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A Kinetic Study of Limestone Dry Micronization in an Ultra-Centrifugal Mill with Peripheral Comminuting Path

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Abstract

Because of its physico-mechanical and physico-chemical characteristics, fine-ground (i.e. micronized) limestone is widely applied in the production of new materials. Limestone can be used as a filler, coating and/or powder in ceramic composites. The effect of its fine micronization depends on the type of equipment used and on the disintegration process. In this study, the emphasis was placed on investigation of the kinetics of the dry micronization milling of limestone in a state-of-the-art ultra-centrifugal mill with a peripheral comminuting path. The efficiency of the ultra-centrifugal mill with a peripheral comminuting path was determined based on a detailed investigation of the limestone dry micronization, which satisfied all the requirements for technological parameters as well as for micronized product parameters. On the basis of the investigation of these parameters and theory of dry micronization conducted in a state-of-the-art mill with use of advanced instrumental techniques for determination and observation of the most significant physical and chemical characteristics, a kinetics model was developed to serve as the basis for quick and effective determination of micronization quality and efficiency. In this paper, the results of grinding in a Retsch ZM-1 ultra-centrifugal mill were analyzed in order to optimize and automate the process of ultrafine micronization.

Keywords: Limestone, fillers for ceramics, mechano-chemical activation, grinding, optimization.

I. Introduction

Over the last few decades, new advanced materials resistant to extreme mechanical, thermal and electrical stresses have been developed in response to the requirements of modern technology. A particular demand exists for finely ground mineral raw materials (i.e. finely and very finely micronized powders). One of these materials is limestone, originally a sedimentary rock that predominantly comprises calcium carbonate ($CaCO_3$) in a quantity exceeding 50 %. Quartz and clay minerals (e.g. kaolinite, hydrous mica, montmorillonite) are two other major constituents of limestone [1]. Since a substitution of calcium with magnesium occasionally occurs, a limestone that contains 5 – 35 % Mg is referred to as “magnesian limestone”. If the Mg content is below 5 %, the rock is classified as a “high-calcium limestone” [2]. The carbonates present in the limestone usually appear as calcite, aragonite and/or vaterite mineral phases. However, the only crystal form of real significance is calcite [3]. Calcite is an important resource and has been the subject of investigations in various scientific fields: mineralogy, chemistry, physics, materials science [4, 5, 6, 7]. Thanks to its physico-mechanical and physico-chemical properties, limestone is a useful mineral raw material that, when micronized into powder form, has found wide application in the fabrication of advanced materials. Limestone is used as a filler in the synthesis of contemporary materials, giving them added quality, owing to its color, density, reflexion index, size, shape, and the structure of its microparticles [4, 7]. Limestone is employed extensively as architectural stone, in lime production, as coarse aggregates and fillers in concretes and mortars, as fillers in paint and polymer fabrication, as metallurgical fluxes, in road building, embankments, soil stabilization agents, etc. [8, 9, 10].

II. Theory of Dry Micronization

The purpose of dry micronization is to grind a mineral raw material to the particle size of a powder and to prepare it for direct application or further technological processing. The dry micronization process is mostly applied for grinding mineral raw materials that have already been pulverized by means of crushing or standard grinding. Micronization is conducted by the action of external forces, and, as in the standard grinding procedure, it is primarily achieved in the planar coalescence, cracks and other structural defects in the mineral grains [11].

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The intensity of the dry micronization process depends on the characteristics of the mineral raw material being processed, its purpose, and the market requirements in terms of the product's quality. During micronization grinding, the grain is reduced in size and changed in shape, which is reflected in the increase in the content of the fine grains as opposed to coarse grains. One of the basic factors that influences the shape and the mutual relation of the content of the certain particles by their size is the type of the process and the type of grinding equipment used. The main elements for the determination of the efficiency of a milling operation are obtained based on analysis of the grain-size composition of the input and the results of the micronization grinding, as well as their mutual comparison [12, 13].

In practice, special attention must be paid to the efficiency of the micronizing mills and final cost of the micronized product, especially when the processed mineral raw material is a low-cost resource with low value on the market. During micronization, special attention must be paid to the following basic parameters of product quality: content (percentage) of the certain grain size classes, specific surface area of the grains, mean particle diameter, and chemical and mineralogical characteristics [14]. Apart from the size, as the basic parameter of the quality of the micronized product, it is necessary to mention other important parameters: volume mass, homogenization, floating capacity, surface activity, shape of the grains, optical characteristics, etc. The quality parameters of the micronized product depend on the physical-mechanical, chemical and mineralogical properties of the input raw material such as: structure, texture, resistance, plasticity, brittleness, hardness, abrasiveness, hollowness, elasticity, and adhesiveness [15], [14]. The grinding procedure itself is not a simple one. As the processing and technical aspects of milling have been developing for years, the theory of the micronization process has been the subject of intensive study. The micronization of the mineral raw materials cannot be considered only as a process applied in order to increase the specific surface area of a material, but also as a process that induces an increase in the free energy, an expense of the surface energy and a change in the chemical balance of the chemical complexes [16].

(1) The basics of dry micronization (fine grinding) kinetics

As the literature data show [17], the curves of the milling activation kinetic have a hyperbolic form, which indicates the existence of stable lawfulness between the content of coarse class in the mill (R) in a specific moment of time (t). The curve of the dependence of residual coarse class in the mill ($+d_i$) and the time of milling is known as the curve of the kinetics of micronizing grinding (shown in Fig. 1) [17].

The kinetics of grinding in conventional mills has been the subject of investigation in many scientific works and various mathematical expressions have been proposed [17]. It has been proven that the content of coarse class in the mill (R), as shown by the mathematical expression of grinding kinetics, is, in its differential form, as follows:

$$\frac{dR}{dt} = -kR^n \tag{1}$$

with

$$R = R_0 e^{-kt} \tag{2}$$

where:
$\frac{dR}{dt}$ is the coarse class grinding rate;
R is the content of coarse class in the mill in a specific moment of time t;
R_0 is the content of coarse class in the mill in a specific moment of time $t = t_0 = 0$;
t is the micronizing/grinding time;
k is the grinding rate constant; and
n is the grinding kinetics order.

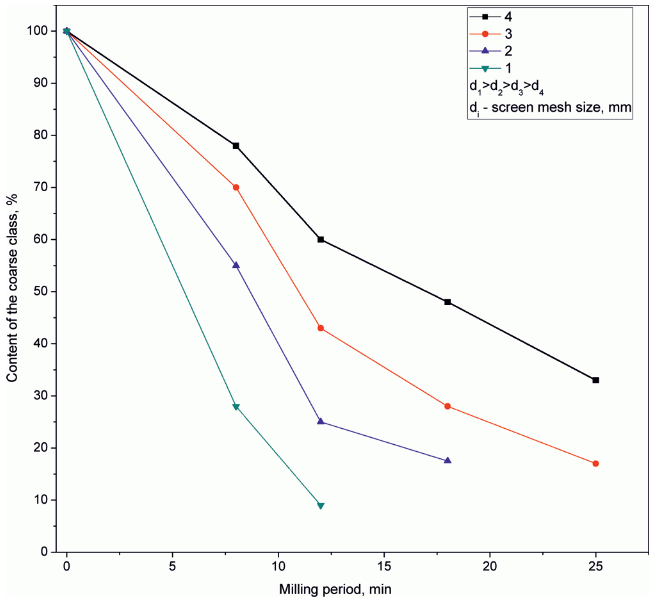


Fig. 1: Dependence of the content of coarse class in the mill in a specific moment of time.

The analogy of the dependence of the grinding rate and the amount of coarse class in an ultra-centrifugal mill is very similar to that of the ball mill, because the chance of collision of coarse grains with rotor cogs is higher if their share in the mill is greater. According to this analogy, one can assume that under certain conditions, the rate of grinding of the coarse class in an ultra-centrifugal mill is directly proportional to the content of coarse class. This means that the kinetics of micronization in an ultra-centrifugal mill with peripheral comminuting path obeys the law of the first order (Eq. (1), (2)). Besides the general assumptions and conditions of the kinetics of the dry micronization of limestone in an ultra-centrifugal mill with peripheral comminuting path, the path also depends on the processing parameters, i.e. the circumferential rotor speed (v) of high-speed mills, the screen mesh size of the exchangeable circular screen, which directly influence the granulometric composition of the product. With the application of the Rosin-Rammler-Sperling diagrams (RRS) [18], a functional dependence of the average grain size (d'), i.e. the coarseness, on the circumferential rotor speed (v) of the ultra-centrifugal mill with peripheral comminuting path can be formed (Fig. 2, a typical layout of this dependence).

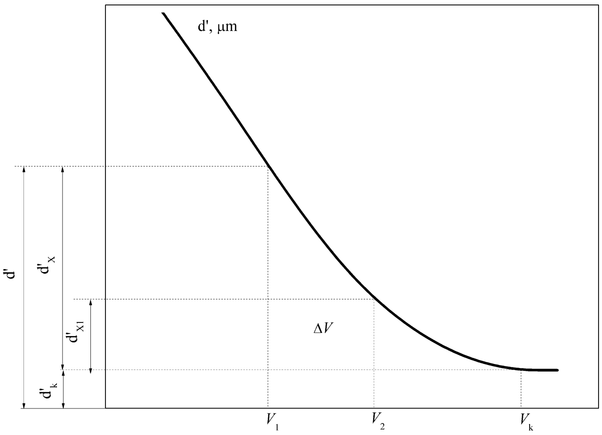


Fig. 2: Functional dependence of coarseness, *d,'* on the circumferential rotor speed, *v*.

In all experimental investigations [19, 20], a functional dependence between the average grain size and the circumferential rotor speed, $d' = f(v)$, where only a slope or position of the curve is changed, as defined by the operational conditions of the ultra-centrifugal mill with a peripheral comminuting path, is obtained. The common characteristics for all curves that represent a dependence $d_i' = f_i(v)$, are that with increase in the circumferential rotor speed, the average grain size abruptly decreases, and this tendency slows down later until the final value ($d' > 0$) is reached, and vice versa. All phenomena where the value of ordinate (y) (d', in our case) decreases in the manner described depending on the value of the abscissa (x) (v, in our case) can be expressed with the exponential function:

$$y = y_0 \cdot e^{-kt} \tag{3}$$

Eq. (3) is analogous to Eq. (2).

For the curve $d' = f(v)$, an interesting situation arises when the value of (d') inclines toward some definite value (d_k') that corresponds to the value (v_k'). In this case, the value (d') is split into two portions: a constant portion (d_k') and a variable portion (d_x'), as shown in Fig. 2. On the basis of analysis of Fig. 2, the following can be written:

$$d' = d_x' + d_k' \tag{4}$$

So, it becomes possible to determine a dependence between the influential parameter (v). If the circumferential speed of the rotor (v) is increased by a slight value (Δv) to the value (v_1), (d_x') automatically decreases for ($\Delta d_x'$) to the value of (d_{x1}'). This must correspond to proportionality of the exponential function Eq. (3), analogous to Eq. (2); so, it arises that $\frac{\Delta d_x'}{\Delta v}$ is proportional to (d_x'). Thus, following the equation with a factor of proportionality (k), the following is obtained:

$$\frac{\Delta d_x'}{\Delta v} = -k d_x' \tag{5}$$

if a differential Eq. (5) of the form

$$\frac{\Delta d_x'}{\Delta v} = -k d_x' \Rightarrow \frac{\Delta d_x'}{d_x'} = -k dv \tag{6}$$

is integrated,

$$\int \frac{\Delta d_x'}{d_x'} = \int -k dv \Rightarrow \ln d_x' \ln d_0 = -kv + kv_k$$

$$\Rightarrow \ln \frac{d_x'}{d_0'} - k(v - v_k)$$

the equation of the following form is obtained:

$$d_x' = d_0' e^{-k(v - v_k)} \tag{7}$$

With Eq. (4) and Eq. (7), the equation for average grain size was obtained:

$$d' = d_x' + d_k' = d_k' + d_0' e^{-k(v - v_k)} \tag{8}$$

In this work, special attention was paid to the kinetics investigation of dry limestone micronization in an ultra-centrifugal mill. Thorough research of dry limestone micronization kinetics provided the elements for determination of the peripheral comminuting path, thus fulfilling the conditions for definition of the technological parameters of micronization and parameters of the micronized product. The following operational parameters were changed: number of rotor revolutions (n_0 = 10 000 and 20 000 rpm), screen mesh size (a = 80; 120; 250; and 500 μm), and current density (I = 1.2 – 3.8 A). The following technological parameters of micronization were monitored: time of micronization grinding, (t, min), circumferential rotor speed, (v, m/s), capacity of the ultra-centrifugal mill, (Q, kg/h), and specific energy consumption, (W_e, kWh/t). The following basic parameters of the product's quality were monitored, too: content of the coarseness classes (R, %), specific surface area (S_t, m^2/kg), average grain size (d', μm), screen mesh size that allows 95 % micronized product to pass through (d_{95}, μm).

III. Materials and Methods

(1) Raw material

Experimental investigations of dry micronization in an ultra-centrifugal mill with a peripheral comminuting path were performed with an ore sample that originated from the "Visočica" limestone deposit. This deposit is the part of the ore region of Bjelopavlici, in the area of Danilovgrad and Spuž.

(2) Experimental methods

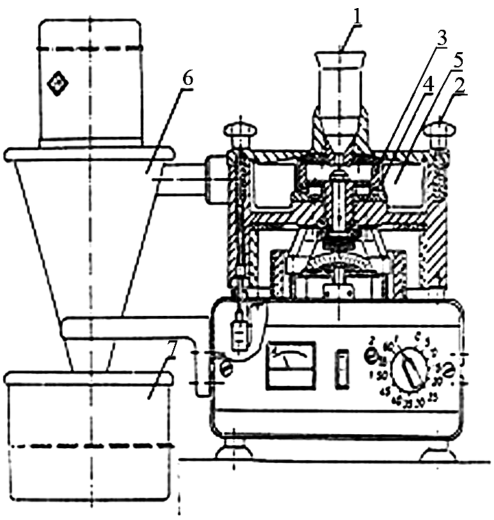
Fine grinding of the limestone was investigated in four experimental series. Dry micronization was realized in a "Retsch ZM-1" high-energy ultra-centrifugal mill. The activator was supplied with a working element (i.e. rotor) made of high-alloyed steel. The number of rotor revolutions can be adjusted to 10 000 or 20 000 rpm. The tolerance between the rotor cogs and circular screen is 1 mm. A ring volume created during the micronization operation was V = 4.74 cm^3. The rotor diameter was 100 mm. The exchangeable circular screens were 80, 120, 250 and 500 μm.

The chemical analysis of the limestone samples was performed by means of atomic emission spectroscopy (AES) on a PinAAcle 900 instrument (Perkin Elmer, USA). For physical characterization, the average grain size and specific surface were determined using a System-Partikel-Technik analyzer supplied by Sympatec GmbH. The parameter d_{95}, i.e. screen mesh size that allows 95 % micronized material to pass through, was determined with calculations based on the exponential Rosin-Rammler equation [19, 20].

$$d_{95} = e^{\left(\frac{n \ln d' + \ln \ln 100 - \ln \ln R}{n}\right)} \tag{9}$$

Table 1: The basic physico-chemical and technological parameters of the limestone deposit.

Granulometric composition		Chemical composition		Technological parameters	
Size class, mm	R, %	Component	Content, %		
-19.10 + 15.90	1.75	SiO_2	<0.10	Whiteness	92.40 %
-15.90 + 12.70	11.57	TiO_2	<0.01	(MgO-100%)	
-12.70 + 9.52	26.78	Al_2O_3	0.011		
-9.52 + 7.93	34.06	Fe_2O_3	0.028	Moisture	0.018 %
-7.93 + 6.35	41.09	CaO	55.27		
-6.35 + 5.00	44.61	MgO	0.31		
-5.00 + 3.36	58.47	Na_2O	<0.01	Specific weight	2.65 g/cm^3
-3.36 + 2.38	65.42	K_2O	<0.01		
-2.38 + 1.60	71.33	MnO	<0.01		
-1.60 + 1.19	77.51	P_2O_5	<0.01	Oil absorption	14.40 %
-1.19 + 0.63	85.15	Cr_2O_3	0.003		
-0.63 + 0.40	88.76	LOI	43.48		
-0.40 + 0.30	90.61	SUM	99.342	Water absorption	19.20 %
-0.30 + 0.20	92.39	C_{total}	12.21		
-0.20 + 0.10	96.20	S_{total}	<0.02	pH	9.35
-0.10 + 0.00	100.00				



1. Input channel
2. Lid screw
3. Excangeable speed rotor (10000 and 20000 rpm)
4. Excangeable circular screen (80; 120; 250; 500 μm)
5. Collecting pot for micronized product
6. Aerocyclon
7. Collecting pot of aerocyclon

Fig. 3: The general layout of a Retsch ZM-1 ultra-centrifugal mill.

The values measured during the micronization experiments were used to calculate the capacity of the high-energy ultra-centrifugal mill (Q) and the specific consumption of energy (W_e). During the activation on a material, the capacity and specific energy consumption depend on the amount of activated powder and the time of activation. The capacity of the high-energy mill is directly proportional to the amount of activated material. On the other side, this parameter has an inverse proportion with the activation [19, 20]:

$$Q = \frac{G}{T} \tag{10}$$

The specific energy consumption parameter is determined with the following equation [19, 20]:

$$W_e = \frac{E}{G} = \frac{N \cdot t}{G} = \frac{N}{Q} \tag{11}$$

where:

Q is the mill capacity, kg/h;

G is the mass of the dry micronized sample, kg;

t is the milling time, h;

E is the energy for micronization milling, kWh; and

N is the power of the mill, kW.

IV. Results and Discussion

The experimental part of the investigation of dry limestone micronization was performed in four series of experiments. In all series, the changeable parameters associated with mill operation, technological parameters and fine micronization product parameters were monitored and the values obtained are listed in Table 2.

As a result of comparative analysis (Table 2), it can be observed that with an increase in the mill load at a nominal number of revolutions $n_0 = 10000$ and 20000 rpm, the current density rose ($I = 1.20 - 3.80$ A) for all investigated screen sizes (a = 80, 120, 250, 500 μm). At the same time, with the increase of ultra-centrifugal mill load, the technological parameters of micronization process also changed, and the following dependences could be observed: (1) the increase in Q leads to a reduction of t; (2) the increase in parameter d_{95} leads to a reduction of Q, d' and v; (3) the increase in parameter d_{95} and decrease of S_t lead to an increase in v, W_e, t, and Q, and (4) the increases in parameters d_{95} and Q lead to a change of S_t and reduction of W_e. During micronization grinding, the product parameters were also changed and the following dependence was observed: (1) reduction of v leads to an increase in d'; (2) reductions in v and W_e lead to changes of Q and an increase in d_{95}; and (3) an increase in Q leads to a change of W_e and a reduction of S_t. Based on the experimental results of the tests, the following diagrams were drawn (Figs. 4 – 6).

Functional dependences $d_{95}\,f(v, Q, W_e)$ show that the parameter d_{95} increases with increasing circular sieve meshes from 80 to 500 μm, reducing the circumferential rotor speed v, as well as increasing the mill capacity Q at the same time. These functional dependences are characterized by the increase in the specific energy consumption W_e, and independence from the rated rpm rotor n_0, i.e. the same process is performed at 10 000 and 20 000 rpm (Fig. 4).

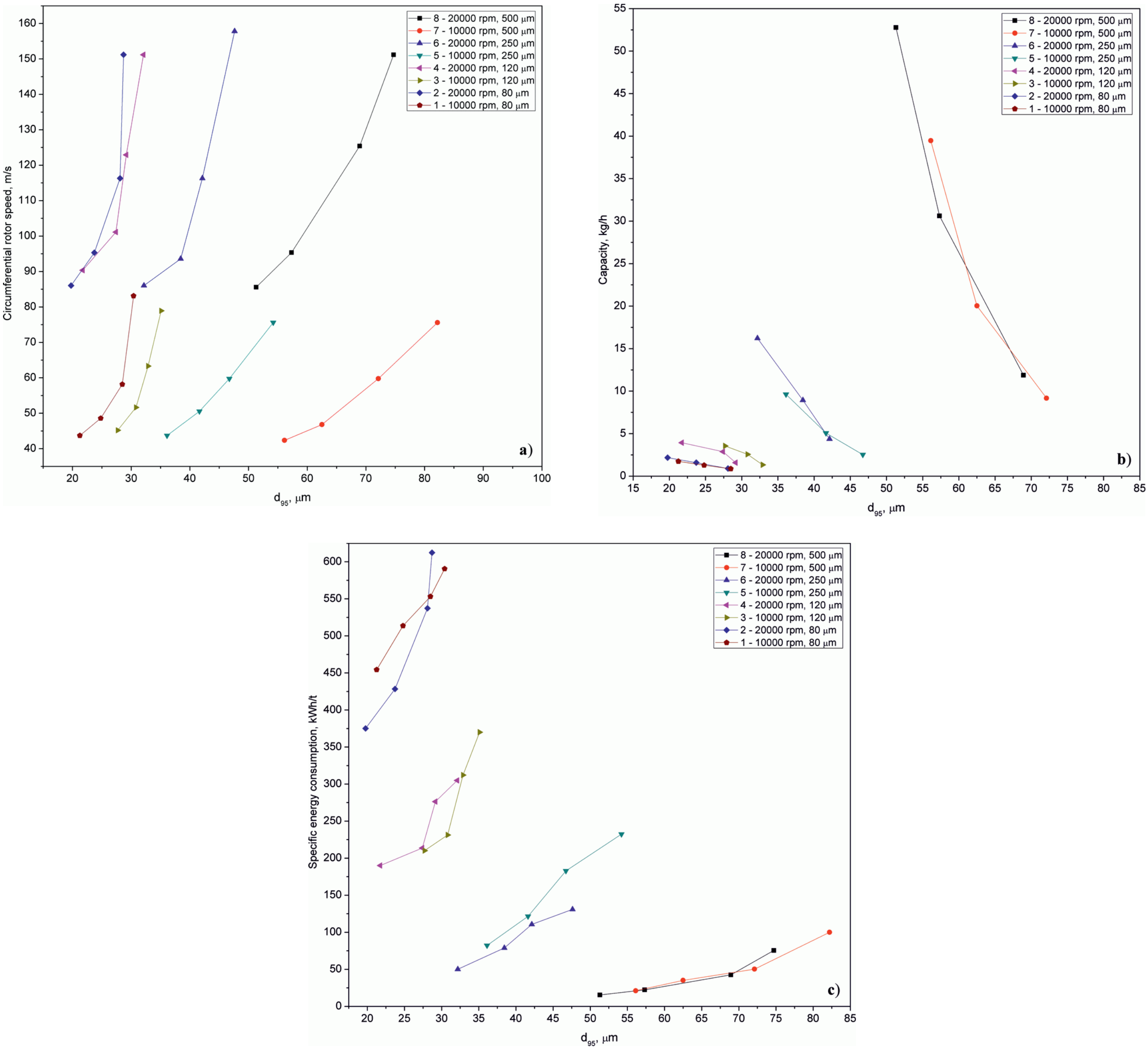


Fig. 4: The functional dependence d_{95}, as a variable parameter of particle size distribution of ultra-centrifugal mill, and *a)* the circumferential rotor speed v; *b)* the capacity Q; *c)* distribution of the specific energy consumption W_e.

Table 2: Parameters of ultra-centrifugal mill operation, technological parameters and micronization of limestone from the "Visočica' deposit".

Ser. nom	Exp. seq. no.	Parameters of ultra-centrifugal mill operation				Technological parameters of micronization				Micronization product parameters				
		n_0 rpm	n_1 rpm	a μm	I A	t min	v m/s	Q kg/h	W_e kWh/t	d_{98} μm	R %	d' μm	d_{95} μm	S_t m^2/kg
I	1	10000	15876	80	1.2	9.5	83.12	0.447	590.60	37.32	89.80	9.47	30.40	1929
	2	10000	11107	80	2.2	7.1	58.16	0.875	553.14	34.89	87.31	7.78	28.49	2572
	3	10000	9278	80	3.0	4.25	48.58	1.285	513.62	32.65	79.76	4.69	24.80	3023
	4	10000	8347	80	3.6	2.5	43.70	1.743	454.39	28.76	76.45	3.04	21.25	3731
	5	20000	28872	80	1.4	7.5	151.17	0.503	612.33	35.12	88.86	8.40	28.70	2181
	6	20000	22214	80	2.2	6.0	116.31	0.901	537.18	34.11	86.93	6.40	28.10	2678
	7	20000	18207	80	3.1	2,5	95.33	1.592	428.39	31.73	78.31	4.21	23.72	3279
	8	20000	16431	80	3.7	1.6	86.03	2.170	375.12	26.87	75.42	2.95	19.76	3945
II	1	10000	15070	120	1.3	5.5	78.91	0.773	369.99	41.52	90.51	11.19	35.1	1522
	2	10000	12093	120	1.9	3.833	63.32	1.339	312.17	40.13	87.67	8.64	32.87	2115
	3	10000	9863	120	2.7	3.25	51.64	2.568	231.31	39.14	82.05	6.55	30.8	2627
	4	10000	8629	120	3.4	2.92	45.18	3.557	210.29	34.13	79.87	4.67	27.69	3009
	5	20000	28872	120	1.4	4	151.17	1.01	304.95	39.51	88.77	9.55	32.1	1837
	6	20000	23476	120	2.0	3.0	122.92	1.592	276.38	37.12	86.14	7.81	29.16	2507
	7	20000	19314	120	2.8	2.17	101.13	2.882	213.74	35.73	84.99	5.70	27.40	2822
	8	20000	17257	120	3.4	2.0	90.36	3.934	190.14	26.05	78.37	4.02	21.73	3104
III	1	10000	14436	250	1.4	3.00	75.59	1.325	232.45	65.52	92.79	14.92	54.2	1135
	2	10000	11411	250	2.1	2.25	59.75	2.525	182.97	57.79	90.67	13.38	46.73	1327
	3	10000	9657	250	2.8	2.0	50.56	5.069	121.52	50.92	88.92	11.89	41.63	1577
	4	10000	8347	250	3.6	1.5	43.70	9.633	82.22	45.57	87.03	10.53	36.11	1766
	5	20000	30140	250	1.3	2.33	157.81	2.185	130.89	58.07	90.45	12.88	47.62	1391
	6	20000	22214	250	2.2	1.833	116.31	4.372	110.70	52.35	88.73	11.62	42.13	1534
	7	20000	17875	250	3.2	1.5	93.59	8.933	78.812	47.44	86.91	10.37	38.44	1639
	8	20000	16431	250	3.7	1.167	86.03	16.225	50.17	40.69	85.79	9.18	32.17	1881
IV	1	10000	14436	500	1.4	1.75	75.59	3.079	100.03	97.97	93.02	17.53	82.2	932
	2	10000	11411	500	2.1	1.33	59.75	9.176	50.35	87.18	91.73	16.01	72.11	1047
	3	10000	8937	500	3.2	1.0	46.79	20.033	35.14	78.26	90.27	14.54	62.5	1125
	4	10000	8090	500	3.8	0.666	42.35	39.467	21.18	67.45	88.87	13.29	56.12	1237
	5	20000	28872	500	1.4	1.417	151.17	4.082	75.45	90.08	91.73	15.71	74.71	1086
	6	20000	23956	500	2.3	1.083	125.43	11.876	42.61	82.87	90.21	14.27	68.93	1127
	7	20000	18207	500	3.1	0.89	95.33	30.623	22.27	69.47	89.16	12.79	57.32	1213
	8	20000	16341	500	3.7	0.5	85.56	52.771	15.43	60.64	87.77	11.43	51.3	1581

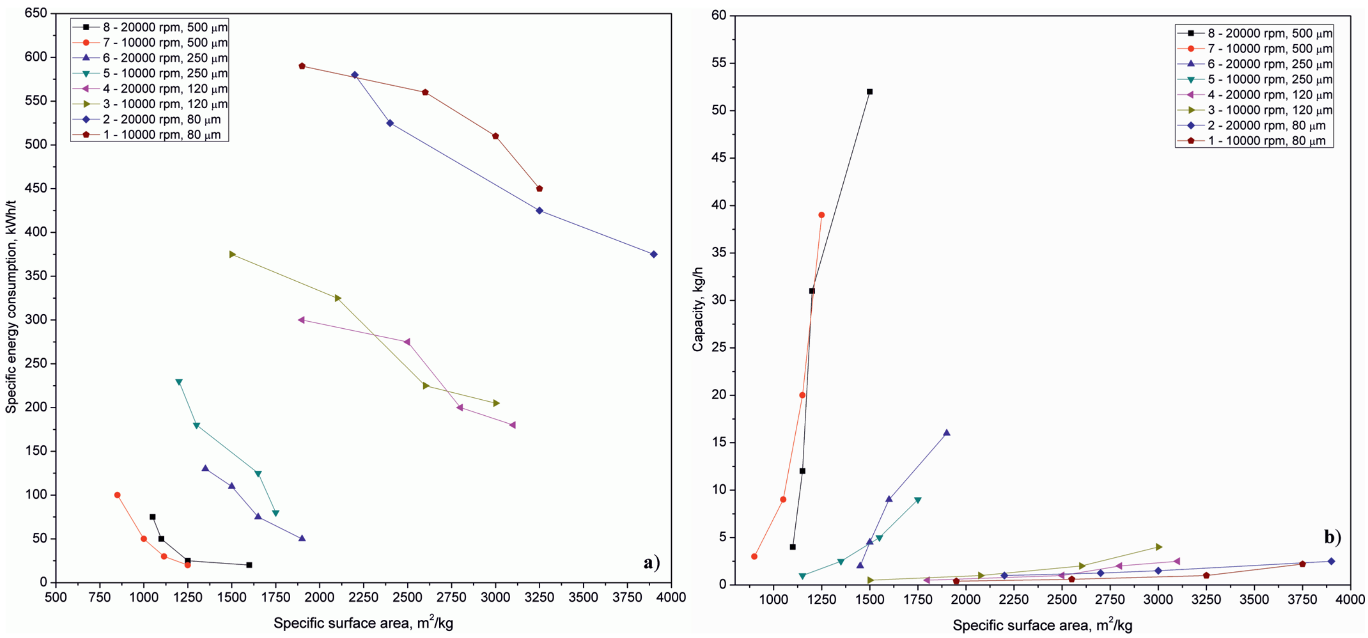


Fig. 5: The functional dependence of the specific surface S_t, and *a)* the specific energy consumption, W_e; *b)* the capacity Q.

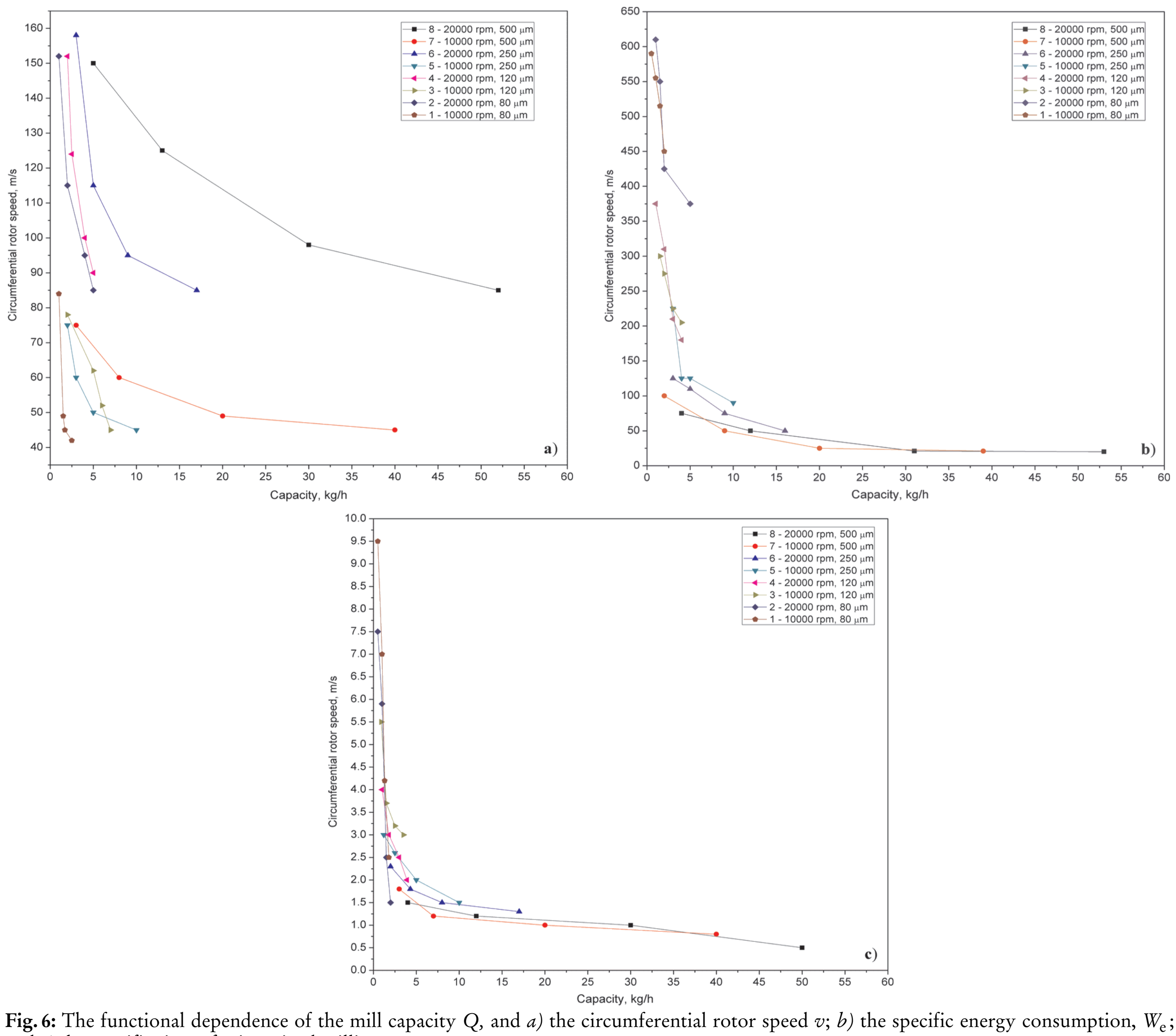


Fig. 6: The functional dependence of the mill capacity Q, and *a)* the circumferential rotor speed v; *b)* the specific energy consumption, W_e; and *c)* the specific time of micronized milling t.

Functional dependences $S_t f(W_e, Q)$ show that the specific surface S_t decreases with circular sieve meshes from 80 to 500 μm and mill capacity Q, which is followed by reduced specific energy consumption W_e (Fig. 5.).

Functional dependences $Qf(v, W_e, t)$ show that the mill capacity Q increases with changing circular sieve meshes from 80 to 500 μm, by reduction of the specific surface S_t, the circumferential rotor speed v, and the micronized milling time t. These functional dependence monitors reduce specific energy consumption W_e and independence of the rated rpm rotor for n_0 =10 000 and 20 000 rpm (Fig. 6).

The analysis of the experimental research results of limestone dry micronization kinetics in an ultra-centrifugal mill with peripheral grinding path indicates that with the increase in the load of the mill there is a change in the technological parameters and the parameters of the micronization products. Specifically, with an increase in the load of the mill, it can be seen that the value of micronized milling time t, circumferential rotor speed v, specific energy consumption W_e and average grain size d' decrease, while the value of mill capacity Q, specific surface S_t and the parameter that defines the micronized grinding fineness d_{95} increase. Based on the experimental results achieved in the ultra-centrifugal mill with peripheral grinding path, where limestone micronized grinding is achieved primarily based on impact, in terms of high speed, it can be said that voluminous circular sieve openings with a different network evidently play a prominent role. Achieved experimental results indicate that the change of circular mesh sieve mesh (80; 120; 200 and 500 μm) leads to an increase in the micronized grinding speed, i.e. the larger the aperture of the circular mesh sieve, the greater is the micronized milling speed, as the basic characteristic of kinetics micronized milling. However, the circular hole mesh sieve is not directly related to the micronized grinding kinetics, but more related to the desired fineness, i.e. desired fineness of micronized grinding dictates the circular sieve and any openings used. On the basis of the experimental investigations and the obtained sieve analysis results, it is evident that the changes in circular sieve meshes from 80 to 500 μm reduce the nominal number of mill revolutions from 20 000 rpm to 10 000 rpm. According to size, the finest products are obtained with an aperture of circular mesh sieve of 80 μm and nominal number of mill revolutions of 20 000 rpm.

The comparative analysis of the achieved experimental results showed that the velocity value of micronized milling, which is the main characteristic of the kinetics of micronization milling, increases: (1) with the load of the mill, and is the highest for nominal mill load; and (2) with increase in the number of mill rotor revolutions, and it is the highest for maximum rotor speed value.

V. Conclusions

On the basis of the experimental investigation and results obtained, it is obvious that investigation of limestone micronization grinding, with regard to contemporary technologies, is a very complex and important task. It is concluded that micronized limestone has a very wide range of application, especially in the production of fillers and fine materials. Specific physical, mechanical and chemical properties (color, density, shape, size and structure of micro particles, etc.) give this raw material distinctive characteristics in respect of the fabrication of new ceramic composites. The industrial demands for micronized limestone can be satisfied only by processing it in high-energy micronization mills, such as an ultra-centrifugal mill with peripheral comminuting path.

The investigations performed in this work enabled: (1) definition of the exact requirements of limestone dry micronization, depending on the optimum values of all significant technological parameters of the process itself, (2) development of a kinetics model, on the basis of obtained results and derived mathematical equations, that can be used in optimization and automation of the dry micronization process in ultra-centrifugal mills with a peripheral comminuting path. During dry micronization of the limestone in an ultra-centrifugal mill with a peripheral comminuting path, where micronization grinding was performed mainly based on impact, under the conditions of high circumferential rotor speeds, it was observed that: (1) the grinding rate, as the basic characteristic of micronization kinetics, increased with the increase in the mill load and number of rotor revolutions; (2) the micronization grinding rate was highest at a nominal load; and (3) the best performance was achieved for a full mill load.

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