The Effect of Ball Type in Fine Particles Grinding on Kinetic Breakage Parameters

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Summary

In the study, the effect of different grinding media on breakage parameters was investigated. Ceramic and steel balls were used as the grinding media. It was observed that the grinding of ignimbrite obeyed first-order breakage kinetics law in the case of ceramic and steel balls. Breakage rates were higher for steel ones comparing to ceramic balls. Furthermore, it was found that the primary breakage distribution function depends on the feed size (i.e., non-normalized), and depends on the different grinding media. The effect of grinding time on the product particle size distribution has also been investigated.

Keywords: breakage parameter, ignimbrite; ball mill, ball type

Introduction

Ignimbrite is material resistant to physical and chemical effects. This is spongy, very porous, alumina-silicate composition volcanic tuff. Ignimbrite is processed by open pit method and then by grinding. Mainly, it is used in civil engineering and agriculture industry. It is also used for germination, rooting, seedling cultivation, land reclamation, cultivation and preservation of ornamental plants. Ignimbrite is used also in heating conditions and as noise insulation in the construction sector [16].

Ignimbrite can also be used as a trass and trass is pozzolan. While pozzolans do not have any binding character, it can be combined in normal temperatures with lime in an aqueous medium. Then, it is capable of binding water-insoluble substances that contain components able to form stable compounds. Once pozzolans are very fine grained, they react chemically with calcium hydroxide in aqueous solution at normal temperature. Their hydraulic properties indicate the natural pozzolanic [9].

For cement production, drug, chemical and mineral industries, dry grinding applications are undoubtedly ones of the most important processes. Energy consumed by this process is very large, especially in case of crushing and grinding processes. There are many types of grinders manufactured and many varieties of machines made for the process. To make an appropriate choice is often a difficult problem [6].

The selection function (S_i) and breakage function ($B_{i,j}$) have been investigated by many researchers using a wide variety of grinding mills and conditions of research [4, 13, 7, 8, 12, 14]. Even now this item is of great interest when considering the performance of a grinding process in the comminution of coarse particles.

The primary function of grinding media is to crush and grind ore particles inside rotating mills, which can be ball, rod or semi-autogenous mills. Sometimes it can occur also in mechanically stirred mills [11]. In recent years, grinding charges with unconventional shapes have appeared on the market. One example is the cylindrically shaped media called pebbles [17, 15]. Pebbles have greater surface area and higher bulk density than balls of similar mass and size, due to their shape. Pebbles of the same diameter and length have 50% greater surface area, and 45% greater weight, than balls of the same material. In addition, they have 9% higher bulk density than steel balls, and even 12% higher than cast balls [11].

In the past, it was thought that a load comprised of two different media shapes other than spherical balls might influence on the performance of a tumbling mill because of variations in load characteristics, charge segregation, power drawn by the mill or breakage kinetics. The extent of this influence has not yet been established [15, 10, 18, 3]. All efforts have exclusively been focused on breakage rate, ignoring other parameters defining mill performance such as load characteristics and mill power.

The analysis of size reduction in tumbling ball mills using the concepts of specific rate of breakage and primary daughter fragment distributions has received considerable attention in recent years [2, 3, 4]. Austin reviewed the advantages of this approach, and the scale-up of laboratory data to full-scale mills has also been discussed in a number of papers, and are summarized by Austin and Bagga [3].

In the present study, the effect of different grinding media on breakage parameters was investigated. Ceramic (zirconium silicate) and steel balls (Alloy steel) were used as the grinding media. It was observed that the grinding of ignimbrite obeyed first-order breakage kinetics in the case of ceramic balls and steel balls, with a constant ball diameter (25.4 mm) and rotational speed of mill ($\varphi c = 0.75$).

Theory

In the analysis of the breakage materials, it is useful to make the initial assumption that the breakage of each size fraction occurs according to first order in nature. That is, the rate of lowering of size 1 due to breakage is proportional to the amount of size 1 material in the mill [17].

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

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 of size 1 at time *t* [4]. The formula proposed by Austin et al, (1981) for the variation of the specific rate of breakage S_1 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 equal to 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 area, each size behaves as having fraction of weak material and the remaining fraction of stronger material. Using a mean value for S_1 in this area, values of Q_i are empirically described by

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

where μ is the particle size at which correction factor is equal to 0.5 and λ is positive number which index shows how rapidly the rates of breakage fall as size increases and in case of higher value of ʌ, the the values decrease more rapidly. 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*". It is commonly used to characterize the size distribution resulting from breakage of material from a particular size interval to a smaller size [1, 2, 17].

The $B_{i,j}$ values can be calculated using the *BII* method which is described in papers [1, 2].

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

The parameter ϕ 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 [1].

Material and Methods

Materials

Ignimbrite was chosen as the feed mineral for this study, because this mineral is one of major raw materials being used in cement and construction industry. The density of these raw materials, measured by a pycnometer, is equal in average to 2.36 g/cm^3 according to three repetitive measurements. Chemical analyses of this material are also given in Table 1.

Grinding tests

The breakage parameters were determined experimentally using one size fraction technique. The size fractions chosen for tests were, -0.106 +0.090, -0.090+0.075, -0.075+0.063 and -0.063+0.045 mm. The standard set of grinding conditions is shown in Table 2.

Results

Determination of S parameters

Grinding media directly affect the load characteristics and consequently the operations of industrial mills in terms of product size, energy consumption and grinding costs. The results indicated that

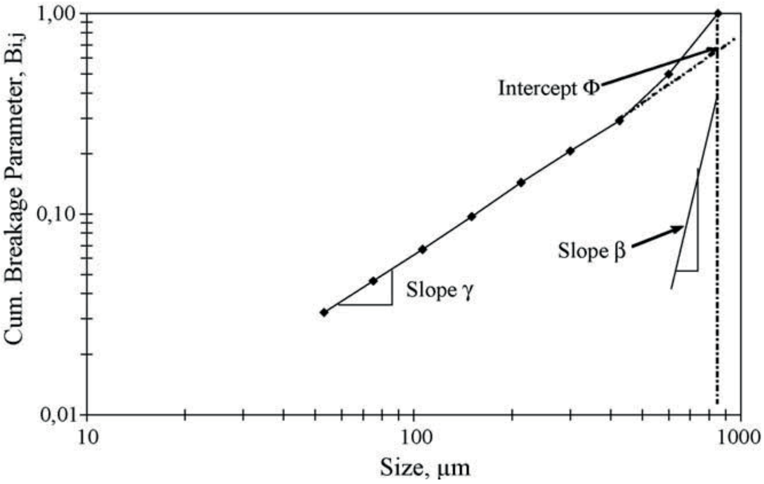

Fig. 1. The primary breakage particle size distribution function parameters for any single size fraction feed ground in the mill

Rys. 1. Podstawowe parametry funkcji rozkładu rozmiaru pęknięć cząsteczki dla każdego pojedynczego pęknięcia podłoża zasilającego młyna

Tab. 1. Chemical composition of ignimbrite

Tab. 1. Skład chemiczny ignimbrytu

Oxides	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	LOI
(%)	71.71	15.03	2.26	0.20	1.49	0.08	1.40	0.28	0.10	0.03	<0.001	7.43

Tab. 2. Ball mill characteristics and test conditions

Tab. 2. Właściwości kuli młyna i warunki testowe

Mill	Diameter, D (mm)	200	
	Length, L (mm)	200	
	Volume (cm^3)	6283	
	Critical mill speed, *Nc* (rpm)	101	
	Operational speed	76	
Media (Balls)	Grinding diameter, d (mm)	25.4	
	Media (balls) specific gravity	7.8	2.7
	Quality alloy	Alloy steel	Zirconium silicate
	Assumed porosity (%)	40	
	Ball-filling volume fraction*, J (%)*	0.30	
Material	Specific gravity	2.36	
	Powder-filling volume fraction f_c *(%)*	0.096	
	Interstitial filling *U (%)*	0.80	

Tab. 3. Characteristic breakage parameters of different ball types obtained from the laboratory test

Tab. 3. Cechy parametrów pękania w różnych typach kul otrzymanych dzięki testowi laboratoryjnemu

Ball Type	Si -75+63 µm	α_T	α	μ	Λ
Ceramic	0.014	0,10	0,59	2,00	7,06
Steel	0.065	0,22	0,44	2,00	4,76

breakage generally do not follow the first order relation, and values of S_i could be determined from the slope of straight line of not-first order plots (Figure 2 and 3). In addition, Figure 4 shows S_i in relation to the different ball type and particle size for ignimbrite. The model parameters are also given in Table 3.

S_i values show that grinding is faster for the steel ball. Addition, it is clearly seen that S_i values increase up to a maximum particle size (0.075 mm), and then start decreasing at around 0.075 mm for both ball types.

In the experimental, aT value was high for steel balls. As the amount of a_T value increased, it is more efficient and broke quickly till undersize of original particle size. The values of a_T increase together with increasing particle size due to the higher impact force pressed to ignimbrite sample. However, the value of α does not appear to vary with increase of ball filling in the normal breakage area.

Breakage distribution functions

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

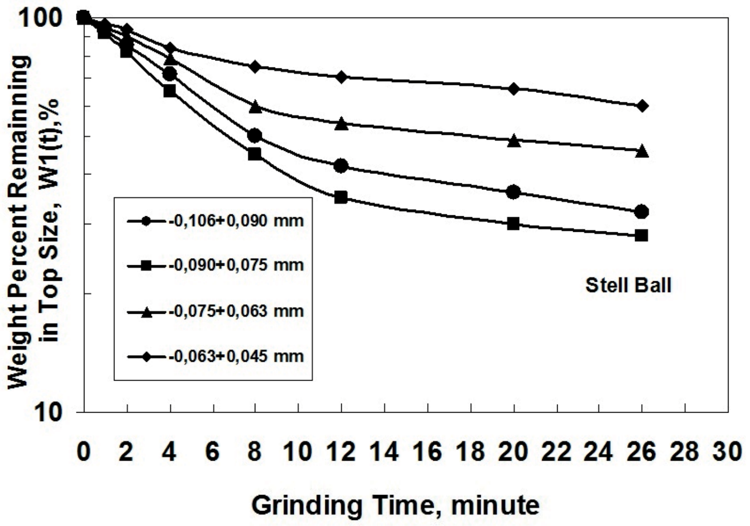

Fig. 2. First-order plots for steel balls

Rys. 2. Wykres reakcji pierwszego rzędu dla kul stalowych

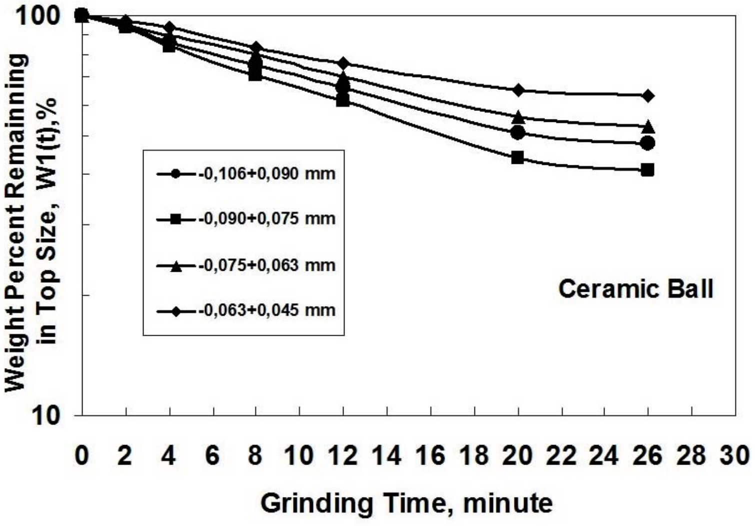

Fig. 3. First-order plots for ceramic balls

Rys. 3. Wykres reakcji pierwszego rzędu dla kul ceramicznych val to a smaller size were determined by means of the BII method [1, 2].The values of $B_{i,j}$ against particle size obtained from BII calculations for each size fractions are plotted in Figure 1. In order to get the $B_{i,j}$ values, BII calculation procedure [4] given below was applied for the shortest grinding time,

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

where $P_i(0)$ = cumulative weight fraction of time 0 for ith 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 on the basis of size distributions at short grinding times using the BII method and are shown on Figure 5. The results showed a typical normalized characteristics so that the progeny distribution did not depend on the feed particle size and the parameter δ was equal to zero. The model parameters are also given in Table 4.

Shi [15] said that the different grinding media have different surface area, bulk density (implicitly the charge mass or volume when one of them is fixed) and contact mechanism in their grinding

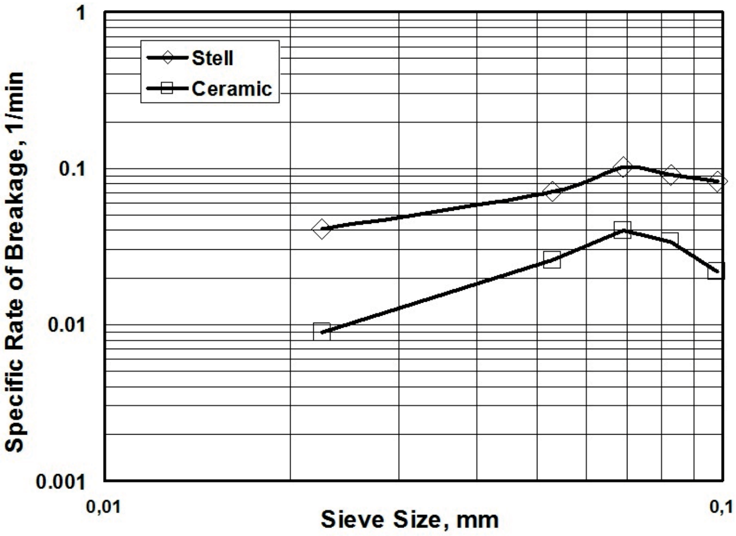

Fig. 4. Variation of S_i values of ignimbrite with particle size for the different ball types

Rys. 4. Zmienność wartości S_i ignimbrytu z wielkością cząsteczki dla różnego typu kul

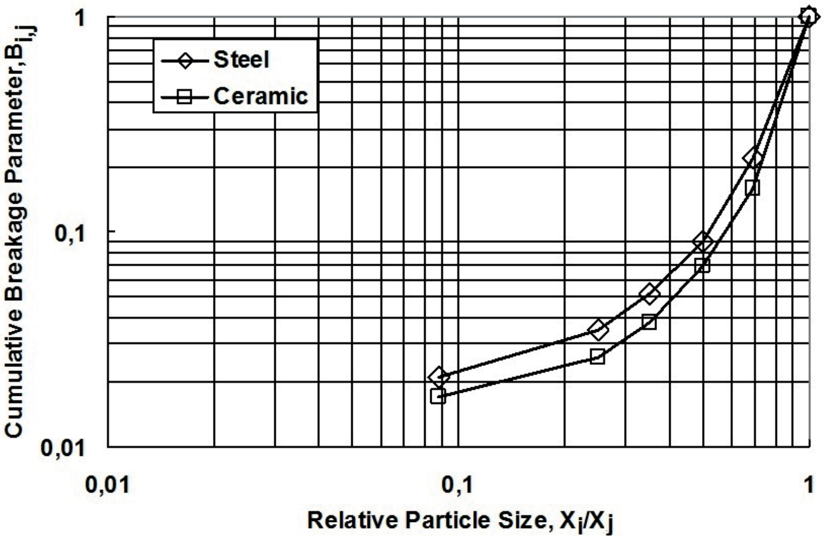

Fig. 5. Cumulative breakage distribution functions for different ball type

Rys. 5. Funkcje łącznego rozkładu pęknięć dla różnego typu kul

Tab. 4. Paremetres of breakage distribution functions for different ball types

Tab. 4. Parametry funkcji rozkładu pęknięć dla różnego typu kul

Ball Type	Φ_j	γ	β	δ
Ceramic	0.0457	0.407	4.630	0.00
Steel	0.0694	0.489	4.961	0.00

actions. All these factors need to be taken into account when comparing the different characteristics as well the milling performance using the different types of grinding media.

The slope of the lower portion of the $B_{i,j}$ curve denoted by γ is also a convenient and measurable parameter for characterizing material oriented breakage properties. It characterizes the relative amount of fine particles produced from the breakage of the top size material and therefore directly relates to the efficiency of the grinding process. A higher value of γ implies that the progeny fragments are coarser, i.e., their size is closer to the size of the parent material being broken and that grinding is taking place at a slow rate. On the other hand, a lower value of γ would imply more efficient breakage action with high production of fine particles [4].

The $B_{i,j}$ values are different for steel and ceramic ball (Table 4). In the experiment, γ value (0.489) for steel ball type are higher than for ceramic ball type (γ = 0.407). It can be caused by increased rate of fine material in the ceramic type because the contact between the material surface and steel balls is lower than in case of ceramic ones.

The values of the coefficient ϕj are related to the coarse end of the breakage distribution function and show the speed with which fractions of size close to feed size pass to the smaller size interval. The model parameter ϕj value of steel ball is much higher than for ceramic balls. Parameter ϕj is related to coarse end of the breakage distribution function and show how fast fractions close to the feed size passes to smaller size interval. This study demonstrates that values ϕj of ignimbrite powder do not cause increasing of production by using ceramic ball. Ceramic balls are not affected by the coarse ignimbrite particles. Since steel ball has a greater load than ceramic balls, the breakage of the top size gave higher production rate by means of steel balls ($\phi j = 0.0694$), and lower production rate by using ceramic balls ($\phi j = 0.0457$).

Conclusions

In this study, the experiments of grinding by means of single type of balls have been performed in laboratory-scale studies. In fact, grinding experiments should be conducted under different conditions according to industrial requirements.

Grinding results of ignimbrite showed that ignimbrite does not obey first-order breakage kinetics law in the case of both steel and ceramic balls. The specific rates of breakage parameters in terms of S_i and a_T values were higher for steel than ceramic balls, indicating that steel balls have higher rates of breakage than ceramic balls. The specific rate of breakage values, S_i, increased up to 0.075 mm and then sharply decreased. This can be explained by the fact that fine particles are difficult to break and grind by the medium, and hence, the grinding efficiency decreased.

The primary breakage distribution functions of ignimbrite were found to be normalized, what means that they are independent on initial feed size in the case of both ceramic and steel balls. The effect of grinding time on the product particle size distribution was also investigated. The ceramic balls produced more fine particles than steel balls; this may be caused by the contact mechanism of ceramic balls. As a result of use of the low density ceramic balls, ignimbrite is more affected due to the effect of cataract at the same rotation speed.

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Wpływ typu kul przy mieleniu drobnych cząstek na kinetyczne parametry pękania

W niniejszych badaniach sprawdzono wpływ różnych mediumów mielących na parametry pękania. Jako mediumy mielące użyto kule ceramiczne i stalowe. Zaobserwowano, że w przypadku kul ceramicznych i stalowych mielenie ignimbrytu było zgodne z kinetycznym prawem pękania pierwszego rzędu. Wskaźniki pękania w przypadku kul stalowych były wyższe w porównaniu do kul ceramicznych. Ponadto odkryto, że podstawowa funkcja rozkładu pęknięć zależy od rozmiaru zasilenia (tzn. nieznormalizowanego) i od różnego medium rozdrabniającego. Sprawdzono również wpływ czasu rozdrabniania na rozkład rozmiaru cząsteczek.

Słowa kluczowe: parametr pękania, ignimbryt, młyn kulowy, typ kuli