Mining Science, vol. 32, 2025, 155–167

www.miningscience.pwr.edu.pl

Mining Science

(Previously Prace Naukowe Instytutu Gornictwa Politechniki Wroclawskiej, ISSN 0370-0798)

ISSN 2300-9586 (print)
ISSN 2353-5423 (online)

Received February 12, 2025; Reviewed; Accepted October 14, 2025

THE INDUSTRIAL EFFECTS OF BALL TYPE ON CERAMIC PORCELAIN TILE BODY GRINDING

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Abstract: Raw materials such as feldspar, kaolin and illitic clay are used in the preparation of ceramic porcelain tile compositions according to their specific properties. Such raw materials are ground in ball mills in order to reduce the particle size to a certain value determined according to the operating conditions. In this study, it was aimed to compare capacity, time and energy spent in the grinding process of porcelain tile composition by using alumina and silica grinding medium from an industrial perspective. In this context, firstly, the grinding properties of the raw materials were determined with porcelain ball mill and Bond mill, separately. Bond Work Index values of magnesite, clay, kaolin and feldspar were determined as 8.7, 7.9, 12.3 and 14.2 kWh/ton, respectively. Then industrial grinding of a porcelain body was executed with a discontinuous horizontal ball mill. The industrial grinding studies showed that porcelain body was ground at 480 and 720 min to reach 2% sieve residue for +45 µm with alumina and silica ball, respectively, which resulted as 625 ton/h capacity difference. Lastly, the ground materials in alumina and silica medium were compared in terms of water absorption, shrinkage, color and SEM analysis after sintering in porcelain tile conditions.

Keywords**:** *ceramic body, porcelain tile, industrial raw material, discontinuous grinding, alumina and silica ball*

1. INTRODUCTION

Ceramic tiles are coating materials produced by firing plastic and non-plastic raw materials such as clay, quartz, and feldspar at high temperatures as a composition after grinding together in wet medium. These materials are widely used on walls, floors, in kitchens, bathrooms, other indoor and outdoor spaces. The application areas of ceramic

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doi: 10.37190/msc/211898

tiles are determined by their properties such as resistance to wear, scratching, breakage, waterproofing, ease of cleaning, frost resistance, hygiene, and aesthetics. In this context, ceramic tiles are classified into different categories based on their measurable properties according to European Standard (EN 14411). The raw materials used in the composition of ceramic tiles also vary depending on their classification. Porcelain tiles are generally produced for use in floor coverings and can be used outdoors due to the unique technical properties (Benkli and Koca 2024). The water absorption value of the porcelain tile body is low (<0.5%) compared to other ceramic tile classes (EN 14411).

Ceramic tile production consists of a series of processes, from the preparation of raw materials to the packaging of the final product (Sacmi 2002). The process begins with the preparation of raw materials that form the body, engobe, and glaze compositions that make up the ceramic tile structure. Raw materials obtained from nature are first reduced to very fine sizes through particle size reduction and classification processes according to size, in accordance with criteria set by manufacturers. At this stage, raw materials are subjected to primary size reduction using jaw, cone, and impact crushers, and are then screened to achieve the desired size for feeding into the grinding/clay mixing system. Porcelain tiles are generally composed of raw materials such as clay minerals, kaolin, and different kinds of feldspar (Niall and Evitt 2000). In the porcelain body preparation step, clay minerals, kaolin, and feldspar are ground in mills in order to reduce the particle size and increase the surface area of minerals.

In recent years, the ceramics industry has increasingly adopted dry grinding and granulation technologies to reduce the high costs associated with water evaporation (Mezquita et al. 2017). Consequently, scientific efforts have focused on formulating ceramic body compositions by using dry raw material preparation methods (García--Ten et al. 2015). Advanced dry grinding techniques have demonstrated effectiveness in generating ultra-fine raw materials using current technological capabilities. Nonetheless, existing dry granulation approaches fall short in achieving uniform mineral distribution within the ceramic matrix. As a result, producers often prefer wet processing systems for body preparation (Ghorra 2008). In this context, ball mills are widely utilized for comminution in aqueous environments, as they yield finer particle sizes. Particle size reduction occurs through the interaction between grinding media and ore particles with adequate residence time and products finer than 50 micrometers can be produced (Genç and Benzer 2019). In the grinding process, parameters other than the material being ground, such as the type of mill (closed/continuous mill), the inner lining material (alumina, silica, rubber), the grinding medium, the mill rotation speed, and the regime, also affect the final particle size distribution (Tao et al. 2017; Bazin and Lavoie 2000; Dan et al. 2022). Since continuous mills consist of two or three compartments, different ball charges can be used, which positively affects grinding efficiency (Amannejad and Barani 2020; Iwasaki and Yamanouchi 2020). Continuous systems, however, may result in broad particle size distributions. So, batch grinding methods are preferred, as they allow continuous removal of fine particles and further processing of coarser fractions to enhance product uniformity (Lyu et al. 2019). In the grinding of ceramic raw materials, ball loading is carried out at 30–40% of the mill volume. After the particle size reduction process, the clay, kaolin, and feldspar groups that are reduced to a fine size are screened and sent to spray dryers to produce porcelain tile granules. The granules are shaped in presses to form green tiles, which are then dried. The dried tiles, which gain strength through drying, are sintered in a kiln after glazing, engobe, and decorative applications to produce the final product. For the tile obtained from the kiln to be suitable for delivery to the customer, compliance with visual and technical standards is crucial. Therefore, the suitability of each process step to production conditions is of utmost importance.

Grinding is one of the most critical steps in this process and, selection of grinding media plays a critical role in reducing grinding duration and minimizing energy consumption (Koçak and Karasu 2019). Media with elevated specific gravity and hardness improve grinding performance by increasing both impact and frictional forces (Abdelhaffez et al. 2022). Additionally, grinding efficiency is influenced by the mill's filling ratio, which refers to the proportion of the mill volume occupied by both the grinding media and the raw material (Fang et al. 2024). In the past, companies turned to local resources due to insufficient technology or inability to access manufacturers, which necessitated the use of flint (silica balls), widely available worldwide, as a grinding medium by shaping it into mill linings and grinding media. However, with the advancement of technology today, alumina balls, which are harder and have a higher specific gravity than flint balls, are preferred in particle size reduction of ceramic body composition (Matsanga et al. 2023).

The world population is growing day by day, and manufacturers are developing different methods to keep up with demand. Grinding constitutes the most energy-demanding phase in mineral processing, consuming over 50% of the total energy utilized in this sector (Petrakis et al., 2025). Consequently, it is essential to optimize processing parameters by integrating appropriate materials and adopting energy-efficient technologies. Moreover, the selection of a grinding medium that is incompatible with the physical and mechanical properties of the ore can significantly elevate operational expenditures (Cleary et al. 2020; Xu et al. 2025). One of the most important factors affecting the porcelain body preparation efficiency is the type of ball media in the grinding process. For these reasons, in this study, the effects of silica and alumina balls on porcelain body grinding were investigated in terms of technical and capacity aspects with laboratory and industrial experiments.

2. MATERIALS AND METHODS

This study aimed to investigate the effect of the grinding media on grinding efficiency in terms of capacity and energy consumption. In this context, chemical and mineralogical analyses of the raw materials used in the experimental studies were first carried out as part of the characterization studies. Chemical analyses were performed using a PANALYTICAL AXIOS MAX model X-Ray Spectrophotometer (XRF) device, while X-Ray Diffraction (XRD) analysis was conducted using a PANALYTICAL X'PERT PRO MPD diffractometer with an angular range of 3–70° for 2θ, a step size of 0.02, a deviation slit of ¼, and a reflection-preventing slit of ½ to determine mineralogical content. The chemical and mineralogical properties of raw materials used in the experimental studies are shown in Table 1.

Table 1. Chemical and mineralogical analysis of raw materials

Chemical analysis	Unit	Feldspar	Clay	Magnesite	Kaolin
LOI*	(%)	0.3	7.3	46.3	7.9
SiO_2		69.9	59.6	6.4	66.6
Al_2O_3		18.6	27.2	2.1	23.2
TiO_2		0.2	1.4	0.1	0.4
Fe_2O_3		0.1	0.8	0.5	0.2
CaO		0.5	0.3	2.5	0.4
MgO		0.1	0.4	41.3	0.4
Na_2O		9.5	0.4	0.1	0.1
K_2O		0.4	2.1	0.1	0.3
Qualitative mineralogical content		quartz	quartz	magnesite	quartz
		albite	illite	montmorillonite	kaolinite
		muscovite	kaolinite	quartz	illite
			anatase	kaolinite	

* LOI: loss on ignition.

As presented in Table 1, the main sources of SiO_2 and Al_2O_3 content together in the chemical analysis of kaolin were kaolinite and illite minerals. Theoretically, if the oxide analysis of kaolinite mineral was considered to consist of 39.5% Al_2O_3, 46.54% SiO_2, and 13.96% chemically bound water, the excess SiO_2 content in kaolin samples was primarily attributed to quartz mineral (Sieben et al. 2022). In the mineralogical analysis of the clay sample, TiO_2 was found to originate from anatase. On the other hand, the main difference between the clay and kaolin samples was that they contained significant amounts of illite and kaolinite minerals, respectively. The significant amount of Na_2O observed in the chemical analysis of the feldspar sample confirmed the presence of albite mineral in the mineralogical analysis. The significant amounts of MgO and LOI content in the magnesite mineral indicated the presence of $MgCO_3$. Other oxides observed in the analyses are present due to alkaline, alkaline earth, iron, and titanium compounds. Some of these are observed in mineralogical analyses, while others were not observed in the analyses because they were present in small amounts.

In order to determine the sintering characteristics, raw materials were ground to reach 2% for +45 µm, and the clay sample was mixed and sieved to -90 µm in a wet medium. Then, the ground slurries were dried in an oven at 105°C. Next, the dried raw materials were ground with agate mortar and pestle, and then sieved to –250 µm and 6% humidified by spraying water to reach granules which were shaped to 5 × 5 cm by a laboratory press with 400 kg/cm^2 specific pressure and sintered in the porcelain tile conditions. Sintering characteristics of raw materials were investigated in porcelain tile firing conditions (Table 2).

Table 2. Sintering characteristics of raw materials in porcelain conditions

	Unit	Feldspar	Clay	Magnesite	Kaolin
Maximum temperature	°C	1210			
Sintering duration	min	60			
Shrinkage	%	11.2	8.1	33.2	0.6
Water absorption	%	1.7	0.0	3.8	20.1
Color	L	83.8	76.9	89.5	94.6
	a	1.9	1.1	1.7	0.8
	b	11.1	13.4	15.1	3.2
	–				

Raw materials showed different shrinkage, water absorption, and color values depending on the mineral content. The porcelain tile body subject to the study currently consists of illitic clay, kaolin, magnesite, and feldspar. The porcelain body recipe was ground in discontinuous mills in the presence of dispersants in an aqueous environment, then screened and transferred to a storage pool. The particle size of the porcelain body slurry was reduced by grinding and sent to a spray dryer to obtain moldable granules with 6% moisture content. The production process used in the preparation of porcelain tile is shown in Fig. 1.

In order to determine and compare grinding times, the raw materials were ground in a porcelain ball mill with a volume of 1100 mL to 2% sieve residue for +45 µm. The grinding work indices of raw materials were also compared using the standard Bond method. The raw materials fed into the Bond work index tests were first completely crushed in a laboratory-type jaw crusher and then prepared by screening to a size of –3.36 mm. In the experiments, a standard Bond mill made of stainless steel with a diameter of 30.5 cm and a length of 30.5 cm was used. The mill was loaded with 22.648 kg of stainless steel balls with diameters of 38.1, 31.75, 25.40, 19.05, and 12.70 mm, corresponding to 22% of the mill's void volume, and operated at 70 rpm, which is 86% of the critical speed. In each experiment, 100% of the ball void volume

(700 mL) was filled with raw materials of 3.36 mm size. The experiments were conducted by using a test sieve of 75 μm according to the standard bond index determination method specified in TS 7700.

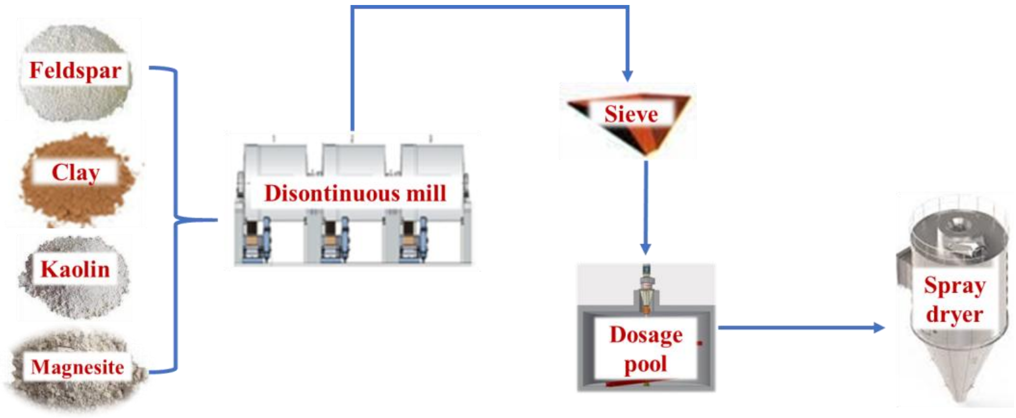


Fig. 1. Flow chart of porcelain tile body preparation process

Industrial-scale experiments were conducted using a REMAS brand batch mill with an alumina lining measuring 310 cm in diameter and 460 cm in length at a constant rotation speed of 14 rpm. After filling the mill separately with alumina and silica balls so that the ball volume was 30% of the mill volume, the effects of the grinding medium on efficiency were also investigated. Alumina and silica balls with specific weights of 3.57 and 2.66 g/cm^3 were used as grinding media. The ball size distribution used in the tests is given in Table 3.

Table 3. Ball sizes and quantities used in industrial grinding trials

Ball size [mm]	25	30	40	50	60
Silica ball weight [kg]	5580	4190	2790	1740	700
Alümina ball weight [kg]	7440	5581	3720	2320	930

In industrial-based porcelain tile composition grinding tests, the size of raw materials was reduced to a size of –10 mm in the crushing and screening plant, and the crushed samples were fed into the mill at a rate of 15 000 kg dry per batch, with the ratios in Table 4 remaining constant.

Table 4. Raw material ratio of porcelain tile composition

Raw materials	Clay	Kaolin	Feldspar	Magnesite
Ratio [%]	23.5	41.0	34.0	1.5

The Tescan brand Vega model Scanning Electron Microscope (SEM) was used to investigate the microstructure of sintered sample surfaces ground by alumina and silica balls. In order to increase the conductivity properties of the samples, the gold-palladium (80–20%) plating process was performed by first applying a vacuum of 8×10^{-1} mbar/Pa and applying a current intensity of 10 mA in the Quorum plating device.

In this study, after determining the grinding properties of the raw materials that make up the porcelain tile recipe, the aim was to determine the time savings and capacity changes in grinding in the presence of silica and alumina balls.

3. RESULTS AND DISCUSSION

The tests conducted on raw materials using laboratory-based ball mill and Bond mill revealed differences in grinding characteristics (Fig. 2). Bond Work Index values were determined as 8.7, 7.9, 12.3, and 14.2 kWh/ton for magnesite, clay, kaolin, and feldspar, respectively. Plastic clayey minerals caused to reduce the Bond Work Index so the almost pure feldspar had the highest value due to the non-plastic character. Besides, grinding times to reach 2% residue for +45 μm values showed a parallel trend with Bond work index.

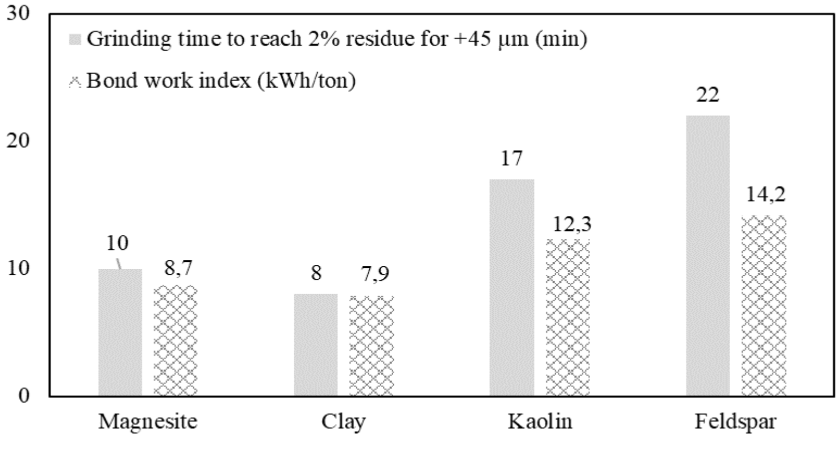


Fig. 2. Grinding characteristics of raw materials used in experimental studies

In ball mills, comminution predominantly occurs through high-energy impacts induced by the motion of grinding media and feed material in conjunction with the rotating shell (Kumar et al. 2023). As the materials are lifted to a sufficient height across the milling chamber and fall under the influence of gravity, colliding with other particles or the mill lining. These dynamic impacts promote fragmentation, particularly in coarser particles, and constitute the primary mechanism of breakage (Hogg and Cho 2000).

Lastly, the particles were ground to a sieve residue forming a particle size distribution. In Figure 3, change in sieve residues for +45 μm size group were given according to grinding times in the presence of silica and alumina ball mediums.

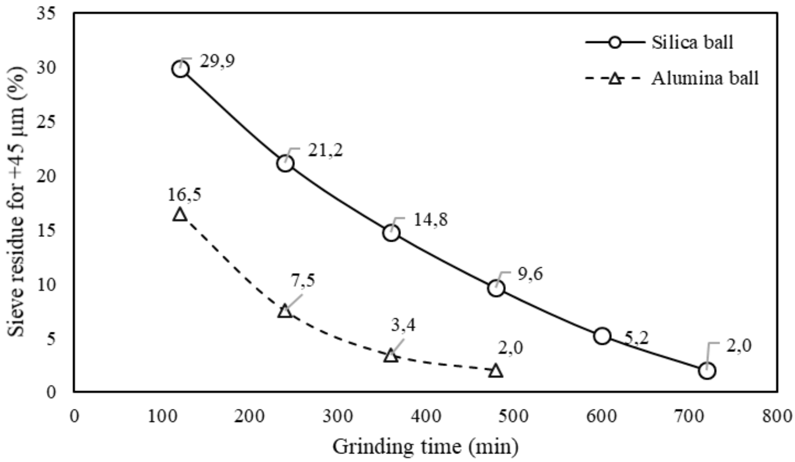


Fig. 3. Comparison of grinding conditions in the presence of silica and alumina balls

As seen in Fig. 3, as the silica balls were used, the grinding time increased significantly compared to alumina balls. This was explained by the fact that silica balls had lower hardness and specific gravity than alumina balls. Silica balls have a Mohs hardness of approx. 7 due to their high SiO_2 content, while alumina balls have an approx. 9, which is close to that of corundum (Staples 1964). On the other hand, the specific gravity value of silica balls is significantly lower than the value of alumina balls. In the presence of silica and alumina balls, porcelain bodies were ground to reach a sieve residue of 2% for +45 μm at 720 and 480 min of grinding time, besides the capacities were calculated as 1250 and 1875 ton/h, respectively. After the porcelain body ground to a sieve residue of 2% for +45 μm, particle size distributions were analyzed for alumina and silica balls, separately (Fig. 4).

Porcelain ceramic bodies contain plastic-like clay minerals and non-plastic mineral groups such as feldspar and quartz. During grinding, the plastic clay minerals first disperse easily in aqueous environments and are reduced to a fine size. However, non-plastic minerals are ground due to the effects of impact and friction forces. At this stage, much more energy is expended compared to the reduction of plastic materials such as clay to a fine size. According to the results of laser particle size measurement performed after the grinding (Fig. 4), the d_{90}, d_{50}, d_{10} values were determined as 46.8, 9.5, 2.5 μm and 47.6, 9.7, 2.8 μm for alumina and silica ball ground porcelain body, respectively. The impact force was effective in the primer particle size reduction, then the friction force made fine particle size reduction. Therefore, high hardness property of alumina balls resulted in finer particle size distribution for the grinding of porcelain body. Alumina and silica ground porcelain bodies were sintered at 1210°C of maximum temperature and 60 min of sintering duration in order to compare sintering characteristics (Table 4).

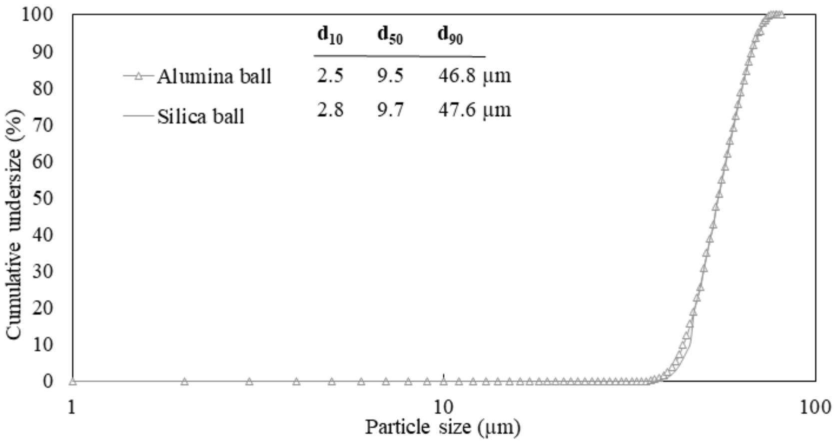
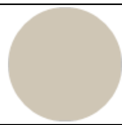
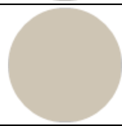


Fig. 4. Particle size distribution comparison of silica and alumina ball ground porcelain body

Table 4. Sintering characteristics of alumina and silica ground porcelain body

	Shrinkage [%]	Water absorption [%]	Color			
			L	*a*	*b*	–
Alumina	8.1	0.0	80.2	1.0	9.8	
Silica	8.0	0.1	80.0	1.1	9.9	

In the sintering studies carried out under porcelain tile conditions, the shrinkage-water absorption values were found to be 8.1 – 0.0% and 8.0 – 0.1% for the bodies ground with alumina and silica balls, respectively. *L-a-b* values after sintering of bodies ground with alumina and silica balls were measured as 80.2–1.0–9.8 and 80.0–1.1 –9.9 (Table 4). The composition prepared by grinding with alumina balls showed a slightly higher shrinkage value and a lower water absorption value compared to the one prepared with silica balls. This situation was explained by the fact that the particle size distribution of the sample ground with silica balls was coarser than that of the sample prepared with alumina balls. This was particularly due to the presence of hard feldspathic minerals and quartz originated from kaolin and clay in the coarse size fraction of the structure, which reacted more difficultly during sintering due to low surface area, resulting in a difference in porosity. The low L value of silica ground composition was attributed to presence of impurities in the natural formation of the grinding medium.

As part of microstructure investigation studies, the SEM images were taken of bodies prepared by grinding with alumina and silica balls and sintered separately under porcelain tile firing conditions.

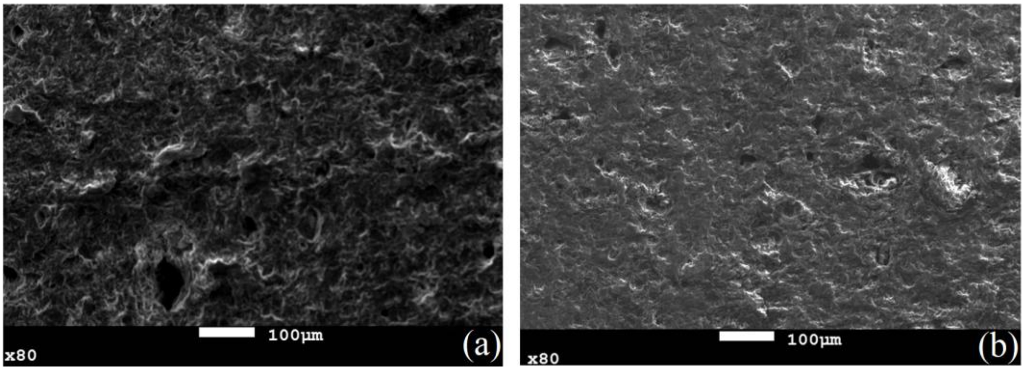


Fig. 5. SEM images of sintered bodies prepared by alumina (a) and silica (b) grinding medium

As a result of SEM image studies, EDX analysis of the surfaces of the structures revealed varying proportions of Al, Si, and Na elements. The sizes of pores observed on the surface were found to vary between 27.5–96.4 µm and 38.2–152.0 µm in the *X* and *Y* axes for alumina and silica ground prepared sintered compositions, respectively. The porosity of ceramic materials is strongly influenced by critical parameters such as the sintering duration and sintering temperature. It is intrinsically linked to the pore characteristics including density, morphology, and size distribution all of which significantly impact the overall performance of ceramics, particularly in terms of water absorption. Hence, bigger pore size for silica ground composition supported higher water absorption values after sintering compared to alumina ground one (Yang et al. 2024).

5. CONCLUSION

This study analyzed the structure of the raw materials that make up porcelain, which consists of kaolinitic and illitic clay, albite, magnesite, and quartz minerals, as well as impurities containing potassium, calcium, titanium, and iron. As a result of studies conducted to determine the grinding characteristics of raw materials, feldspar was hard to grind and needed more energy compared to kaolin, clay, and magnesite. In the industrial-based grinding tests, 2% sieve residue for +45 μm was achieved in 480 minutes with alumina balls, while this value was achieved in 720 minutes with silica balls. This showed that a capacity value of 625 tons/h higher than silica balls, could be achieved with alumina balls. There was no significant difference in particle size distribution and sintering characteristics of ground porcelain body with alumina and silica balls. Grinding with alumina balls showed higher shrinkage and lower water absorption than grinding with silica balls, indicating that the structure was slightly more compacted. The lower color values for silica balls were thought to be due to the natural color of silica balls. The Al, Si, and Na peaks observed in microstructure analyses confirmed the formation of mullite crystals and glass phases after sintering of the raw materials contained in the body. The pores in the SEM images represent the open porosity on the surface. Since the open pores on the surface were not connected to the pores within the sintered structure prepared with alumina balls, water absorption was found to be "0". For silica balls, it was understood that only a small portion of these pores on the surface could reach the interior of the structure. Although the initial investment costs of alumina balls are high, it is clear that they offer economic and capacity benefits over silica balls in terms of operating parameters over time. On the other hand, considering the reduction in specific energy consumption and environmental impacts, alumina ball will also provide benefits in terms of carbon emissions in the grinding step.

ACKNOWLEDGEMENTS

This work was supported by Çanakkale Onsekiz Mart University, The Scientific Research Coordination Unit, Project number: FBA-2024-4812. Besides, thanks to the Kaleseramik R&D Center for experimental support.

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