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Determination of the Bond work index of binary mixtures by different methods

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ABSTRACT

The Bond- and the Hardgrove methods are widely used for the determination of brittle materials' grindability. Generally, the determination of the Bond work index of inhomogeneous materials can be carried out with high deviation using the conventional grindability apparatuses and methods, because of the highly different grindability of components. In the industry the feed of the grinding apparatuses frequently has components with high grindability-difference. The design and operation of the mills can be highly affected by the above mentioned properties. A possible solution can be the combined application of the Bond-method with the determination of the component's weight ratio in the product. The Bond measurement should be performed until the steady state conditions of grindability (G) and chemical composition of the components are reached. To prove the applicability of the above mentioned idea systematic Bond, Hardgrove grindability tests and Karra simulations were carried out of binary mixtures. The experimental results showed that the application of the combined procedure is proven in order to have a more accurate and reliable calculation of the Bond work index of composite materials, especially when the components have significant difference in the grindability and composition. The measurements also showed the possibilities and limits of the grindability tests and calculation methods.

1. Introduction

The determination of the composite materials' grindability is a complex task. The Bond work index of inhomogeneous materials can be measured generally with high deviation, because the components have highly different grindabilities. The Bond work index can be determined by many ways, some of them are as follows: with the traditional standard method in a (1) Bond-ball mill or in a (2) Hardgrove mill with the conversion of the Hardgrove method's result to Bond work index by an empirical formula, (3) with the more work-saving Karra algorithm (compared to the standard Bond method), where the Bond work index is estimated from the results of the Bond method's first two cycles.

Significant difference is shown by the different measurement methods in the case of the certain materials' grindability. Therefore, it is necessary to carry out comprehensive experiment series, which compare the results of different test and calculation methods and open up the possibilities and limits of each test.

Both the national and international literature (Opoczky and Gável, 2003; Ipek et al., 2005a, 2005b; Tsivilis et al., 1999) deal with advantages and disadvantages of separate- and intergrinding of composite cement in details. The grinding energy is one of the most important questions of this subject.

Ipek et al. (2005a) made grindability measurements using the standard Bond method in the case of quartz, kaolin and feldspar and to their binary and ternary mixtures. The Bond work indices of the admixtures containing a softer component (kaolin) were found to be greater than the weighted average of the work indices of the individual components in the mixture.

Hosten and Avsar (1998) showed that the Bond work index of a clinker–trass admixture is not simply the weighted average of the work indices of clinker and trass, and it is higher than the work index of the harder component clinker.

Öner (2000) carried out Bond measurement using clinker and blast furnace slag mixtures. He showed that Bond grindabilities of mixtures are lower than the weighted average of the grindabilities of the components for all slag additions. This indicates that the specific grinding energy per specific surface area necessary to produce blast furnace slag is higher when the components are interground than in separate grinding. In the case of intergrinding, slag having lower grindability accumulates in coarser fractions; with the clinker having higher grindability accumulating in finer size fractions.

Abouzeid and Fuerstenau (2009) showed that in the high pressure grinding rolls (HPGR) the mineral particles with high hardness act as energy transfer agents in the roll gap and enhance the grinding of softer mineral particles in a mixed feed. Tavares (2005) showed that in a high pressure grinding role the coarse particles are damaged preferentially and weakening is more significant at higher pressures if compared to the products of conventional crushing equipment. Particle

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weakening was found to occur irrespective of the position of the particle within the bed. The higher weakening experienced by coarser particles in the HPGR results in decreasing energy savings with finer size reduction of the product in a subsequent grinding stage.

Ellerbrock et al. (1990) showed that the particle size distribution of cement components is dependent on the type and mode of operation of the grinding system and on the grindabilities of the cement constituents.

Fuerstenau and Sullivan (1962) found that the Gaudin–Schuhmann (G–S) size distribution modulus of a ball-mill ground mineral was the same whether it was ground separately or as part of a binary mixture. Using the Charles energy–size reduction relationship (Charles, 1957) and assuming constant grindability of constituent minerals, the above authors formulated the total energy required for grinding a unit mass of a given binary mineral mixture by the following equation:

$$E = m_1 \cdot C_1 \cdot X_{m1}^{-\alpha 1} + m_2 \cdot C_2 \cdot X_{m2}^{-\alpha 2} \quad (1)$$

where subscripts 1 and 2 refer to the components in the mixtures; E is the energy consumed per unit mass of mixture (kW h/t); m is the mass fraction of the component mineral; a is the distribution modulus of the component; X_m is the G–S size modulus of the mineral when ground as a component in a mixture; and C is the grindability constant obtained from single-mineral. Fuerstenau and Sullivan (1962) postulated that the energy split between the components should be proportional to their volume fractions in the mixture, and derived the following equation for the energy consumed by the components:

$$E_1 = m_1 \cdot C_1 \cdot X_{m1}^{-\alpha 1} = \frac{m_1/\rho_1}{\left(m_1/\rho_1 + m_2/\rho_2\right)} \cdot E \quad (2)$$

where E_1 is the energy consumed by component 1, and ρ is the density of each component. Venkataraman and Fuerstenau (1984) verified Eq. (2) for calcite–quartz (equal-density minerals) mixtures, but observed poor agreement for the quartz–hematite (different density minerals) system. Subsequently, Fuerstenau and Venkataraman (1988) observed that the breakage rate function of a softer mineral increased when ground in the presence of a harder mineral and they deduced by simulation that the softer mineral consumed a greater proportion of the grinding energy than did the harder mineral when the two were ground together. Kapur and Fuerstenau (1988) introduced the concept of the energy split factor for the estimation of energy consumed in grinding the individual components of a mixture, which was defined as the ratio of breakage rate functions of the top-size feed particles when ground in mixture and alone.

Fuerstenau et al. (2010) showed that in the case of quartz and limestone mineral systems the cumulative breakage distribution function does not change as function of the mixture composition. On the other hand, the initial breakage rate function of the coarse particles increases as function of the increasing proportion of fines in the mixture. This acceleration could be due to the lower collision cross section of the fines. In addition, the coarse particles appear to be preferentially present at the toe of the mill where most of the grinding takes place.

Ipek et al. (2005b) showed that if a mixture of three materials of nearly equal density is being ground in a ball mill, the size distribution of the mixture product may be predicted if the grindability characteristics of the individual materials, their mass fractions in the mixture and the total grinding energy input are known.

Yan and Eaton (1994) investigated the variation of the Bond work index of ore blends as function of blend composition and found that the work index of a mixture was not simply the weighted mean of the work indices of the components, and that the harder ore had the highest influence on the value of the index.

Opoczky (1992) found that the effect of the components on each other and on the particle size distribution of the ground material cannot be ignored when Portland limestone cement is produced by intergrinding.

Opoczky (1993) showed that the grindability of the three-component composite cement depends on the grindability of the individual components. The harder to grind particles also abrade the easier to grind particles which lead to an enrichment of the easier to grind component in the fine fractions (final product).

The Hardgrove grindability index (HGI) of mineral mixtures was examined by Turgut and Arol (1996), they found that the grindability of mineral mixtures can be estimated if the grindabilities of individual minerals containing the mixture and their volume fraction in the mixture are known and the minerals have close grindabilities. Deviation from linearity was observed for mixtures of minerals of significantly different grindabilities.

Based on the study of the available literature, it can be concluded that many papers deal with the investigation of binary mixture grinding, but only some of them deals with the specific grinding energy test methods. These papers manly focus only on one test method, so it is necessary to make comparative investigation and open up the possibilities and limits of the test and calculation methods.

2. Apparatus and methods

Traditional Bond ball mill (Ø305 × 305 mm) and Hardgrove mill were used for the measurements. The traditional Hardgrove Grindability Index (HGI) was determined by using the following equation:

$$HGI = 13 + 6.93 m_P \quad (3)$$

where m_P means the mass of product particles finer 75 μm in grams. From this number the Bond work index W_{iB} can be calculated by several empirical formulas. We used the equation modified by Csőke et al. (2004) previously

$$W_{i,B,H} = \frac{468}{HGI^{0.82}}. \quad (4)$$

Bond measurements were performed according to the conventional way given by Bond (1954). The following well known formula was used for the evaluation of the Bond measurement:

$$W_{i,B} = \frac{4.9}{x_{\max}^{0.23} G^{0.82} \left(\frac{1}{\sqrt{x_{80}}} - \frac{1}{\sqrt{X_{80}}}\right)} \quad (5)$$

where the maximal size of the product ($x_{\max}$) was 106 μm.

For simulation of the Bond grindability test Karra's algorithm was used according to Karra (1981) equation:

$$Z_i = Z_{i-1} Y + Z_{i-1} N_i K_1 + (X - Z_{i-1}) N_i K_2 \quad (6)$$

where Z_i — is the amount of total product (g) in the i-th cycle; Z_{i-1} — is the amount of total product (g) in the (i-1)th cycle; N_i — is the revolution in the i-th cycle; X — is the amount of the feed (starting material, g); Y — is the fraction of the prepared feed finer than the mesh (now < 106 μm) of grind;

$$K_1 = \frac{(1-Y)}{N_1} \left(\frac{Z_1 - XY^D}{X - XY^D}\right) \quad (7)$$

$$K_2 = \frac{Z_2 - Z_1 Y - Z_1 K_1 N_2}{(X - Z_1) N_2} \quad (8)$$

where

D 2 for fines in the prepared feed if XY > C
D 1 for fines in the prepared feed if XY < C
for ball mill C = X/3.5, now D = 1.