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INVESTIGATION OF ULTRA-FINE GRINDING OF BASALT POWDER IN VIBRATORY MILLS: GRINDING EFFICIENCY AND IMPLEMENTATION POTENTIAL

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Abstract:
In response to the growing demand for eco-friendly materials and low-impact technologies, a study was conducted on the ultra-fine grinding of basalt in vibratory mills, with the basalt used for the experiments originating from the Targowica basalt quarry. Two types of basalt were used in the study: fine basalt consisting of particles with a size below 200 µm, agglomerated into lumps smaller than 100 mm, and aggregate with a particle size below 5 mm. The objective was to obtain a high proportion of the 0-10 µm particle size fraction, applicable in agriculture, construction, and environmental protection. Grinding tests were carried out for two types of feed material and different sets of grinding media. The best results were obtained using a mixture of steel grinding balls (Ø12 and 17.5 mm) with the addition of 0.4% polypropylene glycol, aimed at reducing agglomeration and improving grinding efficiency. In batch-mode operation, up to 70.5% of the 0-10 µm fraction was achieved. Although continuous grinding produced lower results (up to 44% of the 0-10 µm fraction), it demonstrated industrial implementation potential, especially after introducing chamber aeration and a modified material discharge method. The research confirmed the high industrial potential and effectiveness of vibratory grinding of basalt powder and indicated directions for further studies.

Key words: raw materials, grinding process, vibratory mill, fine comminution, micro powders, basalt comminution

INTRODUCTION

A global trend in mineral engineering, particularly in raw material processing operations such as comminution, is the pursuit of reducing the energy consumption of these processes. It is estimated that comminution alone accounts for nearly 5% of global energy use. Therefore, the search for alternative grinding technologies that enable lower energy consumption represents a crucial direction of development with a tangible impact on environmental protection – especially in the case of the highly energy-intensive grinding required to achieve particle sizes below 10 µm. One of the materials that, when ground to such fineness, can be utilized in various industries, including agriculture and cement production, is basalt [2, 3, 4]. In particular, basalt is characterized by a high content of essential macro- and microelements (e.g., Ca, Mg, Fe, K), a high proportion of amorphous phases that favor the slow release of nutrients, as well as pozzolanic and binding activity due to its reactive silica and alumina. These features make finely ground basalt increasingly important in agriculture, where it acts as a remineralizing soil amendment, and in construction, where it improves the strength and durability of composites such as concrete fields [2, 4].

From a process perspective, ultra-fine grinding of mineral raw materials aims to achieve the largest possible grain surface area. This translates into an increased ability of the particles to undergo chemical and physical reactions, making the product a valuable resource, for example, in construction (as an additive in cement production) or as a component of fertilizers used in agriculture. [4]. Due to its rich mineral composition and favorable physicochemical properties, it finds applications in many sectors of the economy.

For many years, intensive research has been conducted to improve concrete parameters or maintain their performance while simultaneously reducing production costs and limiting negative environmental impacts. One of the main areas of focus is the search for alternatives to Portland cement, which is responsible for a significant share of CO_2 emissions in the construction industry [5]. The most commonly studied additives include: fly ash (FA), which improves concrete workability and durability and reduces porosity-leading to better resistance to chlorides and sulfates [6]; ground granulated blast furnace slag (GGBS), which, by replacing part of the cement, improves long-term strength and durability in aggressive environments [8, 9, 10], limestone powder [10] and basalt powder, which not only enhances mechanical properties and durability, but also contributes to CO_2 emission reduction [12, 13, 14, 15, 16]. In addition to mineral additives, research in concrete production also focuses on the use of organic and industrial waste [16], foundry sand waste (SFS) [17], as well as chemical admixtures, nanomaterials[18] and superplasticizers [19, 20]. Basalt powder can successfully serve as a partial substitute for cement or fine aggregate in concrete production. When used in proper amounts in cement composites, it does not reduce mechanical properties (e.g., compressive strength), while reducing the environmental impact of cement production through lower CO_2 emissions and production costs. The use of improved, eco-friendly cements – such as those containing basalt powder – may help reduce production costs and environmental impact, even in applications such as waterproofing membranes that limit pollutant migration [21].

In many mineral processing operations, ultra-fine grinding is commonly performed using energy-intensive ball mills. These mills typically have high energy consumption, large physical dimensions, and significant environmental impacts. Moreover, achieving very fine products – such as those with a d_{90} particle size in the 10-50 µm range, which is increasingly demanded in certain applications – can be challenging and, in some cases, beyond the practical capability of conventional ball mill [22, 23]. As a result, ball mills are being replaced by high-energy mills, whose specific power – that is, the power per unit volume of the grinding chamber – is at least three times greater than that of a ball mill. Such mills offer significantly enhanced technological capabilities and include, among others [23], vibratory, stirred, planetary, centrifugal, and roller mills [24, 25, 26, 27, 28].

MATERIALS AND METHODS

The research focused on assessing the feasibility of producing ground basalt in vibratory mills with a maximized proportion of particles in the 0-10 µm size range.

In the first stage of the research, batch-mode vibratory milling was applied to basalt feed material of two different initial particle size distributions:

- 0-300 µm (agglomerated, high moisture content) – denoted as BD (fine basalt);
- 0-2 mm – denoted as BG (coarse basalt).

The scope of the research included the following:

- Determination of the basic physical properties of the obtained material (moisture content, bulk density, and particle size distribution);
- Preparation of the material for dry vibratory milling tests;
- Laboratory-scale investigation of the milling process for basalt powder with an initial grain size of 0-300 µm;
- Investigation of the vibratory milling of basalt with a particle size of 0-2 mm in order to maximize the content of the 0-10 µm fraction using a batch-mode mill;
- Particle size distribution analysis of milling products using laser diffraction with the Malvern Mastersizer 3000 laser particle size analyzer;
- Preliminary test of vibratory milling of BG basalt in a continuous-mode mill.

To determine the key technological parameters of the comminution process and to define the operating conditions adopted for the laboratory vibratory mills (filling degree, composition of the grinding media charge, and the quantity of feed material), three fundamental physical properties of the ground material were determined: moisture content, loose bulk density, and particle size distribution.

The first material investigated was fine basalt (samples designated with the prefix “BD”). This material, sourced from a dedusting station, had been stored outdoors without shelter, which resulted in a considerable moisture content causing agglomeration and hardening. The high moisture content of the material caused it to become “cemented” into large, hard-to-break lumps. In addition, it is possible that the water dissolved trace amounts of minerals present in the basalt, and upon evaporation, these minerals recrystallized, further strengthening the bonds between particles and making the material more difficult to disintegrate.

Water Content and Loose Bulk Density

The water content of the received materials was determined by oven-drying a prepared sample under controlled laboratory conditions. The material was dried to constant weight at a temperature of 110°C. Based on the conducted measurements, the moisture content values obtained were 16.6% ± 0.1 for fine basalt (BD) and 2.6% ± 0.1 for coarse basalt (BG). The loose bulk density was measured following the PN-EN 1097-3:2000 standard, which is widely applied in aggregate testing. The reported values, representing the average of four individual measurements, were 1.10 ± 0.02 kg/dm³ for fine basalt and 1.51 ± 0.02 kg/dm³ for coarse basalt.

Granulometric Analysis of the Feed

The PSD (Particle Size Distribution) of the fine basalt was analyzed after drying and disintegrating the agglomerated material. The material’s appearance prior to crushing, as well as the crusher’s pin rotor, is shown in Figure 1.

Fig. 1 Fine basalt before crushing and view of the impact crusher chamber

The particle size distribution (PSD) parameters of all samples were measured using laser diffraction with a Malvern Mastersizer 3000 analyzer.

Figure 2 presents the particle size distribution parameters of the fine basalt (BD) following drying and crushing in the impact crusher.

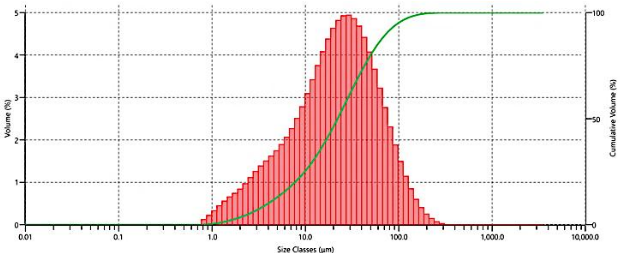

Fig. 2 Granulometric Characteristics of Basalt before Grinding

The granulometric characteristics of the coarse material (BG) was determined using the sieve analysis method. Table 1 presents the averaged results (from three measurements) of the analysis, while the particle size distribution curve is shown in Figure 3.

Table 1
Particle size analysis of the feed – coarse basalt (BG)

Mesh size [mm]	Grain size class [mm]	Class mass [g]	Fraction content %	Cumulative fraction %	Sieve residue %	Passing %
5.0	> 5	0.5	0.1	0.1	0.1	99.9
2.0	2÷5	168.0	16.9	17.0	17.0	83.0
1.0	1.0÷2.0	463.0	46.6	63.6	63.6	36.4
0.5	0.5÷1,0	193.0	19.4	83.0	83.0	17.0
-	< 0.5	169.0	17.0	100.0		
Loss [g]		6.5	0.7	100.00		

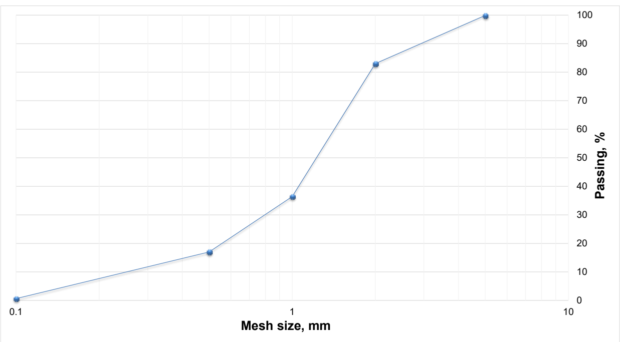

Fig. 3 Particle size distribution of the coarse basalt (BG) before grinding

Based on the particle size distribution analyses, the control particle sizes of the BG feed were determined as follows: d_{10} = 0.32 mm; d_{50} = 1.28 mm; d_{90} = 3.22 mm, while for the BD feed these values were: d_{10} = 4.0 µm; d_{50} = 22.1 µm; d_{90} = 73.2 µm.

Test method and experimental setup of the batch-operating vibratory mill

Experimental grinding tests were carried out using a laboratory-scale vibratory mill operating in batch mode, designed and manufactured by AGH in Kraków. A schematic view of the vibratory mill test stand is presented in Figure 4 [29].

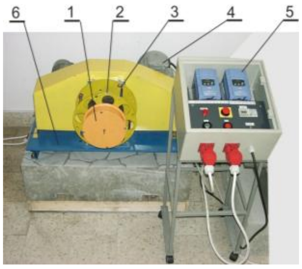

Fig. 4 Laboratory setup of the vibratory mill – view: 1 – chamber, 2 – disc – chamber holder, 3 – drive module, 4 – vibrator motor, 5 – control and power supply system, 6 – supporting structure

During the batch grinding tests, the mill was equipped with a chamber 210 mm in diameter and a capacity of 2.2 dm³. Bearing steel balls were used as grinding media. Due to the intended characteristics and purpose of the ground product, wet grinding was not considered. The mill's operating parameters were set at a vibration frequency of 16 Hz with an amplitude of 6 mm, and due to the mill's design, the resulting vibration trajectory was circular. During the grinding, attempts were made to apply two grinding process activators, namely: ethylene glycol and propylene glycol. Such additives are commonly used to reduce particle agglomeration, improve powder flowability, and thus enhance the efficiency and stability of the grinding process.

The mill was operated under the following conditions:

- Steel chamber with an internal diameter of 0.21 m and a working volume of 2.2 dm³
- Chamber filling with grinding media: 70% for fine basalt (BD) and 75% for coarse basalt (BG)
- Mass of grinding media: 7.0 kg for fine basalt (BD) and 7.6 kg for coarse basalt (BG)
- Mass of feed: 0.68 kg for fine basalt (BD) and 0.64 kg for coarse basalt (BG)

The experimental plan for fine and coarse basalt grinding is presented below in Table 2.

Table 2
Basalt Grinding Experimental Plan

	Sample	Grinding Media Set	Media Diameter, mm	Grinding Activator	Material Type
a)	BD-A1	A1	17.5	–	Fine basalt
b)	BD-A1-GP	A1	17.5	Propylene glycol	Fine basalt
c)	BD-A2-GE	A2	12.0	Ethylene glycol	Fine basalt
d)	BD-A3-GP	A3	12.0 & 17.5 (50/50)	Propylene glycol	Fine basalt
e)	BG-A1	A1	17.5	–	Coarse basalt
	BG-A3	A3	12.0 & 17.5 (50/50)	–	Coarse basalt
	BG-A3-GP	A3	12.0 & 17.5 (50/50)	Polypropylene glycol	Coarse basalt

Test method and experimental setup of the continuous-operating vibratory mill

Based on the analysis of the batch grinding test results, the grinding media set A3 was selected for the continuous grinding tests. The material to be ground was the supplied coarse basalt (BG).

In order to evaluate the potential for ultra-fine continuous grinding, with the highest implementation potential, a variant without feed drying was adopted. This feed was characterized by a borderline moisture content for dry vibratory grinding, which for most materials should be below 3% [30]. However, in most cases, including basalt, the lower the water content in the material, the more favorable the grinding conditions.

For the tests, a grinding chamber with a diameter of 206 mm and a capacity of 10 dm³ was used. The chamber was equipped with a smooth steel liner. The following technological and process parameters were kept constant:

– filling degree with grinding balls: 70%
– vibration frequency: 16 Hz,
– vibration amplitude: 6 mm ± 1 mm,
– vibration trajectory: quasi-circular,
– material feeding method: volumetric, using a screw feeder,
– grinding process carried out with aeration — ventilation of the chamber.

The schematic diagram of the laboratory continuous-operating vibratory mill test stand is shown in Figure 5.

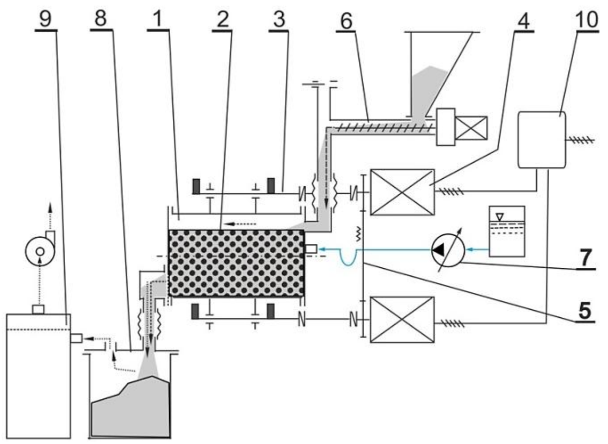

Fig. 5 Schematic diagram of the laboratory continuous-operation vibratory mill test stand:
1 – chamber; 2 – load (grinding media with material); 3 – vibrator; 4 – vibrator motors; 5 – belt drive; 6 – screw feeder with feed hopper; 7 – activator dosing pump with tank (not used);
8 – ground material container; 9 – air aeration and purification system.

Results and discussion – batch-operating vibratory mill

In accordance with the previously outlined research plan (Table 2), the following section presents the results of basalt powder grinding obtained for the selected technological variants:

a) To evaluate the grinding kinetics for the first process variant, grinding was carried out using 17.5 mm balls, and the grinding times along with the corresponding granulometric parameters of the resulting products are presented in Table 3.

Table 3
Results of Grinding Tests – BD-A1

Sample ID	Milling Time, min	Particle Size, µm			Fraction 0-63µm, %	Fraction 0-10µm, %
		d_{10}	d_{50}	d_{90}		
Feed: BD-Nadawa	0	4.0	22.1	73.2	86.5	25.4
BD-A1-t2.5	2.5	3.5	19.7	59.8	91.1	28.0
BD-A1-t5.0	5.0	3.3	17.5	53.5	93.5	31.8
BD-A1-t10.0	10.0	2.7	15.0	44.1	97.0	36.8
BD-A1-t20.0	20.0	2.5	13.8	40.3	98.1	39.1

It occasionally occurs that during ultra-fine grinding, small particles tend to agglomerate and adhere to the grinding media and the mill chamber. This undesirable phenomenon, known as coating, can lead to a significant slowdown or even a halt of the grinding process. The onset of this effect was observed after 10 minutes of grinding. The appearance of the ground material in the chamber after 20 minutes of grinding is shown in Figure 6.. Consequently, in the subsequent test, it was decided to perform the experiment with the application of a grinding aid – polypropylene glycol.

Fig. 6 View of the chamber load – test BD-A1-t20.0

b) In the next stage of the study, grinding media with a diameter of 17.5 mm and a grinding activator (propylene glycol) were used. The addition of this activator aims to prevent excessive particle agglomeration and the occurrence of coating on the grinding media and mill chamber. The activator was added to the material before grinding at a dosage of 0.2% by mass of the ground basalt. After 20 minutes, an additional 0.2% of glycol was added. The particle size distribution results obtained in this series of tests are presented in Table 4. In this table, measurements carried out with particle disintegration using ultrasound are highlighted in blue. The use of ultrasound revealed the presence of agglomerates in the ground material, consisting of fine particles stuck together.

Table 4

Results of Grinding Tests – BD-A1-G

Sample ID	Milling Time, min	Particle Size, µm			Fraction 0-63µm, %	Fraction 0-10µm, %
		d_{10}	d_{50}	d_{90}		
Feed: BD-Nadawa	0	4.0	22.1	73.2	86.5	25.4
BD-A1-G0.2-10	10	2.8	14.9	44.5	96.6	36.8
BD-A1-G0.2-20	20	2.8	13.4	39.2	98.0	39.5
BD-A1-G0.2x2-30	30	2.2	11.1	33.8	99.2	46.4
BD-A1-G0.2x2-30+US2x60s	*30.*	*2.1*	*10.2*	*32.1*	*99.4*	*49.5*
BD-A1-G0.2x2-30+US3x60s	*30.*	*2.0*	*9.4*	*31.1*	*99.6*	*52.2*
BD-A1-G0.2x2-30+US4x60s	*30.*	*1.9*	*9.0*	*31.3*	*99.4*	*53.5*

c) The next series of tests was conducted using grinding media set A2, consisting of 12 mm balls, along with a different activator – ethylene glycol. Based on the results obtained in previous trials, the grinding kinetics were studied for durations of 20, 40, and 60 minutes. After performing the grinding tests for 20 and 40 minutes, agglomeration of the particles and coating of the chamber and grinding media were observed, despite the use of the activator. Consequently, it was decided to add a different activator in powder form after 40 minutes of grinding. This activator was: AEROSIL® 200, which is a fumed silica with a high specific surface area. Its addition was intended to improve the dispersion of fine particles and to reduce their tendency to agglomerate during the grinding process. The results of the granulometric parameters of the grinding products for these trials are presented in Table 5.

Table 5

Results of Grinding Tests – BD-A2-GE

Sample ID	Milling Time, min	Particle Size, µm			Fraction 0-63µm, %	Fraction 0-10µm, %
		d_{10}	d_{50}	d_{90}		
Feed: BD-Nadawa	*0*	*4.0*	*22.1*	*73.2*	*86.5*	*25.4*
BD-A2-GE0.2-20	20	2.9	13.9	32.5	100.0	36.6
BD-A2-GE0.2+.02-20+20	40	2.3	11.5	34.1	99.0	45.1
BD-A2-GE0.2+.02-20+20-US4x60s	*40*	*1.7*	*7.1*	*23.3*	*100.0*	*62.1*
BD-A2-GE0.4-T60-Aeo1	60	2.2	11.2	35.1	99.2	46.4
BD-A2-GE0.4-T60-Aeo1-US4x60	*60*	*1.6*	*6.6*	*21.6*	*100.0*	*63.5*
BD-A2-GE0.4-T60-Aeo1-US6x60	*60*	*1.5*	*6.3*	*21.1*	*100.0*	*64.6*
BD-A2-GE0.4-T60-Aeo1-US8x60	*60*	*1.4*	*5.9*	*19.7*	*100.0*	*66.7*

d) The final variant of fine basalt grinding involved tests using a mixture of grinding media with diameters of 12 mm and 17.5 mm in a 1:1 mass ratio, along with the use of a grinding activator – propylene glycol. The grinding times were the same as those applied in the previous trial. The particle size distribution results for this test are presented in Table 6.

Table 6

Results of Grinding Tests – BD-A3

Sample ID	Milling Time, min	Particle Size, µm			Fraction 0-63µm, %	Fraction 0-10µm, %
		d_{10}	d_{50}	d_{90}		
Feed: BD-Nadawa	*0*	*4.0*	*22.1*	*73.2*	*86.5*	*25.4*
BD-A3-GP0.4-20	20	2.4	11.8	37.9	98.4	44.6
BD-A3-GP0.4-20-US 8x60	*20*	*1.8*	*7.5*	*22.6*	*100.0*	*60.2*
BD-A3-GP0.4-40	40	2.2	11.6	33.1	99.9	44.9
BD-A3-GP0.4-40-US8x60	*40*	*1.6*	*6.6*	*19.3*	*100.0*	*64.0*
BD-A3-GP0.4-60	60	2.2	11.3	36.7	98.8	46.0
BD-A3-GP0.4-60-US8x60	*60*	*1.4*	*5.6*	*17.6*	*100.0*	*69.5*
BD-A3-GP0.4-60-US14x60	*60*	*1.3*	*5.2*	*17.0*	*100.0*	*70.9*

e) The particle size distribution parameters of the coarse basalt (BG) grinding products obtained under the adopted vibratory grinding conditions are summarized in Table 7 and illustrated as particle size distribution curves (frequency histograms) in Figure 7

Table 7

Results of coarse basalt (BG) grinding in a batch-operated mil

Sample ID	Milling Time, min	Particle Size, µm			Fraction 0-63µm, %	Fraction 0-10µm, %
		d_{10}	d_{50}	d_{90}		
BG-Nadawa	0	320.0	1280.0	3220.0	-	-
BG-A1-5	5	11.7	259.0	1570.0	25.8	8.9
BG-A1-10	10	5.1	62.9	472.0	50.0	17.8
BG-A1-20 S	20	2.7	22.1	107.0	78.6	32.0
BG-A1-40 S	40	1.6	9.8	37.9	99.1	50.7
BG-A1-60 S	60	1.3	7.9	33.6	99.7	56.3
BG-A3-10 S	10	3.0	21.8	99.9	80.8	30.5
BG-A3-20 S	20	1.7	10.4	38.1	99.0	48.9
BG-A3-40 S	40	1.2	7.2	31.4	99.9	58.4
BG-A3-GP 0.4- 20 S	20	1.7	10.2	33.7	99.8	49.6
BG-A3-GP 0.4- 40 S	40	1.2	6.7	24.1	100.0	61.8

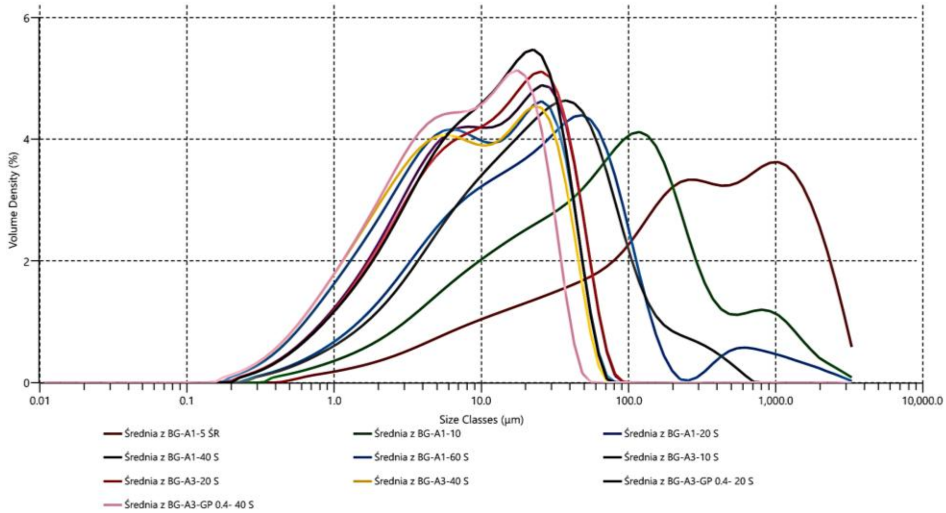

Fig. 7 Comparison of PSD Curves for Coarse Basalt Grinding Products

SUMMARY OF PERIODIC GRINDING TEST RESULTS

The batch ultra-fine grinding tests of basalt conducted in a vibratory mill demonstrated the high efficiency of comminution for this type of material in vibratory mills, even when standard and moderate vibration parameters were applied. The most favorable particle size distribution was achieved using a mixture of grinding media (set A3) combined with propylene glycol as a grinding activator. For this variant, a 70% fraction of the 0-10 µm particle size class was obtained.

A significantly better growth dynamics of the 0-10 µm particle size fraction was observed during the grinding of coarse basalt (BG). Despite the fact that the feed particle size of this material was nearly 25 times coarser (100% passing 5 mm for BG compared to 100% passing 200 µm for BD), for the most effective grinding media set (A3), and with the use of polypropylene glycol as a grinding aid, the following proportions of the 0-10 µm fraction were obtained:

- 49.5% after 20 minutes of grinding;
- 61.8% after 40 minutes of grinding.

Only slightly lower results were achieved for the same grinding media set (A3) without a chemical aid: 48.9% after 20 minutes and 58.4% after 40 minutes of grinding.

It should be emphasized that achieving such favorable results was undoubtedly influenced by the complete drying of the material prior to grinding (the moisture content before drying was 2.6%).

Based on the conducted batch grinding tests, the grinding media set A3 – consisting of steel balls with diameters of 12.0 mm and 17.5 mm in a mass ratio of 1:1 – was selected for the continuous grinding trials.

IMPLEMENTATION AND RESULTS OF CONTINUOUS VIBRATORY GRINDING TESTS

Ultrafine grinding trials were carried out for the following technological variants:

- no chamber aeration; material feed rate: Q = 6.5 kg/h; bottom discharge (MC-A3-Q6.5),
- chamber aeration; material feed rate: Q = 12.5 kg/h; top discharge, vacuum level "1" (MC-G-A3-Q6.5),
- chamber aeration; material feed rate: Q = 12.5 kg/h; top discharge, vacuum level "2" (MC-G2-A3-Q12.5),
- chamber aeration; material feed rate: Q = 12.5 kg/h; top discharge, vacuum level "3" (MC-G3-A3-Q12.5),
- chamber aeration; material feed rate: Q = 6.5 kg/h; top discharge, vacuum level "3" (MC-G3-A3-Q6.5).

The results of particle size distribution measurements for the grinding products obtained under the adopted process conditions are summarized in Table 8. The presented data refer to the particle size distribution parameters after reaching a stable mill operation. Process stability was assessed after two complete material retention cycles in the chamber.

Table 8
Results of coarse basalt (BG) grinding in a continuously operated mill

Sample ID	Feed rate [kg/h]	Particle Size, µm			Fraction 0-63µm, %	Fraction 0-10µm, %
		d_{10}	d_{50}	d_{90}		
BG-Nadawa	-	*320*	*1280*	*3220*	-	-
MC-A3-Q6.5-t60	6,5	1.62	12.7	154	82.36	43.96
MC-G3-A3-Q6.5-t100	6,5	2.09	15.2	61.2	90.49	38.3
MC-G-A3-Q12.5-t 60	12,5	4.15	27.1	98.6	78.23	23.33
MC-G2-A3-Q12.5-t 60	12,5	3.84	24.5	82.7	82.99	25.06
MC-G3-A3-Q12.5-t 60	12,5	2.65	20.1	80.7	84.71	31.56

The results of continuous coarse basalt (BG) grinding obtained under the assumed process parameters demonstrated the feasibility of ultrafine basalt grinding in a continuous mode. The experiments confirmed the high potential of vibratory grinding for this type of material, while also indicating the necessity for broader-scale studies.

In the first technological variant (throughput of 6.5 kg/h, with bottom discharge of the ground product), where no chamber aeration was applied, the highest proportion of the 0-10 µm particle size fraction was obtained – approximately 44%. However, under this feeding and discharge arrangement, the mill chamber could not be adequately filled with material, which resulted in unfavorable mill operating conditions (noise, wear of the grinding media and chamber lining). Therefore, in the subsequent tests, it was decided to modify the material discharge to the upper part of the chamber cover and to apply chamber aeration, with vacuum levels (1-3) measured at the mill outlet. The vacuum was generated to provide aeration of the chamber, with a higher number corresponding to a lower vacuum level. The trials conducted with chamber aeration showed that such a feeding and discharge system could be successfully applied, significantly improving the environmental and operational conditions of the mill (lower noise levels and reduced wear of working components), while achieving seemingly satisfactory particle size parameters. In this case, the most favorable result was obtained with the application of vacuum level "3" (the lowest value), at which the proportion of the 0-10 µm fraction reached approximately 38% for a throughput of 6.5 kg/h and 31% for a throughput of 12.5 kg/h.

The particle size characteristics obtained were inferior to those achieved in batch grinding tests of this material. This may be attributed to the fact that the material was not dried prior to grinding, but more importantly, to the fact that optimal parameters for continuous grinding have not yet been established. Selecting the appropriate process parameters will require more extensive research. Nevertheless, from the grinding perspective, the obtained results can be considered highly satisfactory.

SUMMARY AND CONCLUSIONS

The conducted studies demonstrated the high potential of applying vibratory grinding for the ultrafine comminution of both fine basalt (BD) and coarse basalt (BG). The obtained results confirmed that the appropriate selection of technological parameters, such as the grinding media set and the use of a grinding aid, has a significant impact on process efficiency.

Final conclusions:

– The results confirm the effectiveness of vibratory grinding for basalt, particularly under batch operation conditions.
– Future research should focus on further optimization of continuous grinding parameters, particularly on selecting an appropriate system for material feeding and discharge.
– Even better results may be achieved through continued experiments involving chamber aeration, vacuum level adjustment, and, if necessary, drying the material prior to grinding.
– Despite the need for further studies, the achieved degrees of comminution should be considered very good.
– In many cases, especially when applying chamber aeration in continuously operated mills, it is possible to obtain better particle size characteristics than in batch grinding.

In summary, the vibratory grinding of coarse basalt shows high technological and implementation potential; however, it requires further optimization to ensure maximum process efficiency under continuous operating conditions.

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