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APPLICATION OF THERMAL POWER PLANT ASH AS AN ADDITIVE IN CERAMIC CONSTRUCTION MATERIALS

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Abstract: *This study investigates the possibility of utilizing thermal power plant (TPP) ash as a partial substitute for quartz sand in building bricks. Four ceramic compositions (Br 1–Br 4) with progressively increasing ash content were formulated, processed by semi-dry pressing, and fired at 900–1050°C. The samples were characterized for water absorption, apparent density, porosity, mechanical strength, and frost resistance. Results indicate compliance with relevant standards for all key parameters, revealing a trend toward reduced density and elevated porosity with higher ash concentration. The research demonstrates that TPP ash valorization in construction ceramics simultaneously addresses waste management challenges and reduces extraction of natural resources. This approach aligns with circular economy principles by transforming industrial waste into valuable construction materials, thereby reducing the environmental footprint of both the energy and building sectors.*

Keywords: *thermal power plant ash, waste valorization, ceramic, construction materials.*

INTRODUCTION

The global construction industry is in a constant struggle with the growing need for resources and the prevailing need for sustainable development. Such an issue requires the search for innovative approaches aimed at optimizing production processes, reducing the consumption of natural raw materials, and integrating the principles of the circular economy. In this context, the production of construction ceramic products (bricks, roof tiles, facing tiles, etc.) faces challenges related to the exploitation of traditional materials such as clay and quartz sand, the extraction of which leads to environmental degradation and depersonalization of the landscape (Kovalskiy, V., & Tymoshenko, V., 2023).

In parallel, the energy sector, and in particular thermal power plants (TPPs), produce significant amounts of solid waste, among which ash occupies a major share. The disposal of this ash poses a serious environmental threat, including the risk of contamination of soils, groundwater, and the atmosphere with heavy metals and fine dust particles. Therefore, finding effective and economically viable ways for its utilization becomes an urgent necessity (Triana, D., 2023).

One of the most promising approaches to solving both problems is the use of thermal power plant ash as a secondary raw material in building materials. Its inclusion in the production of building ceramics has the potential for a dual effect: on the one hand, it can serve as a partial or complete replacement for traditional quartz sand, thus reducing dependence on natural deposits (Singh, N., 2022). In addition, its chemical composition, rich in SiO_2 and Al_2O_3, and the presence of a glass phase can have a positive impact on the technological process and the properties of the final product, improving its mechanical strength, durability, and density during sintering (Amarnath, P., Kulkarni, S., & Kumar, P., 2024; Zhao, Y., 2017). On the other hand, this approach has a significant environmental impact, transforming a waste product into a valuable resource. This not only significantly reduces the volumes of landfilled waste and the associated risks but also contributes to achieving the goals of sustainable development and closing the material cycle in industry (Naganathan, S., Subramaniam, N., & Mustapha, K., 2012; Abbas, S., Saleem, M., Kazmi, S., & Munir, M., 2017; Nguyen, V., & Huynh, T., 2022; Peng, J., 2012; Gupta, R., & Chaudhary, S., 2020).

Preliminary studies indicate that bricks and tiles incorporating fly ash may achieve performance comparable to or even superior to conventional products, showing promising improvements in fire resistance, reduced density, and enhanced environmental benefits (Naganathan, S., Mustapha, K., & Subramaniam, N., 2015; Kute, S., & Deodhar, S., 2003; Saleh, A., Al-Majidi, M., & Abbas, S., 2021; Rana, A., 2014). However, further systematic research is still needed to validate these findings and to optimize the processing parameters.

The aim of this study is to assess the possibility of effective utilization of ash from thermal power plants as a raw material additive in the production of building bricks by partially replacing quartz sand in a traditional commercial composition. The study determines the influence of ash and the firing temperature regime on the main physicomechanical indicators of the resulting ceramic products—water absorption, apparent density, apparent porosity, compressive strength, and frost resistance, and their compliance with the requirements of the current standards for building ceramic materials.

EXPOSITION

Materials and methods

The starting materials used for the experiment are ash from the Sliven Thermal Power Plant, clay from the Bachvata deposit, sand from the Bachvata deposit and brown coal. The chemical composition of the raw materials is presented in Table 1. The ash from the thermal power plant is characterized by a high content of SiO_2 (48.32%) and Al_2O_3 (17.90%), as well as a significant amount of Fe_2O_3 (18.01%), which makes it suitable for use in ceramic materials. Chemical analysis shows a significant amount of sulfates (SO_3 - 5.60%), which requires careful control of the temperature regime during firing to prevent desulfurization. The relatively high content of Fe_2O_3 (18.01%) in the ash contributes to the coloring of the final product and can affect the temperature characteristics of sintering.

Table 1 Chemical composition of the starting raw materials, mass%

Raw materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O Na_2O	TiO_2	MnO	SO_3	3H
Ash from termal power plants	48,32	17,90	18,01	4,52	2,34	2,4	0,87	0,04	-	5,60
Clay	63,44	15,25	4,81	5,63	1,46	1,76	-	-	-	7,65
Coal	22,00	10,48	3,68	1,88	0,8	-	-	-	1,16	60,00
Sand	64,71	13,5	3,92	3,58	2,93	4,8	-	-	-	6,56

The clay from the "Bachvata" deposit contains 63.44% SiO_2 and 15.25% Al_2O_3, which defines it as medium-plastic with suitable properties for brick production. The sand from the same deposit has a typical quartz composition with 64.71% SiO_2. Brown coal is characterized by a high ash content (60.00%) and a relatively low SiO_2 content (22.00%).

The fly ash is classified as superacid, which is defined by a basicity modulus of 0.1 (Mb = CaO+MgO / SiO_2+Al_2O_3). This low value, characteristic of class F according to ASTM C618, implies a high melting point and increased viscosity during heat treatment, which can affect the sintering behavior and the final porosity of the ceramic body (ASTM International, 2023; Erol, M., Küçükbayrak, S., & Ersoy-Meriçboyu, A., 2008). The results of the X-ray phase analysis (Figure 1) reveal a complex mineralogy, showing the presence of intense reflections corresponding to the primary crystalline phases: quartz (SiO_2), magnetite (Fe_3O_4) and albite ($NaAlSi_3O_8$). A significant amorphous phase was also identified. The presence of iron oxides, mainly in the form of magnetite rather than hematite, is significant as it can act as a flux, potentially lowering the sintering temperature and contributing to the development of mechanical strength in the final ceramic product (Dana, K., & Das, S., 2004).

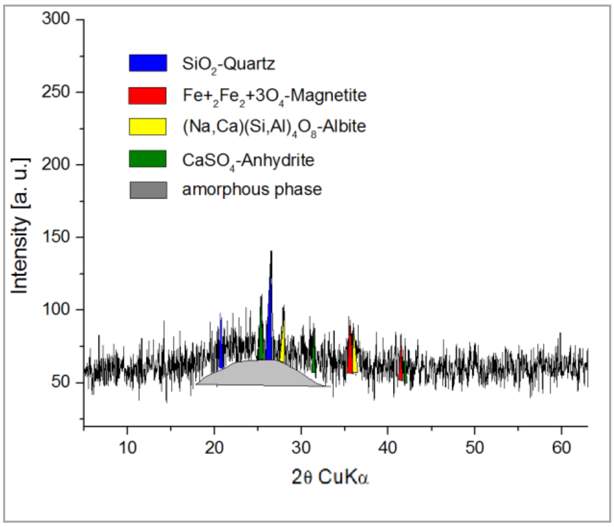


Fig. 1 Diffractogram of ash from a thermal power plant

Based on a traditional brick production composition, experimental ceramic mixes were developed: clay, ash, sand, and coal, wherein the ash is introduced at the expense of sand for batches Br 1 – Br 4. The formulations of the trial ceramic compositions are presented in Table 2.

Table 2 Composition of the experimental ceramic batches**,** mass%

Compositions	**Ash**	**Clay**	**Sand**	**Coal**
Br 1	1,35	63	25,65	10
Br 2	2,70	63	24,30	10
Br 3	6,75	63	20,25	10
Br 4	13,50	63	13,50	10

The chemical composition of the the experimental ceramic batches, calculated based on their formulations, is presented in Table 3.

Table 3 Chemical compositions of experimental ceramic batches, mass%

Compositions	**Br 1**	**Br 2**	**Br 3**	**Br 4**
SiO_2	59,42	59,19	58,53	57,54
Al_2O_3	14,36	14,42	14,60	15,01
Fe_2O_3	4,65	4,84	5,41	6,58
CaO	4,71	4,73	4,76	4,94
MgO	1,78	1,77	1,75	1,73
$Na_2O + K_2O$	2,37	2,34	2,24	1,48
TiO_2	0,01	0,02	0,05	0,12
MnO	0,01	0,01	0,01	0,01
SO_3	0,12	0,12	0,12	0,12
LOI	12,57	12,56	12,53	12,47

The mixes were blended and homogenized through dry milling in a ball mill for 3 hours, followed by plasticization with 8% distilled water. After granulating the mixes through a 0.5 mm sieve, the test specimens were formed via the semi-dry pressing method at a pressure of 50 MPa. The firing of the specimens was carried out within the temperature range of 900–1050°C and isothermal holding for 3 h; heating rate 5°C/min and free cooling.

Results and Discusion

Fig. 2 shows the dependence of the apparent density (ρ_{app}) of the synthesized samples Br 1–Br 4 on the firing temperature in the range 900–1050°C. The data show that for all compositions the density increases with increasing temperature, which is characteristic of the ongoing sintering processes and the more complete densification of the ceramic matrix at higher temperatures (Rahaman, M., 2003). Under the same temperature conditions, the samples with higher ash content (Br 3 and Br 4) demonstrate lower apparent density valuescompared to the compositions with less ash (Br 1 and Br 2). At 900°C the values range from $1,82.10^{-3}$ kg/m³ for sample Br 1 to $1,75.10^{-3}$ kg/m³ for Br 4, while at 1050 °C the values increase to $1,86.10^{-3}$ kg/m³ and $1,79.10^{-3}$ kg/m³, respectively, with the difference between the two compositions remaining distinct, despite the overall increase in density due to more intensive sintering.

The introduction of ash into the compositions leads to a change in the grain size and composition of the mass, with amorphous and fine particles, which at the same temperature regime limit the degree of compaction and increase the total pore volume (Ahmaruzzaman, 2010). On the other hand, the fluxing oxides in the ash (Na_2O, K_2O, CaO) accelerate the formation of a liquid phase, which partially compensates for the negative effect on density at higher temperatures.

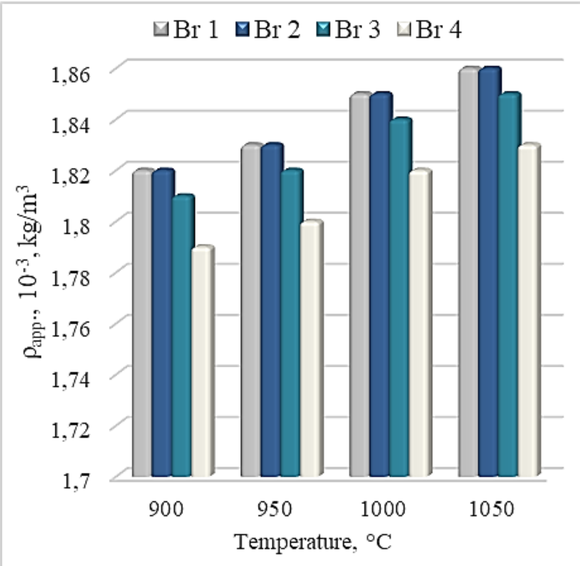
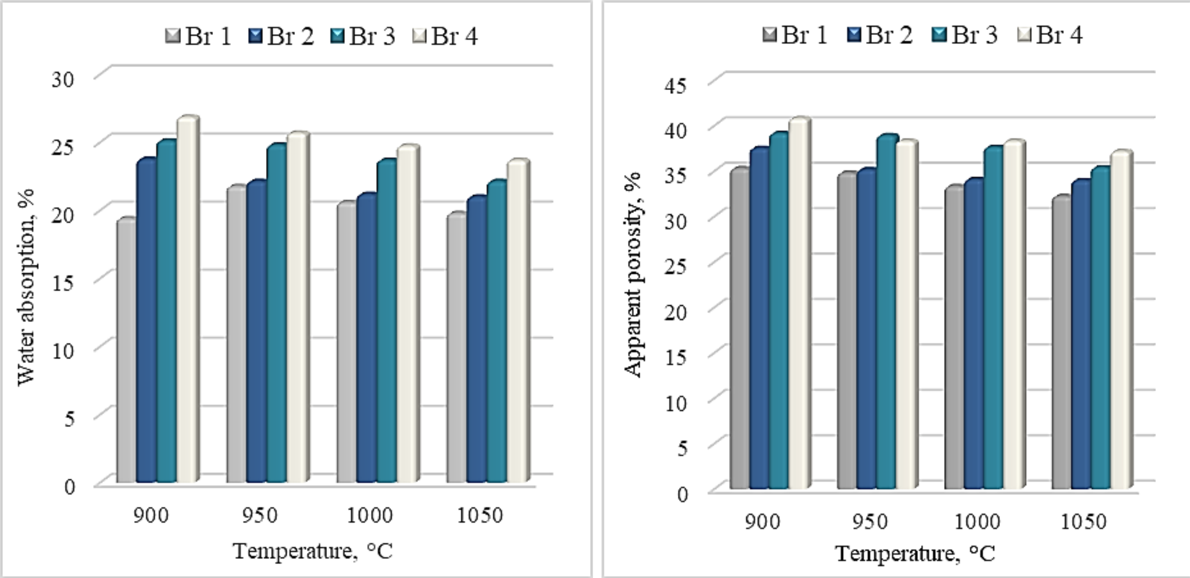


Fig. 2 Influence of ash content on apparent density of samples
at different sintering temperatures

The obtained dependencies are consistent with literature data on the use of thermal power plant ash in fired construction ceramic products, where a decrease in density and an increase in porosity are observed with higher ash content, along with an improvement in the thermal insulation characteristics of the products (Eliche-Quesada, D., Barral, L., Nieto, A., & Losilla, E. R., 2018). This trend is also confirmed by the results presented in Fig. 3a and Fig. 3b, which show the direct relationship between ash content, firing temperature, and two closely related parameters—water absorption and apparent porosity. It is evident that with the increase in ash content in the composition, the values of both parameters increase, whereas raising the temperature leads to a gradual reduction in porosity and correspondingly lower water absorption. This is primarily due to the specific granulometric composition and chemical heterogeneity of the ash. The diversity in particle sizes and shapes, as well as the presence of a significant amorphous phase, contribute to the formation of additional interparticle spaces and create a more developed porous network. Simultaneously, the low basicity modulus (approximately 0.1), which indicates a highly acidic nature of the ash, limits the early formation of a vitreous phase at lower temperatures (900–950°C) and contributes to the retention of higher porosity. At higher temperatures (above 1000 °C), the amorphous phase participates in sintering processes, leading to partial densification of the structure. This effect is particularly pronounced in compositions with higher ash content (Br 2–Br 4), where the open porosity decreases more significantly at 1050 °C, correspondingly reducing water absorption as well.



a b

Fig. 3 Influence of ash content on water absorption (a) and apparent porosity (b) of samples at different firing temperatures

For the Br 1 composition sample, where the ash contain is minimal, water absorption remains practically unchanged—from 19,39% at 900°C to 19,77% at 1050°C, indicating that the structure is stable and weakly sensitive to temperature variations. In contrast, for Br 4 sample, the decrease is noticeable from 26,84% at 900°C to 23,67% at 1050°C. Concurrently, the apparent porosity also decreases: for Br 1, from 35,29% to 32,22%, and for Br 4, from 40,79% to 37,16%. The comparison of the results clearly demonstrates that the incorporation of ash leads to a more porous microstructure with higher water absorption, while increasing the temperature to 1050°C partially compensates for this effect through densification and reduction of interconnected pores.

The study of the mechanical properties of ceramic materials shows a clear dependence on the composition. With increasing ash content, a systematic decrease in compressive and tensile strength is observed (Fig. 4). The highest values were found for sample Br 1 – 25 MPa in compression and 3,8 MPa in tension, while for Br 4, containing the largest share of ash, they dropped to 19 MPa and 2,9 MPa, respectively. The decrease in strength indicators is due to the increased porosity and lower density of samples with a higher ash content. Additional stress concentrators resulting from the porous microstructure, as well as differences in the coefficients of thermal expansion between ash particles and the ceramic matrix, favor the formation of microcracks and reduce mechanical resistance.

Despite the clear reduction in strength with increasing ash content, all studied compositions retain values that meet the requirements for building ceramic materials. This confirms the possibility of effective technological application of ash from the Sliven TPP as a raw material additive, allowing for the simultaneous utilization of industrial waste and preservation of the necessary operational characteristics.

The values obtained for the mechanical strength of the test specimens correlate with the values of the apparent density. In terms of compressive strength and bending strength, the bricks meet the requirements of BDS EN ISO 10545.

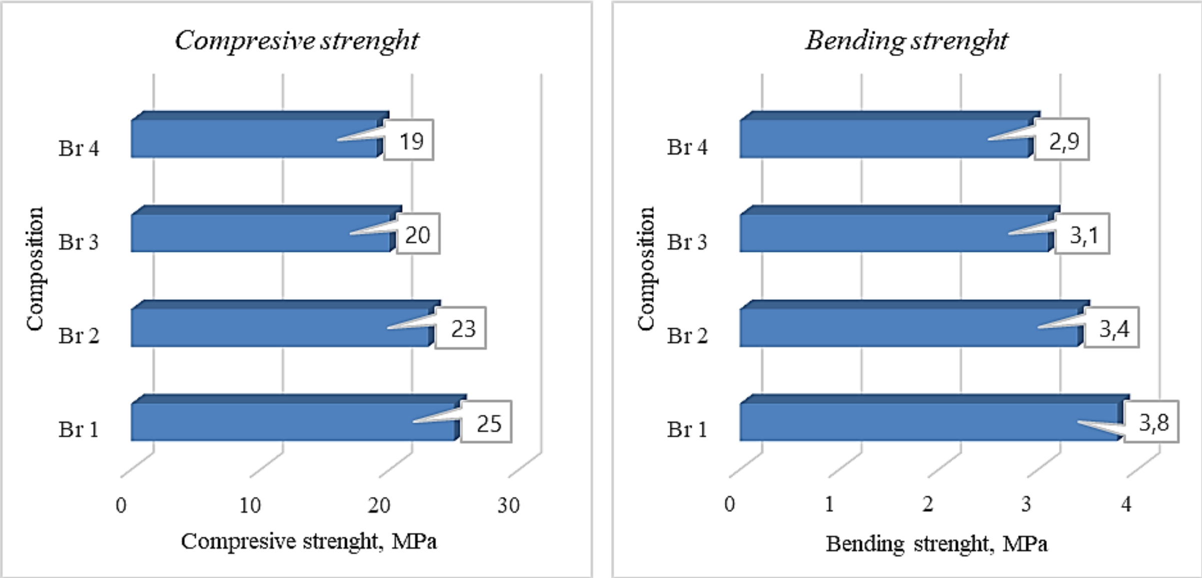


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Fig. 4 Influence of ash content on compresive strenght (a) and bending strenght (b) of samples at a sintering temperature of 1050°C

The X-ray phase analysis of the samples of compositions Br 2 and Br 4 presented in Figures 4a and 4b shows that the main crystalline phases in the fired materials are albite ($NaAlSi_3O_8$) and quartz (SiO_2), and in a subordinate amount hematite (Fe_2O_3) is registered. This crystal phase ratio is characteristic of both compositions and indicates the stability of the mineral structure at the applied firing temperature regimes.

In the composition Br 4, containing a higher proportion of ash, a distinct increase in the intensity of diffraction reflexes characteristic of albite is observed compared to Br 2. This can be explained by the additional introduction of albite through the ash from the Sliven TPP, the preliminary analysis of which confirms the presence of this phase (Fig. 1). The increased concentration of albite in the system creates prerequisites for more intensive crystallization of this phase during heat treatment.

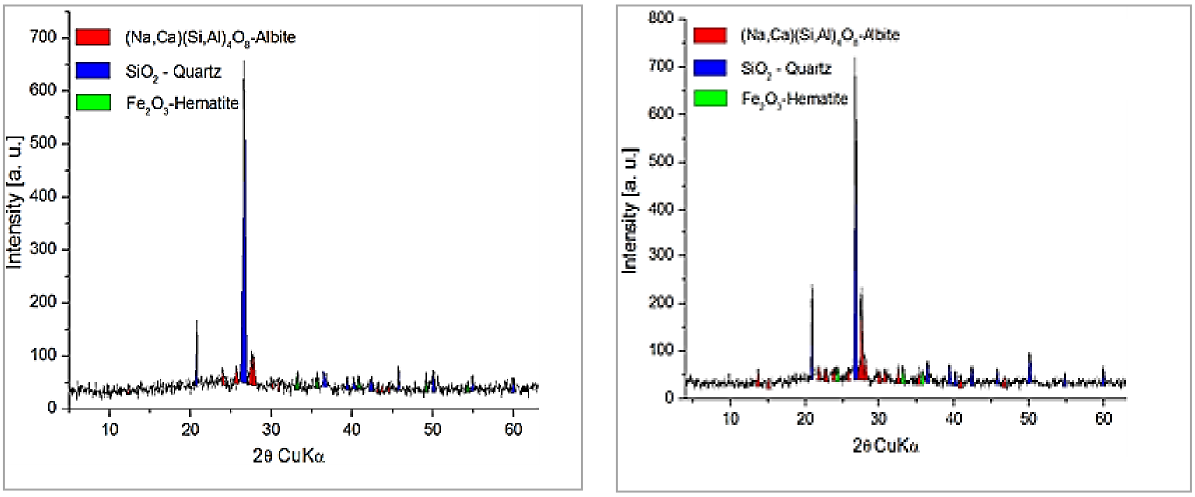

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Fig. 5 Diffractograms of sample compositions Br 2 (a) and Br 4 (b) at a sintering temperature of 1050°

In parallel, a relative decrease in the intensity of quartz reflexes is observed in Br 4, which suggests possible solid-phase interactions leading to a partial transition of quartz into an amorphous glassy phase or to the formation of intermediate aluminosilicate compounds. These results demonstrate that the inclusion of TPP ash does not fundamentally change the crystal phase structure of the resulting ceramic materials, but leads to quantitative changes in the ratio of crystalline phases, which may have an impact on their performance characteristics.

Figure 6 presents the results obtained for the frost resistance of the ceramic samples from the four investigated compositions fired at 1050 °C. The measured number of freezing–thawing cycles sustained before the occurrence of damage are as follows: Br 1 – 25 cycles, Br 2 – 22 cycles, Br 3 – 27 cycles, and Br 4 – 34 cycles**.**

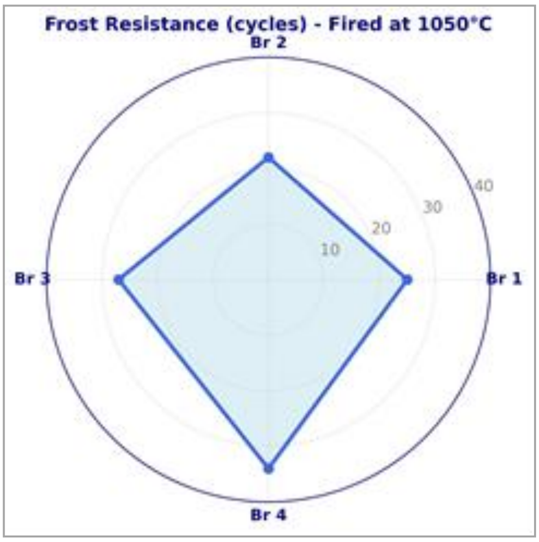

Fig. 6 Frost resistance of bricks at a sintering temperature of 1050°C

According to the requirements of the BDS EN ISO 10545-12 standard for frost resistance (a minimum of 15 freezing–thawing cycles without mass loss exceeding the specified limit), all tested samples from the four compositions meet the regulatory criteria. The obtained results demonstrate that the incorporation of ash from the Sliven TPP within the studied concentration ranges does not negatively affect the frost resistance of the materials. All measured values exceed the minimum requirement of 15 cycles, confirming the suitability of the produced ceramics for application in outdoor environments exposed to freezing conditions. This finding is particularly significant, as frost resistance represents a key indicator of the durability and long-term performance of building materials under climatic conditions characterized by winter frosts and pronounced temperature fluctuations.

CONCLUSION

The present study demonstrates the successful introduction of ash from the „Sliven“ Thermal Power Plant as a partial substitute for traditional quartz sand in the production of building ceramic products. The experimental results confirmed that for all studied compositions and firing regimes at 1050°C, characteristics are achieved that fully comply with the requirements of BDS EN ISO 10545 in terms of water absorption, frost resistance, and mechanical strength. It was found that increasing the ash content leads to significant structural changes, including an increase in apparent porosity and water absorption, a decrease in density and mechanical characteristics, as well as modifications in the crystal phase structure with an increase in the albite content. Despite these changes, all studied compositions have operational properties within the framework of regulatory requirements.

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