

Received August 11, 2012; reviewed; accepted November 22, 2012

SELECTED MINERAL MATERIALS GRINDING RATE AND ITS EFFECT ON PRODUCT GRANULOMETRIC COMPOSITION

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Abstract: The article presents investigation on the grinding rate constant. A selection function was measured for different raw materials using a ball mill, and effects of the grinding ball diameter and feed particle sizes on the materials grinding rate constant were investigated. The study was conducted for the mill on a semi-technical scale. The process was carried out periodically using several sets of grinding media. Relations for all investigated materials were expressed by the modified Snow equation. Additionally, the descriptions of the grinding rate was examined. The tendency in the variation of the grinding rate constant with the particle size was similar for all materials used, and was independent of the ball diameter. The author used two selection functions derived theoretically by Tanaka.

Keywords: *ball mill, specific grinding rate, contact points, size distribution*

Introduction

The industry producing ceramic materials most often uses milling devices, operating principle of which is based on the energy of free grinding media in order to grind the feed. The simplest constructional solution is ball mill with steel or alubit grinding media. Material particles grinding in mills of this type takes place mainly between grinding elements and to a much lesser extent between grinding media and the internal surface of the drum. Ground material particles which are between moving surfaces of the adjacent balls (this movement can result from both progressive and rotary ball motion) are mainly abraded and sheared with a possibility of the crushing mechanism participation. With a cataract ball motion (very desirable in ball mills) there will also occur an impact mechanism of the balls falling down. The ball size and related to it their number also have effect on the contribution of grinding mechanisms. It is obvious that at the same volume of the bed of balls (and at the same time the degree of

filling the drum with balls) the larger are the balls, the smaller will be the number of balls. Larger balls means larger mass of a single ball and higher forces of their mutual interaction. The smaller number of balls related to this means smaller number of contact points, thus reducing mini-areas in which at any given time loads damaging the ground material particles may occur.

Selection of balls diameter depends on the ground material strength as well as the diameter of raw material particles. Generally, for larger particles, which require higher forces to be damaged, larger balls should be used, while in the case of smaller particles (materials weak in strength) better results are obtained by increasing the number of balls' contact points, i.e. by increasing their number at the expense of diameter.

The simplicity of the mill construction is not accompanied by the effectiveness of the grinding process. The low efficiency of the grinding process, caused by the grinding media energy dissipation, forces process engineers to search for such a ball composition for which the decrease of the mean particle dimension is the fastest. This will provide an opportunity to use the operation time of the mill more efficiently.

For many years, the grinding process in ball mills is the subject of statistical analyses and description of kinetics (Epstein 1948; Herbst and Fuerstenau 1968). During grinding in batch ball mills, the mass flow between the separate size classes is analyzed. The selection function, describing the probability of particle grinding, and grinding function, describing the size distribution of raw material ground particles, among others are used for the description of this phenomenon. The mentioned functions enable the description of mass balance for particle size classes by means of an expression (Gaudin and Meloy 1962; Reid 1965):

$$\frac{dm_i(t)}{dt} = -S_i m_i(t) + \sum_{\substack{j=1 \\ j < i}}^{i-1} b_{i,j} S_j m_j(t), \quad i = 1, 2, \dots, n, \quad (1)$$

where $m_i(t)$ is the mass of particle fractions from the size range i , S_i is the selection function, $b_{i,j}$ is the rate in which the feed particles from the size range j become particles from the size range i , while t is grinding time. Additionally, it is assumed that in the case of the first size class (particles with the largest size), that is for $i = 1$, the rate of decreasing of this class can be described by the following first order equation:

$$\frac{dm_1(t)}{dt} = -S_1 m_1(t). \quad (2)$$

The form of the selection function S_1 was determined and analyzed by many researchers for ball mills differing in construction, process and equipment conditions, including Kelsall et al. (1968), Austin et al. (1976), Kanda et al. (1978), Zhao and Jimbo (1988), Nomura et al. (1991) or Olejnik (2012). Despite this, the issues of efficiency and rate of the feed comminution process continue to arouse interest. Also

Obraniak and Gluba (2012) used the general form of equation (1) for the description of the granular material granulation rate.

Equation (2) shows that the feed particles disappearance rate decreases. Disappearance in time of the largest feed particles $m_i(t)$ can be described by a dependence:

$$-\frac{dR}{dt} = K_1 R \quad (3)$$

where R is the mass of the feed contained in the largest size fraction, while K_1 corresponds to the constant value of the grinding rate (selection function S_i) for the largest size fraction of particles.

Aim of the study

The author's earlier publications pointed to the dependence between the rate of grinding, the value of partition function and the selection function for batch grinding in a ball mill for variable process parameters. Studies were conducted in a limited range and the obtained results were encouraging enough to undertake further studies and analyses of the process kinetics, with particular emphasis on the rate of grinding the largest particle size fractions (Olejnik 2010, 2011).

Experimental studies

Three rock materials were used for the studies they were: granite, quartzite and graywacke. The value of the batch density and hardness according to the Mohs scale is included in Table 1.

Table 1. Bulk density and mineral hardness

Raw material	Density, kg·m ⁻³	Mohs hardness
Granite	1402	6
Quartzite	2315	7
Greywacke	1267	5

Mineral raw materials used in the studies were characterized by various of flexibilities and grindabilities initially were crushed to a give particle size in the range of 5÷8 mm.

Granite is a solid, acidic magma-deep rock, medium or thickly-crystalline of overtly-crystalline structure distinguished by clear symmetry planes, usually in three orthogonal directions (Cappell and White 2001). The bulk density of granite was determined after a free drop and after 10 minutes of shaking of the measurement

sample. The bulk density was, equal to 1394 kg/m^3 and 1410 kg/m^3 , respectively, and its average value was equal to 1402 kg/m^3 .

Cambrian sedimentary quartzite was from the Swietokrzyskie Mountains. Majority of the sedimentary quartzite consisted of closely adherent particles bound by silica. Bulk density was, respectively, equal to 1236 kg/m^3 and 1298 kg/m^3 , and its average value was equal to 1267 kg/m^3 .

Greywacke is a sedimentary elastic multi-component rock rich in chippings of various finely crystalline rocks (above 25% of dendrite material). Granite is a lithic, acidic, magmatic-intrusive rock, medium or thickly crystalline rock of clearly crystalline structure displaying a visible joint in three perpendicular directions. Greywacke bulk density average value was equal to 1267 kg/m^3 .

The comminution was conducted in a dry mode. The milling kinetics tests were carried out in a semi-technical mill. The internal diameter of the mill's chamber was 0.5 m, whereas its total capacity 0.112 m^3 . The mill's rotational frequency was constant and amounted to 0.517 s^{-1} , which constituted 54% of its critical rotational frequency. Filling of the mill (grinding media and feed) was determined for circa 35% of mill capacity. The process of milling was conducted in a periodical mode using balls of different diameters. Ball sets, differing in diameters, are presented in Table 2. Total mass of balls applied for milling was about 40 kg. Feed sampling was performed every 20 minutes, collecting mass of about 0.6 kg for the particle size analysis. The samples were subjected to a particle size analysis using a laser particle size analyzer Analysette 22 (FRITSCH). The analysis of the shape of particles and granulometric composition was carried out with the analyser AWK 3D made by Kamika Instruments. The results of analyses allowed to determine the granulometric composition of the milled material in particular moments of comminution. The particles' shape was determined using the classification according to Zingg (1935).

Table 2. Ball specification for particular compositions

Series	A	B	C	D
Ball diameter, mm	Ball mass, kg			
10	–	6	1	–
20	–	12.3	12.5	11
30	–	12.3	12.5	15
40	–	10	15	15
60	40	–	–	–
Sum	40	40.6	41	41

Results and discussion

In diagrams (Figs 1–4), a dependence between the mass of the fraction of the feed, found on a sieve with the largest size of 3 mm and grinding time for four measurement series, differing in ball composition, is presented. They show almost a linear

dependence in a semi-logarithmic system between the particle composition with the largest size class and grinding time. Therefore, it is possible to determine constant K_1 from Eq. 3. The course of curves variation points to the influence of K_1 value on the percentage of the feed particles in the largest size fraction. Austin et al. (1976) and Zaho and Jimbo (1988) proposed the following equation to express the relationship between the change in $K_1 = S_1$ and the size of the feed particles:

$$S_1 = ax_f^\alpha Q(z) = ax_f^\alpha Q\left(\frac{\ln(x_f/\mu)}{\ln \sigma}\right) \tag{4}$$

where a and α are constants. $Q(z)$ is a Gaussian distribution function, x_f describes the value of the feed particles size while z is a dimensionless parameter. The feed particles size for $Q(z) = 0.5$ was labeled with μ , while $\ln \sigma$ determines the standard deviation.

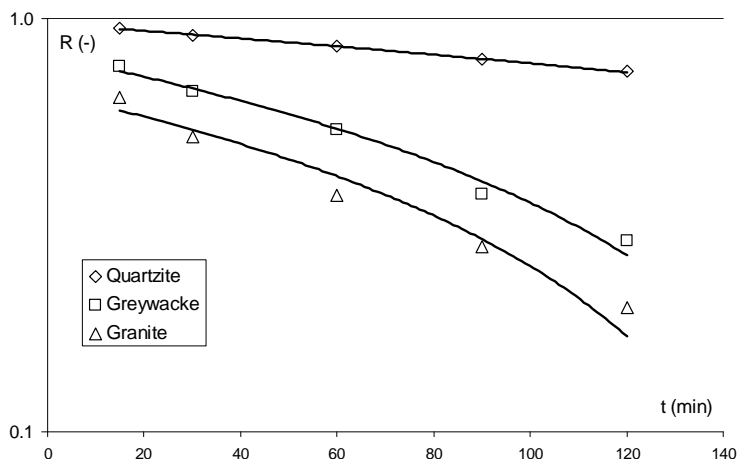


Fig. 1. Dependence between mass of the largest feed particle fraction and grinding time. Ball composition A

From the studies of Austin et al. (1976) and Zhao and Jimbo (1988) it resulted that dependence (4) can be used for describing grinding of very fine particles. For big particles (Eq. 4) was not applicable. Snow (1973) citing data of Kelsall et al. (1968) proposed that the dependence between S_1 and the feed size can be described by Eq. (5)

$$\frac{S_1}{S_m} = \left(\frac{x_f}{x_m}\right)^\alpha \exp\left(-\frac{x_f}{x_m}\right) \tag{5}$$

where x_m is the feed size, at which S_1 reaches the maximum value of S_m .

Using the concept of Austin et al. (1976) and assuming that for the feed, equality holds between the constant of grinding, determined from equation Eq. 3, and S_1 for each composition of balls and ground raw materials, the constant of grinding rate was determined.

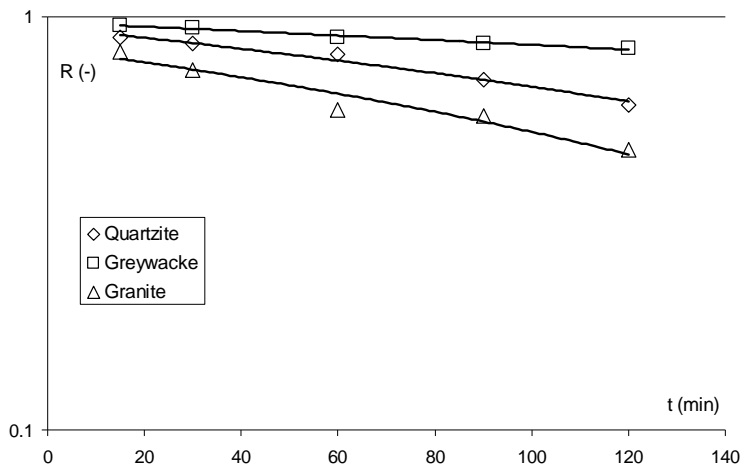


Fig. 2. Dependence between mass of the largest feed particle fraction and grinding time. Ball composition B

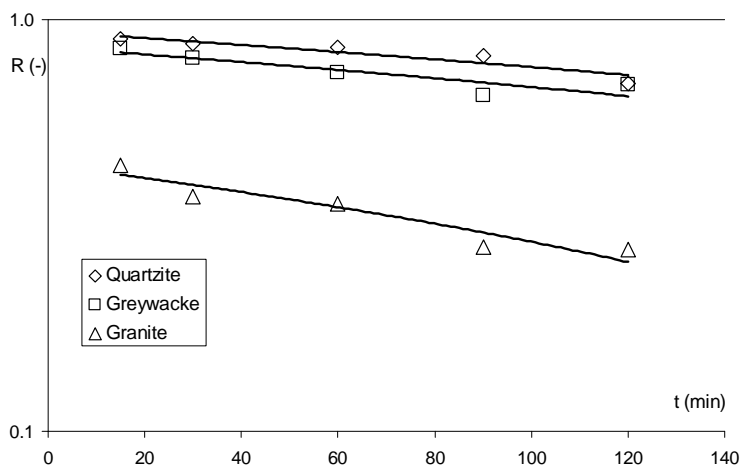


Fig. 3. Dependence between mass of the largest feed particle fraction and grinding time. Ball composition C

Figure 5 contains a dependence between the constant of grinding rate K_i and the feed granulometric composition x_j for grinding of quartzite. The diagram was drawn in the logarithmic form. Different compositions of grinding media were the parameter.

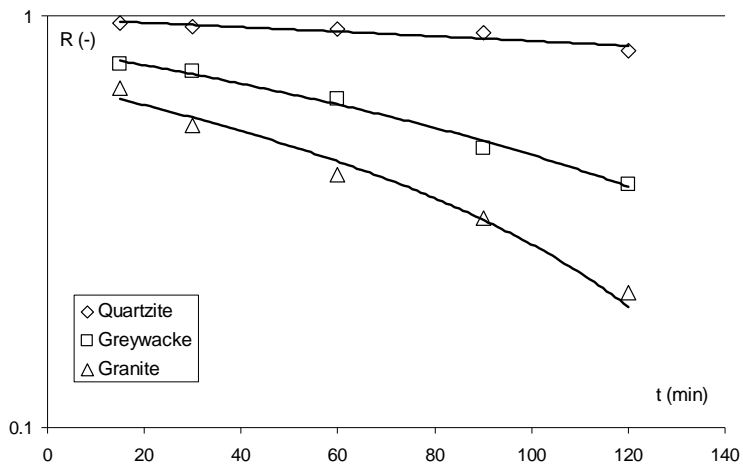


Fig. 4. Correlation between weight of feed particles largest fraction and grinding time. Balls composition D

The feed granulometric composition was determined in terms of weight for separate size fractions after 30 minutes of grinding. A significant effect of the grinding media size on the value of the grinding constant K_I can be observed for particles above 2 mm.

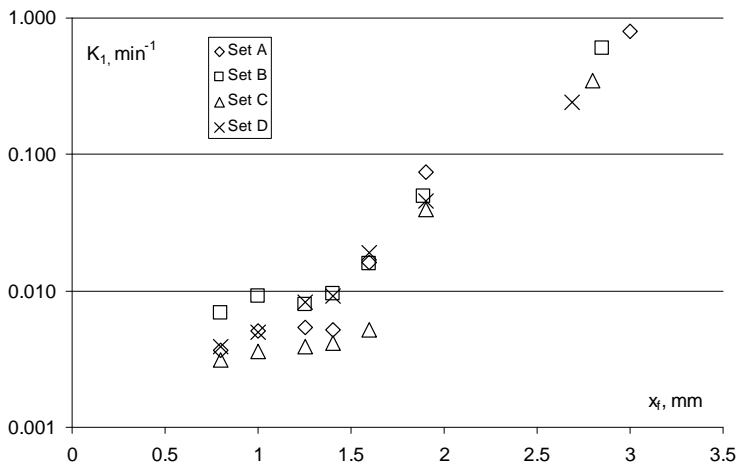


Fig. 5. Change of grinding constant value K_I , with feed granulometric composition after 30 minutes of grinding of quartzite for four ball sets

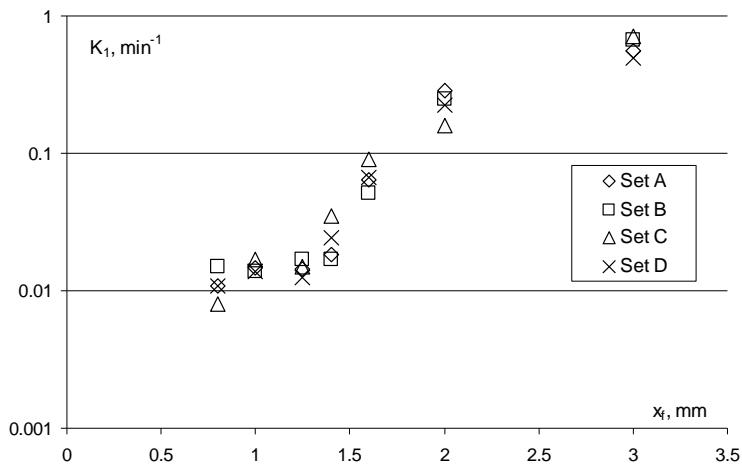


Fig. 6. Change of grinding constant value K_1 and feed granulometric composition after 30 minutes of grinding for sgreYWacke for four ball sets

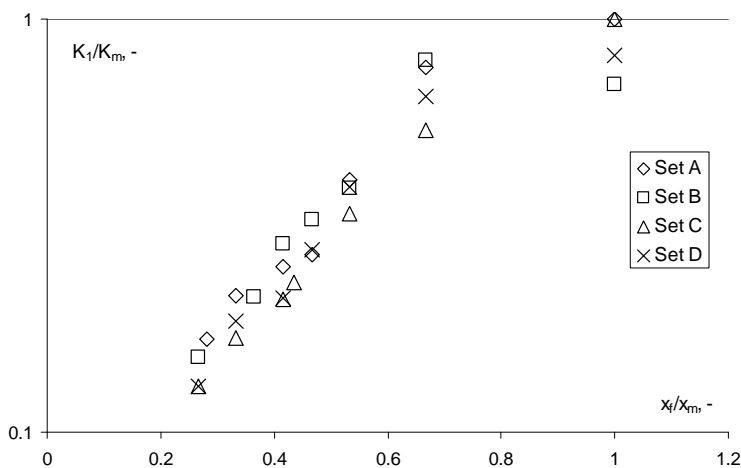


Fig. 7. Change of grinding constant value K_1 and feed granulometric composition after 30 minutes of grinding of granite for four ball sets

Analysing the course of constant K_1 variability presented in Figs 5–7 it can be stated that they are similar in nature to the three investigated materials. Simultaneously, the course of the dimensionless parameter K_1/K_m value variability presented in Figs 8–10 for the dimensionless feed particle x_i/x_m is arranged along straight lines, while the grinding media diameter had no significant effect on its value. A possible explanation of this intriguing fact can be that in the first grinding stage, the grinding rate depended on the grinding medium diameter determining mechanisms

playing a key role in grinding of the feed particles with the largest size (Notake et al. 2002).

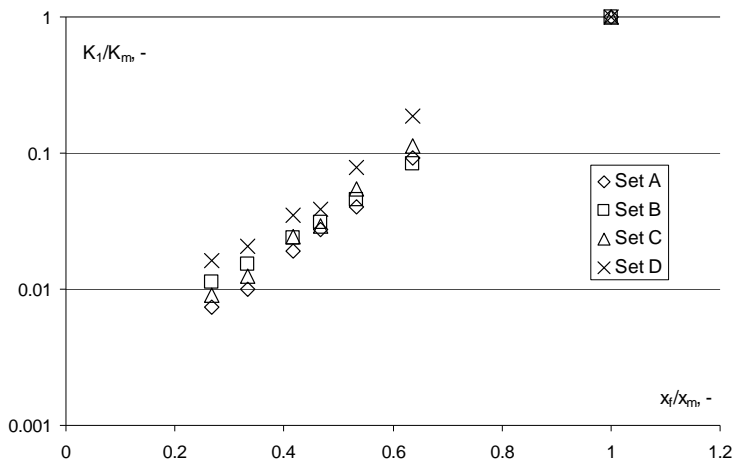


Fig. 8. Change of dimensionless constant of grinding K_1/K_m for quartzite

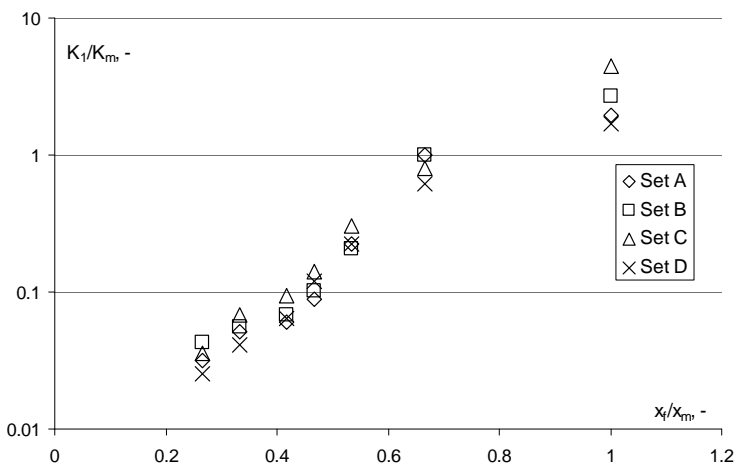


Fig. 9. Change of dimensionless constant of grinding K_1/K_m for greywacke

Figure 11 shows a graphical dependence between the mean particle dimension for the largest size fraction x_m , and the equivalent diameter of grinding media d_B , calculated for each ball set for the three ground materials. The nature of the course of the correlation curves for granite and greywacke is different from the course of the correlation curve for quartzite. Different nature of the course of curves is caused by different morphological structures of raw materials. Quartzite is the material with

almost perfect elastic properties while greywacke and granite are structures with granular structure, characterized by significant grindability.

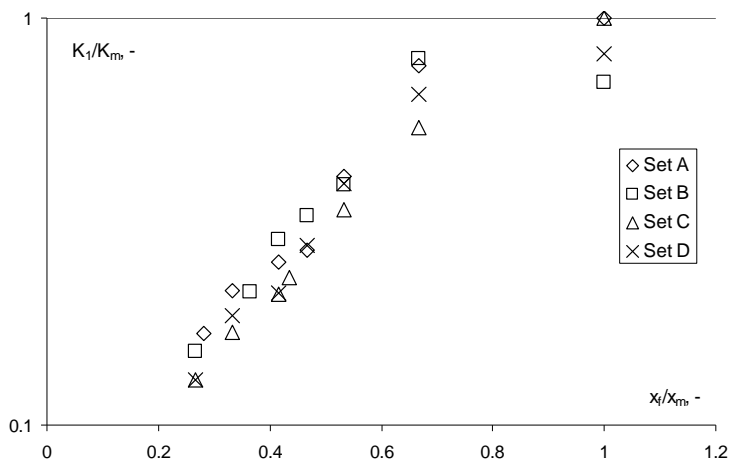


Fig. 10. Change of dimensionless constant of grinding K_1/K_m for granite

Correlation curves, dependencies of the optimum composition of the feed x_m and diameters of grinding media d_B , are described by equations 6-8:

$$x_m(d_B) = 1.7169 d_B^{0.1456} \quad (\text{quartzite}) \quad (6)$$

$$x_m(d_B) = 17.267 d_B^{-0.5304} \quad (\text{greywacke}) \quad (7)$$

$$x_m(d_B) = 28.983 d_B^{-0.8222} \quad (\text{granite}). \quad (8)$$

For the investigated range of ball compositions, in two cases, there is a negative correlation between the ball size and the size of dominating particles contained in the feed. This concerns greywacke and granite. It is assumed that in the considered range of the grinding media variability, for the largest particles of the feed, the relationship between the size and number of balls decides about grinding rate. For grinding media large in size, there is more energy which is used for damaging the internal structure of particles. In the case of raw materials with very heterogeneous particle morphology, also the number of contact points of grinding media with the feed is important. There the ball compositions are differentiated, and with such conditions we had to do in the case of the conducted studies, then with maintaining a constant total mass of grinding media with simultaneous reduction of their size, there is an increase in the probability of finding a particle in the grinding medium impact area. Therefore, for greywacke and granite, grinding media smaller in size enable grinding the feed particles larger in

size. Also abrasive interactions, not only impact interactions, of grinding media decide about the grinding kinetics (constant K_1).

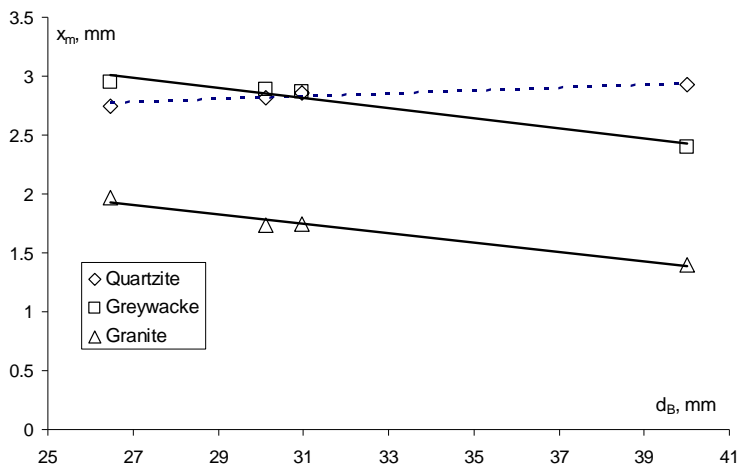


Fig. 11. Correlation between optimum feed size x_m and ball diameter d_B

For quartzite, which is characterised by a high elasticity, the feed particles larger in size must be ground by grinding media larger in size. The direct impact interactions of grinding media decide about rate of the feed grinding K_1 . The larger the size, the more energy necessary for damaging the regular quartzite structure. This correlation is consistent with the literature data by Zhao and Jimbo (1988).

Conclusions

The article discusses the results of batch grinding in a ball mill of rock materials such as quartzite, greywacke and granite, and the effect of grinding media composition on the grinding rate constant value (selection function) of the feed particles. Among conclusions concerning the scope of the study, the following should be enumerated:

1. The change in dimensionless parameter describing the grinding rate constant K_1/K_m , depending on the feed particle size, is independent of the size of grinding media.
2. There are correlations between the optimum feed particle x_m and grinding media size as well as between the largest value of the grinding rate constant K_1 and size composition of balls for the three investigated rock materials.
3. The number of contact points, apart from the grinding media size, decides about the grinding rate.

Acknowledgments

The project was financed within the frame of the research project N R05 0009 06/2009 financed by the Ministry of Science and Higher Education in the years 2009–2012.

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