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On the issue of mechanical activation of burnt moulding waste

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Abstract: This article is devoted to the study of the processes of mechanical activation of burnt moulding waste (BMW) with the aim of using it as a highly active mineral additive in building materials. In the course of the work, the kinetics of BMW grinding and its dependence on technological parameters were studied. Experiments have shown that mechanical activation leads to a significant increase in the specific surface area of BSF and its amorphisation, which increases the reactivity of the material. The data obtained confirm that BSF, after mechanical activation, can serve as an effective component for improving the properties of cement composites.
Keywords: mechanical activation, burnt moulding waste, grinding kinetics, amorphisation, specific surface area, building materials

1. Introduction

Mechanical activation is a fundamental and highly versatile technological method in modern industry, designed to transform a wide range of raw materials into high-performance technical products. This process is not a mere comminution or size reduction; it represents a deliberate and profound modification of the internal structure of solid materials through intense and controlled mechanical energy input. This targeted processing imbues the material with entirely new, often unique, physical, chemical, and mechanical properties, making it suitable for a diverse array of applications. Among the various types of comminution equipment used for mechanical activation, drum ball mills are particularly effective and widely recognized for their efficiency and versatility [1-8]. During mechanical activation, the processed material undergoes significant structural and morphological transformations. The intense mechanical impact leads to a substantial accumulation of crystal lattice defects, such as dislocations and vacancies, resulting in a pronounced increase in the material's internal energy. Furthermore, the surface relief of the particles becomes increasingly rough, which dramatically enhances their reactivity. It is also noteworthy that high-energy mechanical impact can initiate various phase transformations, including the transition from a crystalline state to an amorphous one. This process, known as amorphization, ultimately results in the formation of highly disordered structures. The resulting fine-grained particles, due to these complex structural and morphological changes, exhibit significantly higher chemical activity and reactivity, which is of paramount importance for subsequent technological processes and applications. This section presents a detailed account of the experimental studies focused on the process of mechanical activation of burnt waste forms (BWF). The research aims to evaluate the effectiveness of this method in converting BWF into a valuable, highly reactive material with enhanced properties for potential use in the construction industry. The findings contribute to the understanding of the mechanisms governing mechanical activation and its practical application for waste valorization.

2. Research methodology

These studies focused on analysing the main indicators of the dispersion state of the products obtained, namely the relative particle surface area, average diameter and aggregation process. These properties were determined for materials processed in the impact-friction mode of a ball mill, which allows the effectiveness of mechanical activation and the degree of grinding to be assessed. A special laboratory ball mill ШЛМ-100 was used to conduct laboratory experiments on the grinding of BWF. This device was chosen because it provides an impact-wear grinding mode, which is optimal for achieving a high degree of material activation. The working volume of this mill chamber is 100 litres, which allows a sufficient amount of material to be processed for research. Filling the mill with grinding media is an important indicator: 40 litres of the total volume is filled with hardened steel balls, which provide the necessary impact and wear action. The amount of material loaded into the mill was strictly defined and amounted to 25% of the total volume of the working chamber. This ensures optimal grinding conditions and prevents the material from overheating.

The degree of grinding is the main indicator for a comprehensive characterisation of the dispersed state of powdered materials obtained in the process of mechanical activation. Its quantitative assessment was carried out by determining the specific surface area using a high-precision ПСХ-11А device. This method allows the degree of particle distribution to be reliably determined. In addition, to control and reduce the effect of particle aggregation (clumping), which is extremely important for obtaining a homogeneous and reactive product, a standardised sieve analysis method was used with sieve No. 008. This approach allows for the verification of aggregation, which can reduce the efficiency of subsequent technological processes.

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3. Results and Discussion

An exhaustive analysis of the experimental data obtained from studying the grinding of burnt waste forms (BWF) has provided a comprehensive understanding of the kinetics and mechanisms of the process. The results, specifically the dependence of the degree of grinding and productivity on key parameters, are clearly presented as graphical relationships in Figures 1-3.

In materials science and industrial practice, it is widely recognized that the grinding process, particularly during mechanical activation, is nonlinear and can be conceptually divided into several distinct and sequential stages [9-13].

The first stage is characterized by primary dispersion and the initial fracture of large structures. During this nascent phase, the material undergoes an intense and rapid breakdown, exposing both macroscopic and microscopic pores. The dominant mechanical actions, such as impact and attrition, effectively overcome the strong macroscopic cohesive forces, leading to the formation of primary fragments of various sizes. It is particularly noteworthy that in this initial stage, the relative surface area of the material increases almost in direct proportion to the electrical energy consumed. This linear relationship highlights the high efficiency of energy expenditure, as the majority of the applied mechanical energy is productively converted into the creation of new surface area.

The second stage marks a transition to microstructural comminution and defect accumulation. As the process continues, the material reaches a degree of fineness where it no longer fractures into conventional, easily separable particles. Instead, the focus of the grinding shifts to the internal structure, targeting individual crystals and grains. This phase is significantly more energy-intensive, as the resistance to grinding increases dramatically. The number of readily breakable surfaces diminishes, and the energy is now required to overcome stronger bonds within the crystal lattice and to create new defects, such as dislocations and vacancies. The work required to break these internal bonds is highly dependent on the material's microstructure and its phase composition. While the rate of increase in relative surface area slows down during this stage, a linear relationship between energy consumption and surface area growth is still maintained, albeit with a reduced proportionality coefficient [14-17].

The third and final stage is defined by aggregation and the attainment of the grinding limit. At this advanced stage of intense mechanical action, a critical point of dispersion is reached. A distinguishing feature of this phase is the phenomenon of re-aggregation, where the previously separated, highly dispersed particles begin to cluster together. Due to their extremely high surface energy and enhanced reactivity, these fine particles are highly susceptible to forming larger agglomerates through van der Waals forces and electrostatic attraction. This aggregation process effectively counteracts the ongoing comminution, reducing the efficiency of further grinding. This can even lead to a paradoxical outcome: a stabilization or even a slight decrease in the relative surface area, despite the continuous input of energy. The third stage, therefore, serves as a crucial indicator that a technological limit to grinding has been reached under the current conditions. To achieve further dispersion, it becomes necessary to modify the process parameters or to introduce additional methods aimed at preventing this undesirable aggregation.

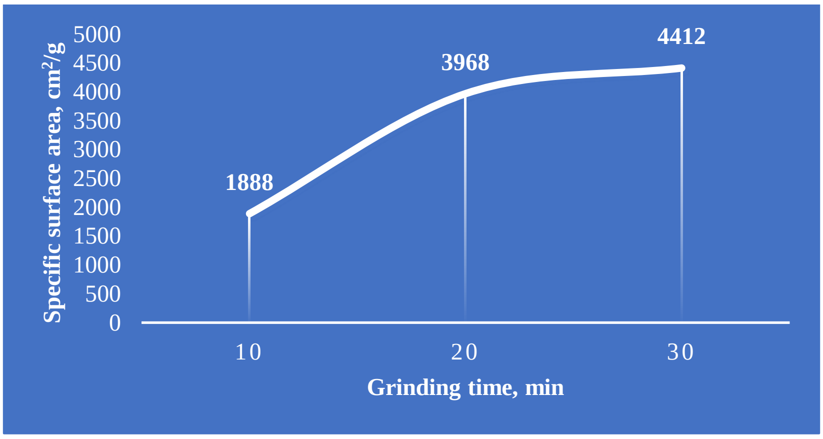

Figure 1. Effect of grinding duration on the relative surface area of BWF

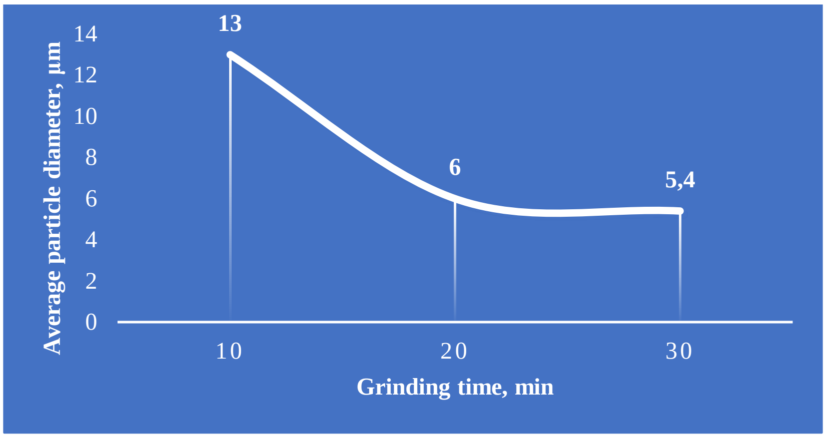

Figure 2. The effect of grinding duration on the average diameter of BWF particles

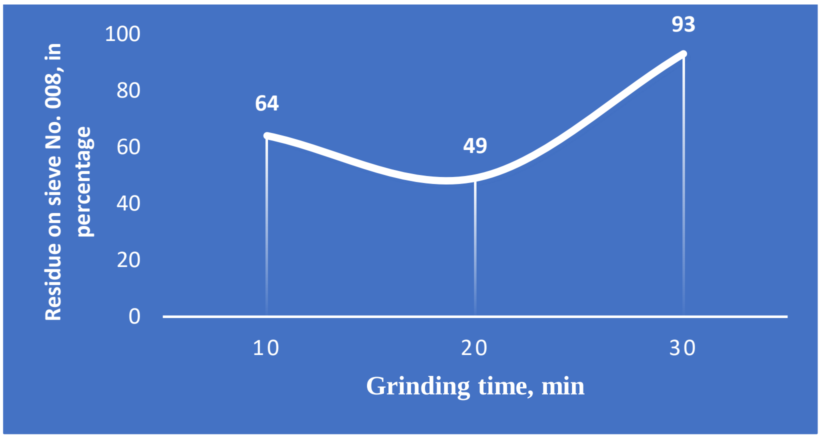

Figure 3. Effect of grinding duration on the aggregation of BWF particles

Experimental studies conducted to analyze the effects of mechanical activation on Burnt Waste Forms (BWF) demonstrated a profound change in the material's relative surface area. It was established that with a grinding duration of 30 minutes, the relative surface area of the BWF reached a peak value of 4412 cm²/g. This significant increase is a direct indicator of enhanced dispersion and elevated reactivity. Simultaneously, a corresponding decrease was observed in the average particle diameter of the BWF, which was reduced from an initial 13 µm to just 5.4 µm. This reduction in particle size is a clear and quantifiable result of the intense mechanical action, confirming the effectiveness of the grinding process in achieving the desired fineness.

The fundamental principle of comminution dictates that as the size of individual particles decreases, the total surface area of the substance increases multifold, while the total volume remains constant. This rapid increase in surface area leads to the accumulation of a significant amount of surface potential energy. This stored energy acts as a powerful driving force for subsequent physicochemical processes, making the material highly reactive in applications such as composite material manufacturing or reactions at a phase boundary. However, research indicates that upon reaching a certain dispersion limit, the surface potential energy can escalate to critical levels, which frequently triggers the spontaneous aggregation of particles into larger clusters. This phenomenon, which is particularly evident in highly dispersed materials, can nullify the positive effects of mechanical activation, reducing reactivity and impairing the final product's technological properties. The formation of these conglomerates from previously separated particles can lead to a decrease in the overall relative surface area and a loss of material homogeneity.

Further analysis, specifically a sieve analysis using sieve No. 008, corroborated the observed dispersion dynamics. Initially, the residual content on the sieve for BWF decreased from 64% to 49% as the grinding duration increased. However, when grinding continued for more than 30 minutes, a sharp and dramatic increase in the residue on the sieve was observed, reaching an alarming 93%. This abrupt rise serves as a clear indication of intensive particle adhesion and the formation of large aggregates, demonstrating that continuing the grinding process beyond this point is counterproductive. Increased agglomeration not only diminishes the efficiency of the grinding process itself but also poses a potential risk to the physical and mechanical properties of the cementitious materials produced from such an activated substance.

The crushability of a material is determined by a combination of its main physical properties, including its hardness, brittleness, and specific microstructural features. To allow for a comparative assessment, data on the grindability of various materials are often normalized relative to Portland cement clinker, with its value taken as a unit [18-23]. This approach provides an objective benchmark for evaluating the energy consumption and grinding efficiency of different raw materials. Materials that are softer or more brittle than clinker will have a grindability value greater than 1, indicating they are easier to grind and require less energy. Conversely, materials with a value less than 1 are harder and demand more energy to achieve the same level of fineness. Beyond these properties, a material's grindability is also influenced by its chemical and mineralogical composition, as well as the specific grinding conditions used in the process.

Within this study, a comparative assessment of the grindability of burnt waste forms (BWF), quartz sand, and cement clinker was performed. To ensure the comparability of the results, all initial materials were first pre-ground to a standardized specific surface area of 500 cm²/g. After this initial processing, the materials were stored at a temperature of 25°C for 24 hours to stabilize them before the main experiment.

Table 1

Grindability of various raw materials

The Nomenclature of Materials	Crushability
Limestone	0,6-0,8
Blast furnace slag	1,2-1,8
Opoka	1,1-1,2
Trass	0,5-0,6
Quartz sand	0,8-0,9
Cement clinker	1,0

The grindability assessment was conducted using an SHLM-100 laboratory ball mill as shown in Fig. 4. This controlled milling process allowed for a precise evaluation of how each material responded to grinding. By starting with a uniform particle size and using the same equipment and conditions for each sample, the researchers were able to objectively compare the energy and time required to achieve a desired fineness, thereby determining the relative grindability of each material.

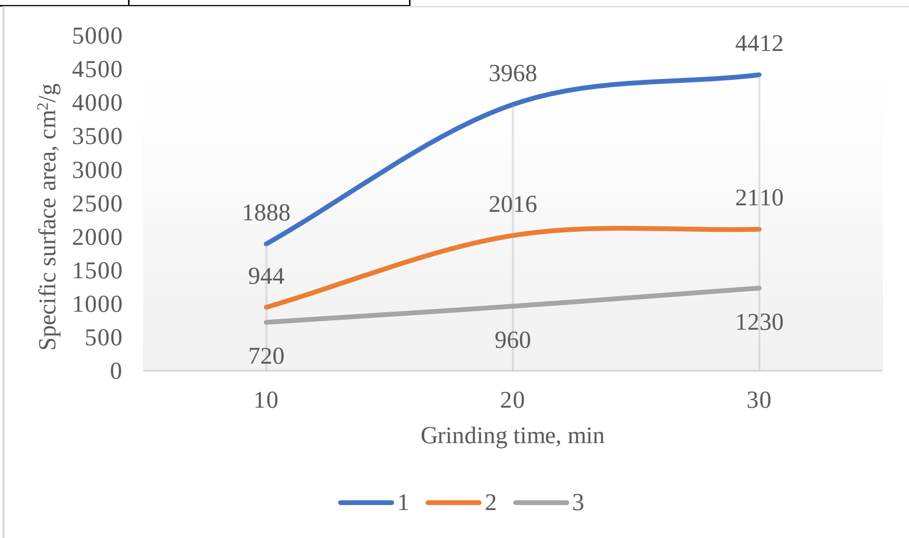

Figure 4. Grindability of BWF (1), quartz sand (2), and clinker (3) in the impact-abrasion mode of a ball mill

The conducted research has definitively established that, among the materials studied, burnt waste forms (BWF) exhibit superior grindability. As a result of mechanical activation, this material achieves a remarkable specific surface area of approximately 4400 cm²/g in just 30 minutes. This exceptional performance underscores the high efficiency of its dispersion and its pronounced susceptibility to comminution. The superior grindability of BWF is scientifically attributed to its unique structural characteristics and high-temperature origin. It is hypothesized that the primary factor is the intensive amorphization of the slags within the BWF, a process that occurs during their formation at high temperatures. This thermal treatment disrupts the ordered crystal lattice, leading to a high concentration of structural defects and a significant increase in the amorphous phase. Consequently, the bond strength between individual structural elements within this amorphous material is considerably lower compared to other additives, which predominantly have a crystalline structure or stronger intergranular bonds. This weakened internal structure allows external mechanical energy to overcome internal bonds more easily, facilitating the rapid breakdown of the material into smaller particles. This, in turn, contributes to the rapid increase in specific surface area. The inherent amorphous state and low interphase boundary strength of BWF make it a highly promising material for technological applications requiring a high degree of dispersity and reactivity.

4. Conclusion

Studies have shown that mechanical activation is an effective method for modifying burnt moulding waste (BMW), transforming it into a valuable raw material component for the construction industry. Achieving a high specific surface area and amorphous state of BFA as a result of mechanical activation significantly increases their pozzolanic activity, making them comparable to traditional mineral additives. This opens up broad prospects for the use of BFA as an active component that improves the physical, mechanical and operational properties of cementitious materials, as well as solving the problem of industrial waste disposal.

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