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A technique to investigate pulverising and abrasive properties of bulk materials

K e y w o r d s

Abrasiveness, grindability, internal friction, bulk material.

S ł o w a k l u c z o w e

Ścieralność, kruszalność, tarcie wewnętrzne, materiał sypki.

S u m m a r y

A new method which covers the determination of a bulk material's basic mechanical properties such as internal friction, shear strength, abrasiveness and grindability is presented and discussed. Several fine bulk materials have been tested and classified. The apparatus consist of a drive shaft and a disc rotating in a closed cylindrical chamber. A normal pressure is applied to the disc through the drive shaft. The wear element consists of a bar fixed to the underside of the disc. The space in the bottom of the cylinder is filled with a given mass of the sample of fine bulk material. The disc is then rotated for a given number of revolutions and the mass loss of the bar is determined as well as the size reduction of the bulk material. This newly proposed method has the advantages of easy testing procedures and the better defined attrition conditions than the standard test method.

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Introduction

The operating costs of a mineral or any bulk solids processing and transportation are made up mainly of power input to overcome friction losses within the mechanical systems and of the replacement of systems elements due to wear, including the wear losses on the interfaces between bulk solids and the machine elements [1, 2]. Thus, the bulk material properties which affect power input, wear, and throughput of the processing and handling systems are of direct interest to such system designers.

This paper presents a new concept for determining a bulk material's basic properties such as shear strength, apparent cohesion, friction angle, abrasiveness and grindability. Abrasiveness and grindability of any material are not inherent properties of the material but properties of the tribological system. Therefore, any numerical evaluation of these properties obtained from laboratory apparatus may lead to errors when applied directly to the industrial conditions [3, 4, 5].

Review on methods of abrasive wear testing in comminution

Abrasive wear can be defined as wear due to hard particles or hard protuberances forced against, and moving along, a solid surface, and can be classified into: gouging abrasion, high-stress (grinding) abrasion and low-stress scratching abrasion. There are several different types of method and tester with which to measure the wear rate of these mechanisms, and some of these are presented in Figure 1. As wear can take place over a long period it would be impractical to measure the wear of actual components during their service life. Thus, a series of accelerated wear tests has been developed which can be correlated to actual conditions. However, it is not always easy to simulate every type of abrasion, particularly when abrasion goes together with corrosion and comminution.

Wear tests, utilising predominantly an attrition grinding mechanism include (Fig. 1) the YGP, hammer mill, tribotester and BCURA-roll mill. The marked-ball, jaw crusher, rotating electrode and dry-sand rubber wheel abrasion tests have significantly smaller areas of contact than in the previous examples and involve predominantly compression, shear and impact forces. The remaining tests illustrated in Figure 1, namely the Hardgrove mill, loaded column wear test and vibratory chamber impact tester, exhibit wear characteristics intermediate between the extremes of the other categories of test just described. In these tests a combination of attrition, compression and shear forces is involved [17].

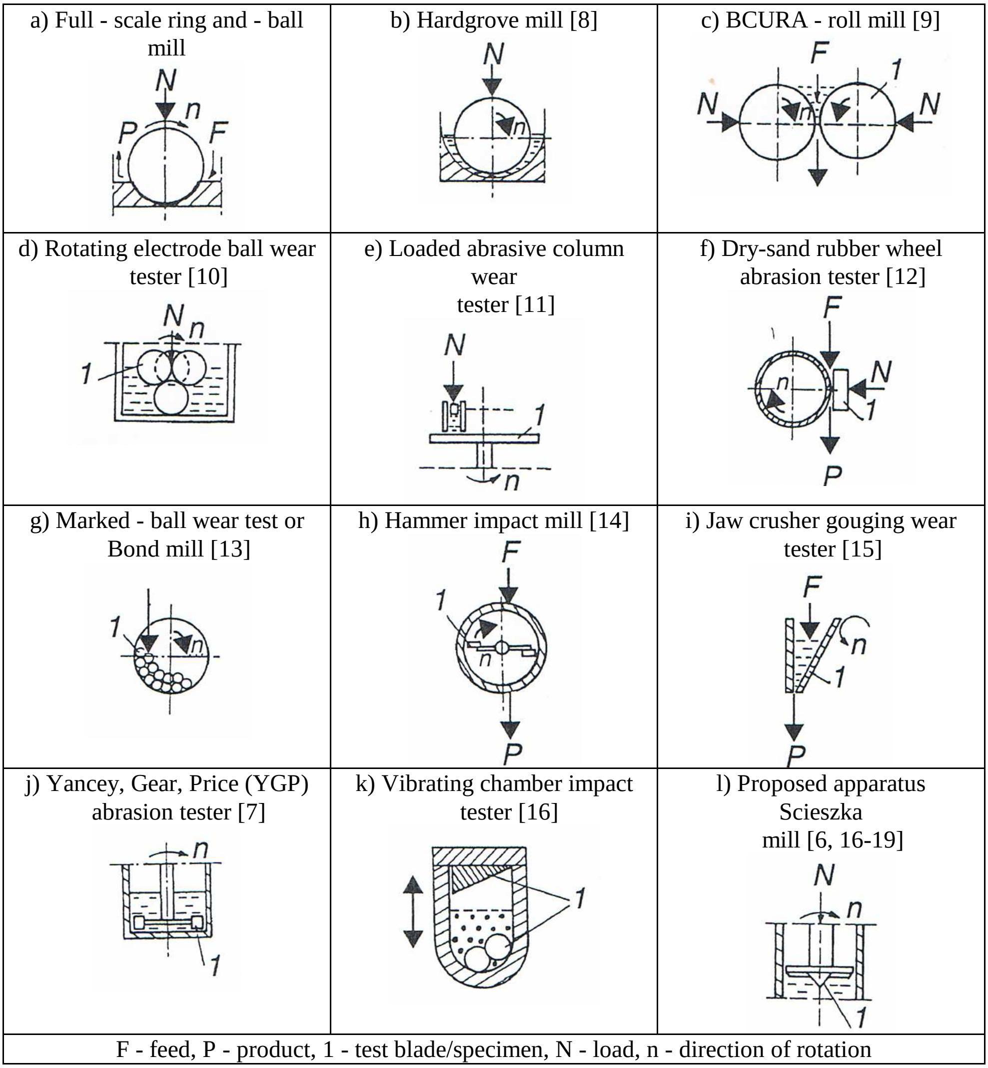

Fig. 1. Test methods for abrasive wear in comminution processes
Rys. 1. Metody łącznego badania ścieralności i kruszalności

In the main course of this investigation a recently developed method [16–19], which allows for much closer simulation of abrasive wear conditions found in actual mills [18], was used. The method is faster and less expensive than the standard Hardgrove test [8], and any material combination (i.e., material of blade or type mineral sample) can be used under any operational condition.

Basic mechanical properties of fine bulk materials

Shear strength of fine bulk materials

The shear strength of fine bulk materials is the maximum available resistance that it can offer to shear stress at a given point within itself. When this resistance is exceeded, continuous shear displacement takes place between two parts of the fine materials. The shear strength of fine materials depends on three factors:

1) sliding friction between adjacent grains;
2) rolling friction, as some of the grains will change position by rolling; and
3) the resistance to moving individual grains generally called the effect of interlocking action.

For a given bulk solid (granular abradant), the portion of the shear strength that is due to interlocking action varies with density. Interlocking is affected somewhat by particle shape and grain size distribution. A typical pattern of fine material behaviour in a shear test is shown on Figure 2.

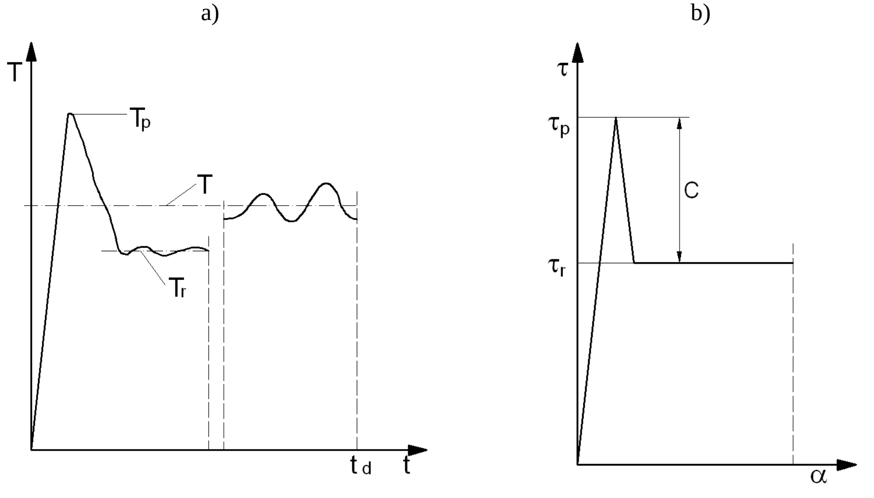

Fig. 2. Torque diagram (a) and schematic representation of fine cohesive material behaviour in a shear test (b). For non-cohesive materials component C→0 and $\tau_p = \tau_r$
Rys. 2. Wykres momentu (a) i schematyczny przebieg badania ściernego próbki materiału sypkiego kohezyjnego (b). Dla materiału bezkohezyjnego składnik C dąży do zera a $\tau_p = \tau_r$

The shear stress diagram consists of peak and residual values. After the peak value of torque is reached at a small value of angular displacement, the shear strength decreases and the torque necessary to continue the shear displacement is reduced to the final residual value of torque. Shear displacement takes place across a shear zone. Stress σ acting at any point within the plane of shear action can be resolved into two components: σ_n and τ.

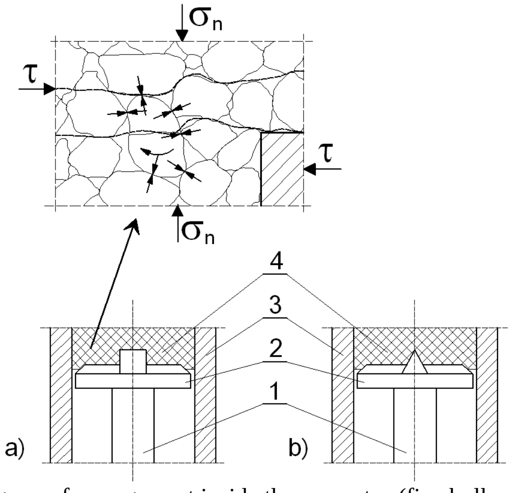

Fig. 3. Schematic diagram of arrangement inside the apparatus (fine bulk material versus disc-bar assembly with two different shapes of bar: a) rectangular and b) triangular and interpretation of interaction between the particulate mineral and the bar within shear zone, where: 1 – drive shaft, 2 – disc-bar assembly, 3 – cylindrical container, 4 – particulate mineral – abradant

Rys. 3. Schemat wnętrza części testowej stanowiska badawczego z uwzględnieniem układu współdziałania tarczy i beleczki z materiałem sypkim, dla dwóch kształtów próbki (beleczki): a) prostopadłościennej i b) o przekroju trójkątnym. Schemat wzajemnego odziaływania beleczki i materiału sypkiego, gdzie: 1 – wał napędzający, 2 – układ tarcza–beleczka, 3 – cylindryczny pojemnik, 4 – materiał sypki – ścierniwo

Fig. 4. The view of the apparatus built by the Institute for Sustainable Technology, Radom with mounted cylindrical tribotester (1), loading pulley (2), normal load and torque indicators (3)

Rys. 4. Stanowisko badawcze zbudowane w Instytucie Technologii Eksploatacji w Radomiu z zamontowanym cylindrycznym tribotesterem (1), krążkiem obciążnika (2), czujnikami siły i momentu (3)

Table 1. Specification of the apparatus and experimental details
Tabela 1. Ogólna charakterystyka stanowiska badawczego

Name	**Apparatus - tribotester**
Load used [N]	1000
Drive shaft Speer [rpm]	30
Test duration [rev]	from 1 to 200
Mean sliding distance [m]	0.05 and 6.0
Abradants	Coal, SiO_2, Al_2O_3, and SiC (300 – 1200 μm)

An examples of results from the experiments carried out in the proposed apparatus (Figures 3 and 4, and Table 1) are shown in Figure 5. The results pointed out that the magnitude of the resistance could be evaluated from Coulomb's equation:

$$\tau_p = C + \sigma_n \tan\phi = \frac{3T_p}{2\pi R^3} \cdot 10^{-6}, \quad \text{MPa} \tag{1}$$

and

$$\tau_r = \sigma_n \tan\phi = \frac{3T_r}{2\pi R^3} \cdot 10^{-6}, \quad \text{MPa} \tag{2}$$

where:

- T_p – peak value of torque, Nm,
- C – apparent cohesion, MPa,
- T_r – residual value of torque, Nm,
- R – radius of cylinder, m,
- τ_p – peak value of shear strength, MPa,
- τ_r – residual value of shear strength, MPa,
- $\sigma_n = \frac{F_n}{\pi R^2}$ – normal stress, MPa,
- F_n – normal force, N.

In a body of fine bulk materials under normal stress, the particles are in a state of static equilibrium. To displace them tangentially, it is necessary to overcome the resistance offered by the existing adhesion bonds between the particles and by a considerable degree of interlocking (i.e. by the apparent cohesion). After a peak stress is reached at a small value of shear displacement, the degree of interlocking decreases and some of the adhesion bonds are ruptured. The shear necessary to continue shear displacement is reduced by approximately the value of apparent cohesion (Figures 2 and 3). The decrease in the degree of interlocking is caused by the particles being crushed and broken and by the redistribution of the particles (sliding, rolling and lifting). The magnitude of internal resistance while shearing, i.e., the internal frictional angle depends on the grain size and environment, e.g. moisture content (Equation 3). Therefore, consistent, bulk-solid sample preparation is important.

$$\varphi = \arctan\frac{\tau_r}{\sigma_n} = \arctan\frac{3T_r}{2RF_n}, \quad \text{deg} \tag{3}$$

Grinding and abrasion of fine bulk material

The shear process is accompanied by wear of the bar (Figure 3). The grains of particulate material become ground to a greater or lesser degree, which can be determined by the index of comminution (IC). This index characterises the ease of pulverisation of the material. A prepared sample of the material receives a definite amount of grinding energy (energy input), and the change in size is determined by sieving. IC is expressed in mg of pulverised bulk material (fraction <75 μm particle size) per joule of energy input.

Relative displacement between the layers of fine material and the bar's surface (Figure 3) provides considerable abrasion wear of the bar material due to the grains of the bulk material sliding across the surface. They may also move relative to one another and may rotate while sliding across the wearing surface. In various industrial situations, as well as in laboratory test apparatus, high stress abrasion occurs. In the high-stress abrasion conditions, bulk solid particles or abradant particles are intensively crushed and abrasion is increased.

The abrasion property of bulk solids is represented by the abrasion factor (AF) and the intensity of abrasion (IA). The abrasion factor is the mass of metal lost by abrasion from a bar when rotated in a specified mass of bulk solid under specified conditions, expressed in mg metal lost per kg of pulverised bulk solid, i.e., bulk-solid particles <75 μm. The intensity of abrasion does not include the bulk solid's size reduction effect during the tests and is expressed in mg of metal lost in 1 s from m^2 of the bar surface exposed to abrasive action. Wear resistance (WR) and relative wear resistance (ε) give the best indication of a material's resistance to wear. Wear resistance is represented as the energy input required to wear the blade, when rotated in a specified mass of bulk material under specified conditions, expressed in MJ of energy input per g of metal lost. Relative wear resistance (ε) is the ratio between the wear resistance of the tested material and the wear resistance of a standard material.

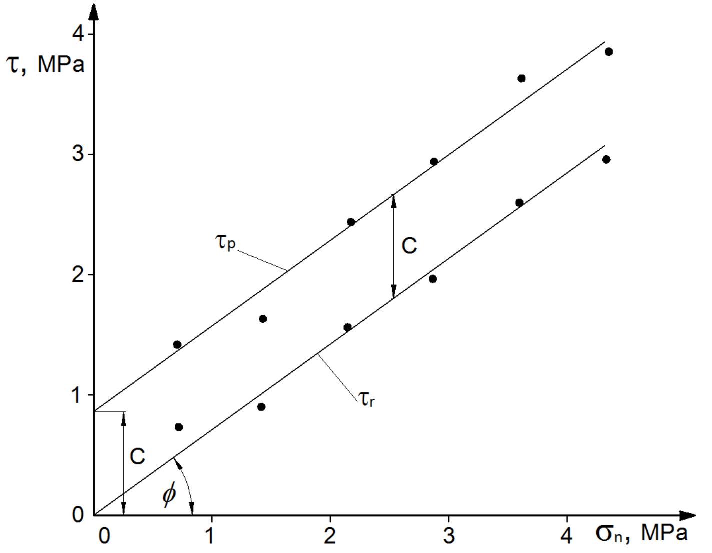

Fig. 5. Shear strength of fine coal as a function of normal stress, and Coulomb's parameters ϕ and C (Equation 1)

Rys. 5. Przykładowy wykres zmiany wytrzymałości na ścinanie warstwy węgla w funkcji naprężenia normalnego oraz parametry równania Coulomba ϕ i C (równanie 1)

The above properties can be calculated as follows:

$$IC = \frac{PC}{EI} \text{ – index of comminution, } \frac{mg}{J},$$

$$AF = \frac{\Delta W}{PC} \text{ – abrasion factor, } \frac{mg}{kg},$$

$$IA = \frac{\Delta W}{S \cdot t_d} \text{ – intensity of abrasion, } \frac{mg}{m^2 \cdot s},$$

$$WR = \frac{EI}{\Delta W} \cdot 10^{-6} \text{ – wear resistance of bar material,}$$

$$\varepsilon = \frac{WR\ (\text{specimen tested})}{WR\ (\text{standard})} \text{ – relative wear resistance,}$$

where:

PC – fraction of pulverised material <75μm, g,
EI – energy input, J,
ΔW – wear of bar, g,
S – area of surface exposed to abrasion, m^2,
t_d – duration of test.

Results and conclusion

The use of the proposed method leads to the determination of a number of parameters of interest in mineral processing and bulk solids handling.

A series of tests have been performed on one coal, coal water slurry, and three abradants. The results are summarised in Table 2.

Table 2. Basic mechanical properties of selected bulk materials
Tabela 2. Przykładowe własności mechaniczne wybranych materiałów sypkich

No	Properties	Coal	Coal water slurry	SiO_2 99%	Al_2O_3 99%	SiC 99%
1	Vicker's hardness, HV	~65	-	~970	~1500	~2500
2	Shear strength $\tau = \tau_r$, MPa	1.58	0.833	2.58	2.99	2.97
3	Apparent cohesion C, MPa	1,11	1,49	~0	~0	~0
4	Internal friction angle φ, deg	33.4	19.1	53.1	55.8	55.4
5	Index of comminution IC, $\frac{mg}{J}$	0.512	0.491	2.030	1.792	1.858
6	Abrasion factor AF, $\frac{mg}{kg}$	69	33	140	437	2655
7	Intensity of abrasion IA, $\frac{mg}{m^2 \cdot s}$	39	11	111	403	2253

The proposed method is much more flexible than the standard method [12], and it may quite closely simulate attrition conditions inside various mineral-processing systems and bulk solids handling equipment such as-mills, chutes and conveyors. The method also allows for a quick and inexpensive determination of the abrasiveness and grindability of bulk material in any operational condition (viz. pressure, sliding velocity and temperature) and in any material configuration (viz. material of bar and sample of particulate material-abradant). In the proposed method, a sample of only about 20 g of abradant (range of particles size 600 μm -1200 μm) was used and normal loading, F_n=1000 N, was applied.

The results of tests to determine the abrasiveness of bulk materials (AF and IA) will differ in relation to material configurations (with various bar materials). Therefore, the abrasive property of a bulk material should be tested with bars made from materials currently used or considered for use in the equipment. Only results from tests that completely simulate operational and material conditions in the industrial installation can be directly applied to design calculations. In the tests presented in Table 2, WC-6%Co bars were used.

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Metoda badania kruszalności i ścieralności dla materiałów sypkich

S t r e s z c z e n i e

Przedmiotem tego artykułu jest nowa metoda, która obejmuje wyznaczanie podstawowych własności materiałów sypkich, takich jak tarcie wewnętrzne, odporność na ścinanie, ścierność i kruszalność. Za pomocą ww. metody przebadano kilka materiałów sypkich. Zasadnicza część stanowiska badawczego składa się z wałka napędzającego i tarczki umieszczonych w pojemniku cylindrycznym. Próbka poddawana procesowi zużywania ma kształt beleczki przymocowanej do tarczki, która jest dociskana do wypełniającego cylinder materiału sypkiego o określonej masie. W trakcie testu próbka – beleczka obraca się określoną liczbę obrotów, a po teście wyznacza się ubytek masy próbki i stopień skruszenia materiału sypkiego. Do zalet testera należy łatwość przeprowadzenia próby i precyzyjnej identyfikacji warunków procesu ciernego.