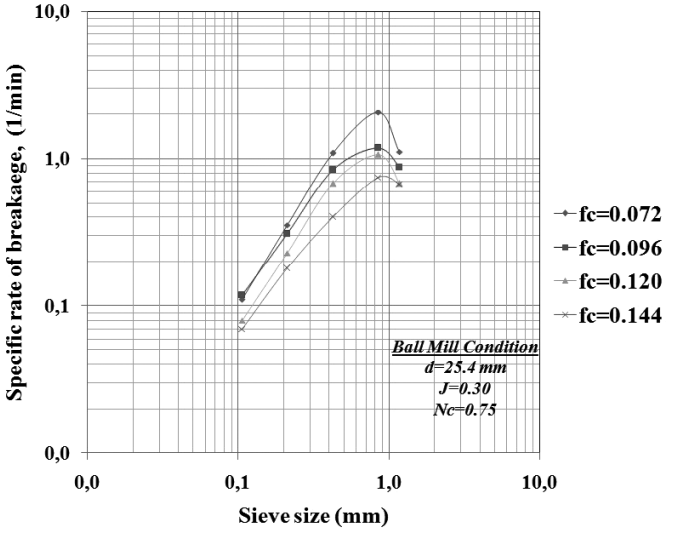

Fig. 2. Variation of S_i values of calcite with particle size for the different

4.2. Breakage distribution functions

From the size distributions at the shortest grinding times, the values of cumulative breakage distribution functions, $B_{i,j}$, which is commonly used to characterize the size distributions resulting from breakage of material from a particular size interval to a.

Smaller size were determined using the BII method [1, 5, 9]. The values of $B_{i,j}$ against particle size obtained from BII calculations for each size fractions are plotted in Figure 6. In order to get the $B_{i,j}$ values, BII calculation procedure [4] given below was applied for the shortest grinding time (0.5 min),

$$B_{i,j} = \frac{\log[(1-P_i(0))/(1-P_i(t))]}{l\,\mathrm{og}[(1-P_2(0))/(1-P_2(t))]}, \quad i>1 \tag{8}$$

where:

$P_i(0)$ — cumulative weight fraction of time 0 for i-th interval,
$P_2(0)$ — cumulative weight fraction of time 0 for second interval,
$P_i(t)$ — cumulative weight fraction of time t for interval t,
$P_2(t)$ — cumulative weight fraction of time t for second interval.

The values of B were determined from the size distributions at short grinding times using the BII method and are shown in Figure 3.The results showed a typical normalized behavior so that the progeny distribution did not depend on the feed particle size and the parameter δ was zero. The model parameters are also given in Table 4 and 5.

TABLE 4

Characteristic breakage parameters of different powder-filling volume fraction f_c (%) obtained from the laboratory test

fc	*U*	a_t	α	μ
0.072	0.60	2.61	1.66	1.27
0.096	0.80	2.24	1.65	1.05
0.120	1.00	1.66	1.63	1.17
0.144	1.20	0.76	1.21	1.65

TABLE 5

Characteristic breakage distribution functions of different powder-filling volume fraction f_c (%) obtained from the laboratory test

fc	*U*	Φ_j	γ	β	δ
0.072	0.60	0.45	0.41	2.90	0.00
0.096	0.80	0.44	0.61	4.04	0.00
0.120	1.00	0.35	0.64	3.80	0.00
0.144	1.20	0.33	0.78	4.02	0.00

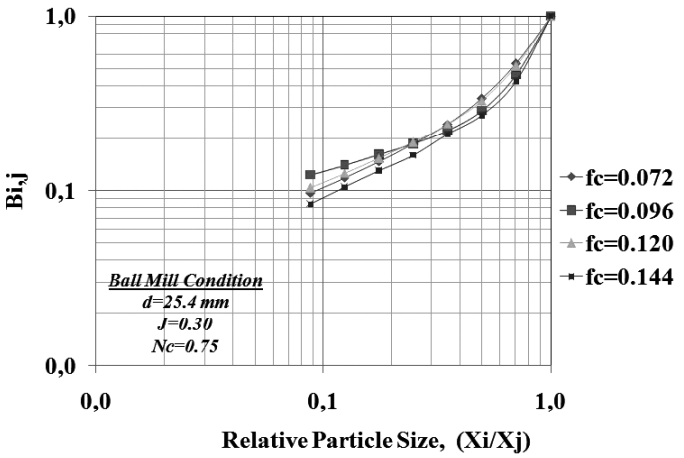

Fig. 3. Cumulative breakage distribution functions for different powder filling

It can be seen from the data in Table 3 and 4. that model parameter values of the powder filling is similar to the literature on the powder filling. As powder filling increases, a_T value

were decreased. γ value increases with increasing powder filling, the material Φ_j value decreases with increasing load is observed. Powder filling increases, while decrease the specific rate of breakage is due to the increase in the rate of gap filling. The same argument can be based on reason for the lack of increase in the rate of fine material.

4.3. Modeling of Grinding System with MODSIM©

Models for comminution operations are comparatively well developed and comminution circuits are comparatively easy to model and simulate. Comminution processes are quite complex and it is necessary to understand what kind of information and data is required to model and simulate comminution circuits successfully. It is also necessary to have an appreciation of the different model types that are available.

MODSIM is a simulator that will calculate the detailed mass balance for any ore dressing plant. The mass balance will include total flow rates of water and solids, the particle size distribution of the solid phase, the distribution of particle composition and the average assay of the solid phase. The assay can include mineralogical composition, metal content and element content. Other special particle properties that are specific to particular systems can also be accounted for. Some are calorific value, volatile matter, pyritic sulfur, organic sulfur and ash content for coal, and magnetic susceptibility and electrical conductivity for mineral systems that are processed by magnetic or electrostatic separators. Other, sometimes very subtle, particle properties such as particle shape, mineralogical texture and surface characteristics have important influences on the behavior of some of the unit operations of mineral processing. MODSIM can accommodate all of these particulate properties. The main unit operations of ore dressing include the size-reduction operations, crushing and grinding, classification operations for separation of particles on the basis of size, concentration operations that separate particles according to their mineralogical composition and solid-liquid separations. MODSIM provides a repertoire of standard models for these operations [2].

MODSIM has a completely modular structure which allows models for the unit operations to be added into the simulator. Thus the models that are used to simulate the operation of the various unit operations can be developed and modified to suit the plant under any operating conditions and can be tuned to meet the needs of any application. This characteristic of MODSIM also allows the user to develop and incorporate the results of ongoing research in the mathematical modeling of the unit operations of mineral processing. The repertoire of models available to the system increases continuously as more are added by users. The user can call on any available model [2]. Figure 4. are shown how to enter the mill feed material, the cumulative sieve analysis.

At the heart of MODSIM are the unit models. The simulator is only as good as the models that it contains. If any model does not accurately describe the operation of the unit the simulator cannot give a reliable picture of the behavior of the plant. Models must be chosen with care and for accurate work they should be carefully calibrated against appropriate experimental data [2].

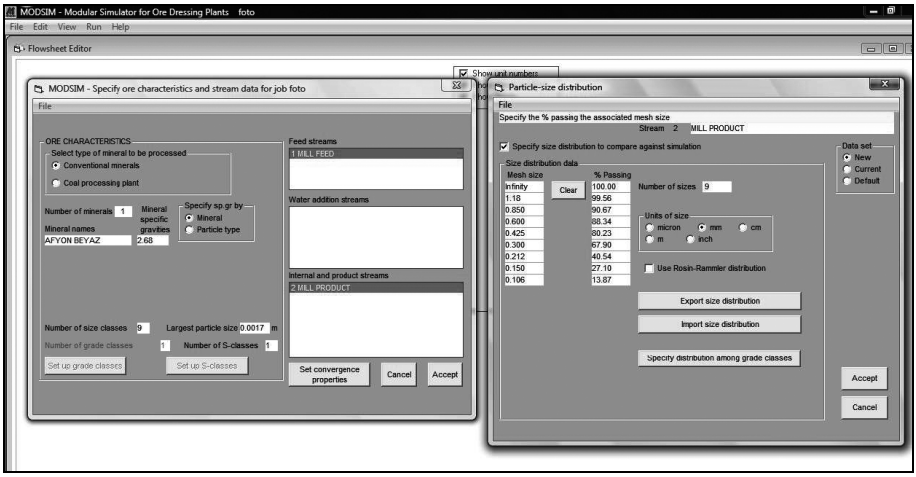

Fig. 4. Input format of cumulative sieve size of the mill feed in the MODSIM

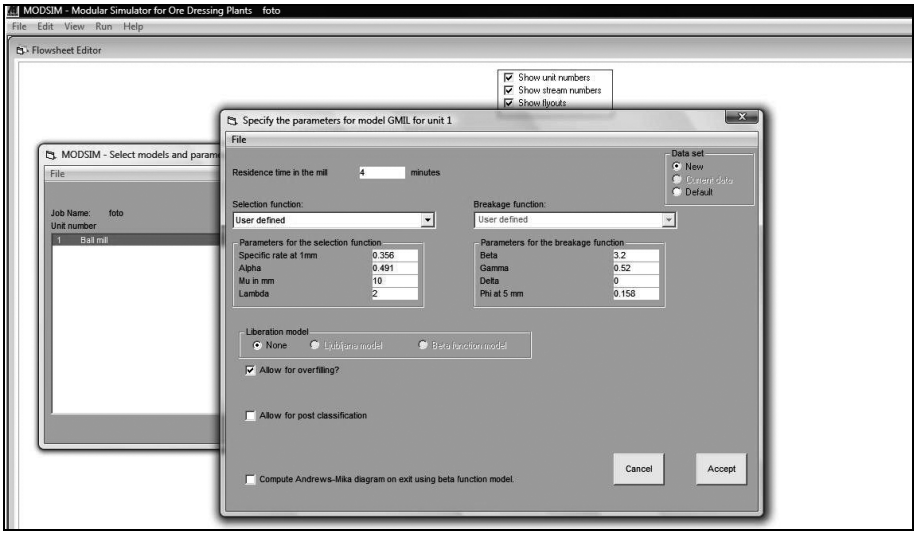

Fig. 5. Input format of selection and breakage function model parameter in the MODSIM

Figure 5 are shown depending on the conditions of the mill, how to breakage function and the cumulative distribution function of the model parameters are done.

This is the simplest model for the ball mill using the selection and breakage functions. The mill is assumed to consist of a single perfectly mixed region. The selection function is the standard Austin function including the maximum that defines the decrease of the breakage rate as size gets large.

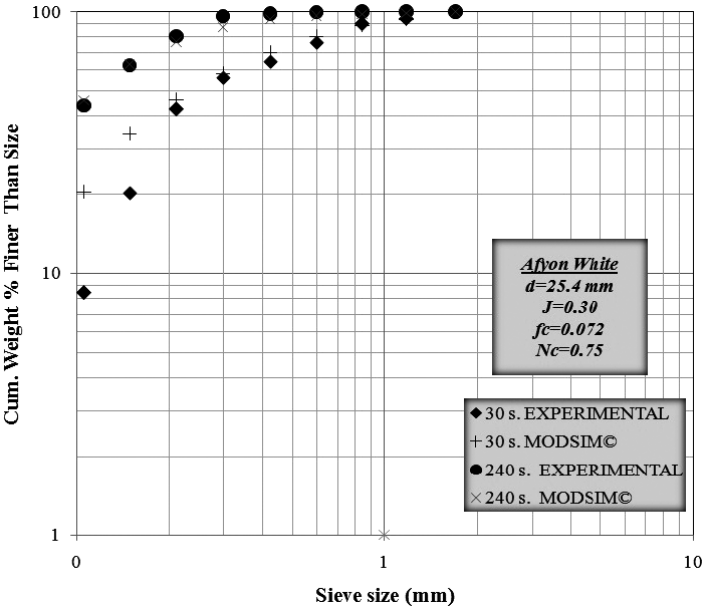

Fig. 6. Comparison of MODSIM and experimental product size distributions of calcite at 0.072 of powder filing

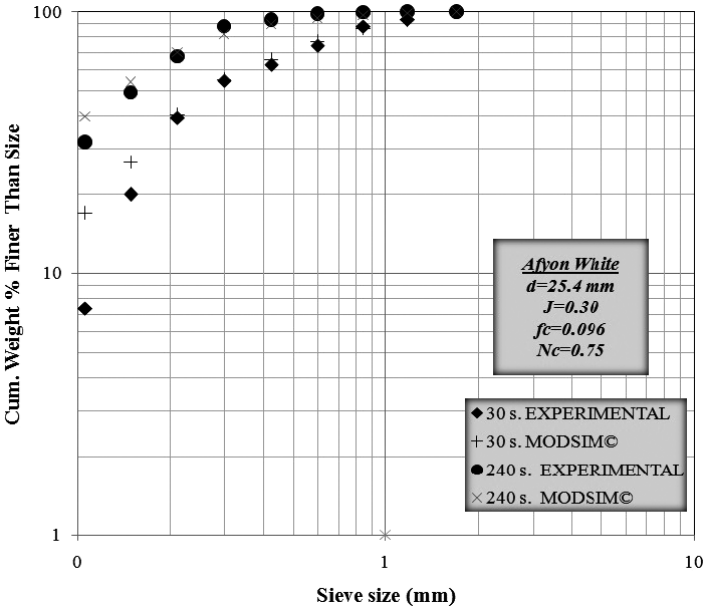

Fig. 7. Comparison of MODSIM and experimental product size distributions of calcite at 0.096 of powder filing

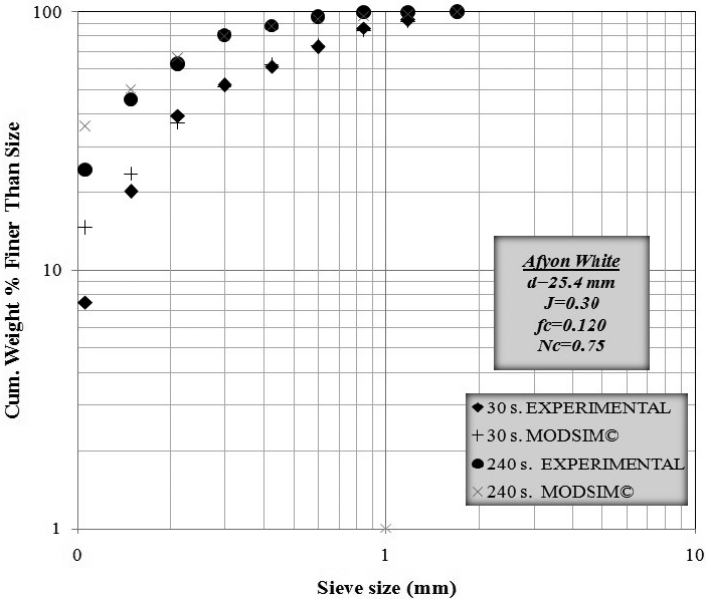

Fig. 8. Comparison of MODSIM and experimental product size distributions of calcite at 0.120 of powder filing

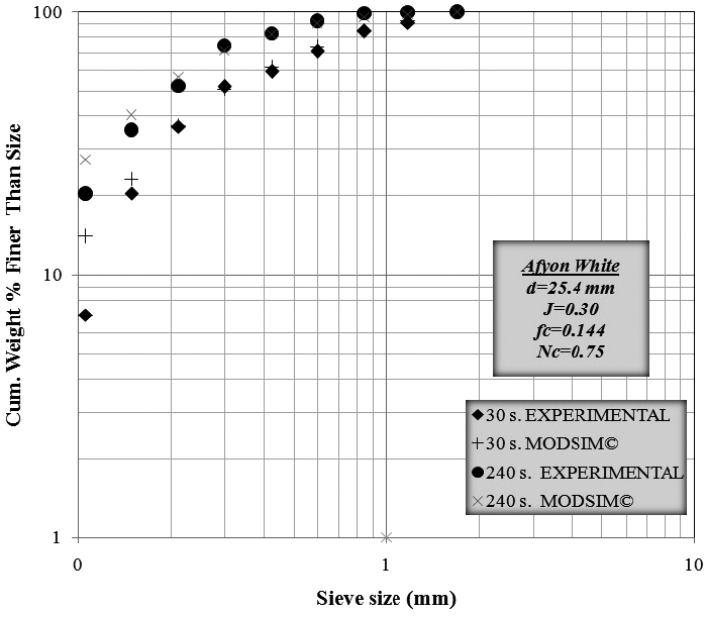

Fig. 9. Comparison of MODSIM and experimental product size distributions of calcite at 0.144 of powder filing

Experimental studies on the samples used in the same mill conditions 30 and 240 seconds in the amount of specific products were obtained from a feed mill. Then, the kinetic model parameters were carried out using the MODSIM simulation program estimates for the same periods.

4.5. Comparison of MODSIM© and Experimental Product Size Distributions

The obtained simulation results are given in the Table 4 with data obtained in real time. Comparison of the data is widely used in recent years, *RMSE* (*Root Mean Square Error*) and *VAF* (*Variance Account For*) is based on indices. To assess the performance of the MODSIM© models the following performance indexes were used namely, the variance account for *VAF*, (Eq. (9)) and the root mean square error *RMSE* (Eq. (10)) [10].

$$VAF = \left[1 - \frac{\mathrm{var}(t - t_i^*)}{\mathrm{var}\,(t)}\right] \tag{9}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(t - t_i^*)^2} \tag{10}$$

where:

var — denotes the variance,
t — is the measured value,
t_i — is the predicted value,
N — is the number of samples.

The above performance indices are interpreted as follows: the higher the *VAF*, the better the model performs. For instance, a *VAF* of 100% means that the measured output has been predicted exactly (perfect model). *VAF* = 0 means that the model performs as poorly as a predictor using simply the mean value of the data. The lower the *RMSE*, the better the model performs. Contrary to *VAF*, *RMSE* also accounts for a bias in the model, i.e. an offset between the measured and predicted data. Table 6 and 7. gives the *VAF* and the *RMSE* indices for both the identification and the validation data. As can be seen, the prediction accuracy in terms of both indices is better for the validation sets.

TABLE 6

Statistical evaluation of data from experimental and modeling on the powder filling f_c = 0.072 and fc = 0.096

Analyses	f_c = 0.072 30 s	f_c = 0.072 240 s	f_c = 0.096 30 s	f_c = 0.096 240 s
RMSE	6.73	3.85	4.19	4.27
VAF	97.26	97.48	98.72	96.85

TABLE 7

Statistical evaluation of data from experimental and modeling on the powder filling f_c = 0.120 and fc = 0.144

Analyses	f_c = 0.120 30 s	f_c = 0.120 240 s	f_c = 0.144 30 s	f_c = 0.144 240 s
RMSE	2.91	4.61	2.89	3.62
VAF	99.13	97.08	99.43	98.39

5. CONCLUSIONS

Simulation techniques are popular because they allow complex problems to be tackled without the expenditure of large resources. MODSIM© has proved itself to be an excellent teaching tool both for conventional courses.

The model parameter values of the powder filling are similar to the literature on the powder filling. Powder filling increases, a_T value were decreased. γ value increases with increasing powder filling, the material Φ_j value decreases with increasing load is observed. As powder filling increases, while decrease the specific rate of breakage is due to the increase in the rate of gap filling. The same argument can be based on reason for the lack of increase in the rate of fine material.

The main advantage of using quantitative models is that they permit the complex interactions between different unit operations in a circuit to be explored and evaluated. Almost all of the models described are strongly nonlinear and are not usually amenable to straightforward mathematical solutions, nor are they always very convenient for easy computation using calculators or spread sheets. In order to investigate interactions between models, the simulation method is strongly recommended, and the focus throughout this study has been on the development of models that can be used in combination to simulate the behavior of complex mineral dressing flow sheets.

Generally, it showed that grinding kinetic parameters could be different for sample. Therefore, it has appeared that using the grinding kinetics for each material must be estimated to the product size distributions and energy

REFERENCES

[1] *Austin L.G., Yildirim K., Luckie P.T., Cho H.C.*: Two Stage Ball Mill Circuit Simulator: PSUSIM, Penn State University, USA 1989.

[2] *King R.P.*: Modeling and Simulation of Mineral Processing Sisytem, Department of Metallurgical Engineering University of Utah, USA 2001.

[3] *Yan D., Eaton R.*: Breakage properties of ore blends, Minerals Eng. 7 (1994) 185–199.

[4] *Austin L.G., Klimpel R.R., Luckie P.T.*: The Process Engineering of Size Reduction, SME-AIME, New York, 1984, p. 561.

[5] *Austin L.G., Bagga P.*: An analysis of fine dry grinding in ball mills, Powder Tech. 28 (1981) 83–90.

[6] *Austin L.G., Bhatia V.K.*: Experimental methods for grinding studies in laboratory mills, Powder Tech. 5 (1971/1972) 261–266.

[7] *Austin L.G., Luckie P.T.*: The estimation of non-normalized breakage distribution parameters from batch grinding tests, Powder Tech. 5 (1971/1972) 267–271.

[8] *Ipek H., Uçbaş Y., Yekeler M., Hoşten Ç.*: Dry grinding kinetics of binary mixtures of ceramic raw materials by Bond milling, Ceramics International 31 (2005) 1065–1071.

[9] *Austin L.G., Luckie P.T.*: The estimation of non-normalized breakage distribution parameters from batch grinding tests, Powder Tech. 5 (1971/1972) 267–271.

[10] *Alvarez Grima M., Babuslka R.*: Fuzzy model for the prediction of unconfined compressive strength of rock samples, International Journal of Rock Mechanics and Mining Sciences 36 (1999) 339–349.