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Review Article

Geopolymer-Based Ceramics, Raw Materials, Mechanisms, and Applications

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ABSTRACT

Geopolymer-based ceramics are composed of aluminosilicate raw materials that can undergo polymerization reactions using alkaline activators and transform into ceramics following heat treatment in the 800 to 1200°C range. During this process, the originally formed amorphous structure is subjected to the formation of ceramic crystalline phases, allowing one to reduce the amount of porosity and increase the material density. In terms of its further application, four classes of initial materials were selected: (1) natural aluminosilicates (basalt, volcanic ash, kaolin, metakaolin, illitic clay), (2) industrial wastes (fly ash, blast furnace and steel slags, ceramic waste), (3) additives (waste glass powder, basalt fibers) and (4) alkaline activators (sodium and potassium hydroxides, silicates, sodium aluminate). On the basis of the results of the research, using the associations of oxides it was possible to predict the mechanisms of formation of geopolymer ceramics for each group. It should be noted that this approach was not used previously for this system. In this context, it was found that the predominant mode of ceramicization can be selected on the basis of SiO_2/Al_2O_3 and $(CaO+MgO)/SiO_2$ ratios. For instance, metakaolin (SiO_2/Al_2O_3 =1.9) allows one to expect the achievement of compressive strength of up to 95 MPa due to the crystallization of N-A-S-H gel. In turn, blast furnace slag containing about 40% calcium oxide will provide the formation of a liquid phase at 800-950ºC due to the C-A-S-H gel. Thus, four main mechanisms of ceramization were found: (1) the formation of N-A-S-H vs. C-A-S-H gels, (2) the viscous flow sintering, (3) the crystallization of ceramic phases (leucite, mullite, cordierite) and (4) the self-healing of the glassy phase, thereby reducing the open porosity to less than 1%.

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1. INTRODUCTION

Geopolymer-based ceramics are produced through the alkali activation of aluminosilicate raw materials, such as basalt, kaolin, or illitic clay. Geopolymer ceramics are considered to be modern composite materials and the manufacturing of the latter involves a process called heat treatment. In the aforementioned process, which is conducted at specific temperature between 800 to 1200°C, the amorphous phase of the geopolymer is turned into the ceramic phases. Sintering was identified as the reason behind a considerable reduction of porosity to the maximum level of 3.5% and an increase in density of the composites up to g/cm^3 = 2.11. Increased density of the composite means improved mechanical performance. Also it should be noted that the innovative

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processing is able to make use of the waste products for the manufacturing of ceramic materials thus leading to the environmental benefits in the process which were observed during the experiments within the project that aimed to investigate this technology (Wu et al., 2026).

1.1. THE IMPORTANCE OF USING GEOPOLYMERS IN CERAMIC PRODUCTION

Geopolymers have emerged as a viable alternative material in modern ceramics with the aim of reducing the energy consumption during the creative process. Although standard materials and equipment found in studios, including kaolin, feldspar, clay, and porcelain will be used in the manufacture of geopolymers, materials behave differently than clay because of two facts: absence of plasticity and lack of thixotropic properties (liquefaction when being vibrated). Hence, geopolymers cannot be considered as a full substitute for clay but, rather, serve as an alternative for the methods like casting and 3D printing. Curing temperature in the case of geopolymers ranges from 60 to 80 degrees and thus can enable energy savings of about 80%. From the perspective of circular economy, the utilization of waste material is a great way of saving money and solving environmental problems. While in traditional ceramics color of raw materials is altered during firing process, geopolymers maintain the original color of filler, thus being an opportunity to create colorful products without glazes and other expensive pigments (Kaarakainen, Falin, Huaman, Mäkelä, & Lautenbacher, 2023).

1.2. DEFINITION OF GEOPOLYMER

A geopolymer is defined as a polymeric material composed of aluminosilicates and has a three-dimensional structure varying between amorphous and semi-crystalline; it is produced by activating aluminum- and silica-rich precursors at a low temperature via either alkaline or acidic methods (usually below 100 degrees Celsius). As opposed to Portland cement, which relies on hydration and the formation of C-S-H gel, geopolymers obtain durability and strength through polycondensation and the establishment of stable covalent bonds between silicon and aluminum (S. G. Mohan Kumar, J. M. Kinuthia, J. Oti, & B. O. Adeleke, 2025).

The main goal of the previous research was to uncover the effects of the raw materials, technology of obtaining, or application of geopolymer ceramics. While in current investigation authors are willing to make predictions about the dependence of chemical composition of raw materials used, the dominant mechanism of forming a ceramic and properties of a resulting material, thus using knowledge gained from the earlier works. More specifically, the analysis of two oxides ratios, namely SiO_2/Al_2O_3 and $(CaO+MgO)/SiO_2$ is carried out to predict the phases obtained, uses of ceramics and behavior of material, which is the major innovation of this research.

1.3. RESEARCH METHODOLOGY

The timeframe for the articles considered spans from 2003 to 2026; however, emphasis was placed on recent years to highlight the latest advancements in the field.

1.3.1. INCLUSION CRITERIA

1. Articles that have been analyzed by the English specialists, conference presentations, and segments that have been published in well-known journals.
2. Studies aimed at the process of creating geopolymers using different raw materials that undergo a process known as ceramization.
3. Articles demonstrating the application of the various materials shown in Figure 1.
4. Studies including a focus on mechanical properties (compressive/flexural strength), physical properties (density/porosity), or thermal stability, as well as the synthesis method.

1.3.2. EXCLUSION CRITERIA

1) Non-English references.
2) Articles whose content was merely referenced elsewhere.

1.3.3. RESEARCH LIMITATIONS

The limitations of this study include the following: 1) Since the experimental conditions of the studies were highly diverse, it was not possible to perform comprehensive statistical analysis. 2) The use of only English-language references created language limitations. 3) In some cases, such as the use of specific types of steel slag or municipal solid waste ash, there was limited research. Therefore, an attempt was made to classify the materials in a way that could provide researchers with an overview without limiting the materials to those presented.

1.4. DEFINITION OF GEOPOLYMER-BASED CERAMICS

In this article, the term "geopolymer-based ceramics" refers to materials made from aluminosilicate geopolymers that are transformed into a ceramic body upon heating above 800°C. The process of transformation includes analyzing the formation of crystalline phases, densification, and the growth of sintering necks. Ceramic formation is defined as the thermal transformation of a gel into ceramic and it is assumed to occur when at least two of the following

phenomena occur simultaneously: formation of the crystalline phase, disappearance of the gel, vitrification, densification, controlled shrinkage, sintering neck formation, or enhancement of mechanical qualities at high temperatures (Bell, Driemeyer, & Kriven, 2009; He, Jia, & Wang, 2013; Nur Bahijah Mustapa et al., 2023).

2. TYPES OF MATERIALS USED IN THE PRODUCTION OF GEOPOLYMER_BASED CERAMICS

Four categories of materials are used to produce geopolymer-based ceramic composites; their classification is presented in Figure 1.

Figure 1. Classification of raw materials suitable for the production of geopolymer-based ceramics.

Subsequently, each of the mentioned raw materials and their production processes will be described, respectively. A graphical representation of the main components of geopolymer material is provided in Figure 2. According to the graphics, the main constituent of geopolymer is materials rich in aluminosilicates. Different types of these groups of materials are shown in Figure 2. Additionally, besides water and alkaline solutions, different kinds of fertilizers should be included as well.

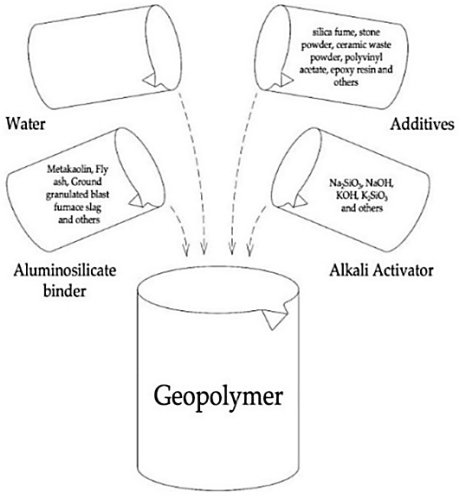

Figure 2. Main components of the geopolymer composition (Shcherban' et al., 2023).

2.1. USE OF ALUMINOSILICATES

Aluminosilicates form the key materials that are used in this geo-polymer product that is formed using the ceramic conversion process. These materials may be regarded as comprising of silica and alumina and which are important to give rise to geopolymer. Initially, these materials are amorphous but after the dissolution in alkaline solution, they will polymerize and crystallize into solid state (Romisuhani, Bakri, & Ain, 2014).

There are various types of aluminosilicate raw materials suitable for producing geopolymers via the ceramic process; these are illustrated in Figure 1. Research related to each type will be discussed individually below.

2.1.1. BASALT

Basalt is a silica-alumina-bearing volcanic rock that is abundant in the Earth's crust. It is used as a partial replacement for metakaolin (MK) in the synthesis of geopolymers. Basalt alone exhibits low geopolymeric reactivity; consequently, it cannot harden through the use of alkaline activators alone. Therefore, a certain amount of metakaolin, a reactive pozzolanic material, is added to facilitate the geopolymerization process. The optimal proportions of the added materials are determined for this purpose. By varying the raw materials, the properties of the resulting material, including maximum compressive

and flexural strengths, are investigated (Figure 3) (Mrozek, Mrozek, & Krzywoń, 2025).

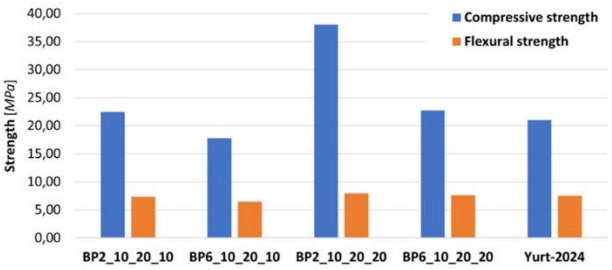

Figure 3. Compressive and flexural strength plots for geopolymers fabricated using basalt powder at 10% and 20% proportions, cured at 70°C (Mrozek et al., 2025).

It has been established that replacing 80% of the metakaolin with basalt powder leads to an 80% decrease in manufacturing costs while elevating the density of the produced sample. The heat treatment of such geopolymers turns the product into ceramics (Mrozek et al., 2025).

The other usage of basalt is as a reinforcement in geopolymers (Ahmadi, Tabarsa, & Bilondi, 2026; Welter, Schmücker, & Mackenzie, 2015). The basalt fibers are described as the means of energy dissipation, micro-crack inhibition and flexural and tensile toughness increase (Chakkor, 2025). The basalt fibers allow for compressive and flexural strength increase and mass loss decrease in an acid environment, while being responsible for bridging cracks and increasing matrix density to avoid surface degradation in hostile environment (Ahmadi et al., 2026).

Geopolymers may be made from basalt in combination with other materials, for instance waste glass, which is utilized as a source of silica and a fluxing agent as a compensatory mechanism to improve the compressive strength of basalt-based geopolymers. The findings show that the increase in temperature to 750? should yield the compressive strength of 9.77 MPa, however, when increased to 1000?, the strength drops considerably due to the formation of micro-cracks. It was also determined that at optimum holding time of 30 min at 750?, the maximum strength produced and maximum self-amorphous phase produced. The addition of 10 wt% of glass powder to the samples treated at the temperature of 1000? for 30 minutes increased the compressive strength significantly to 16.6 MPa thanks to the function of silica present in glass powder filling the micro-cracks, thus porosity is reduced, density increases, polymerization increases. Furthermore, glass powder promotes sintering and microstructural densification through lowering the softening point of 908? to 890? and ensuring formation of liquid phase at high temperatures like pyrocerams do. Thus, this ceramized geopolymer with great strengths, low porosity and great thermal stability up to 1000? can replace commercial materials in construction and ecological applications (Wu et al., 2026).

2.1.2. VOLCANIC ASH

Volcanic ash is chemically similar to basalt and exhibits high reactivity, yet it is found only in limited regions. The pozzolanic classification of volcanic ash can be determined through chemical composition analysis as well as quantifying the various oxides. X-ray diffraction (XRD) can be used to ascertain the amorphous or crystalline nature of the ash as that helps determine its ability for use with geopolymer. If the ash is found unsuitable, then other conventional materials could be added like lime, metakaolin, blast-furnace slag, or fly ash. If the SiO_2/Al_2O_3 ratio is less than 3.9, then the volcanic ash is considered to be fit for use in geopolymer product formulations. If volcanic ash is not suitable due to certain properties like compressibility or angle of internal friction, then it can be used for making cement, mortar, asphalt, ceramics, and bricks or used for problematic soil stabilization (Melentijević, López-Andrés, & Estaire, 2024).

In some cases, for dealing with problems of reactivity, activating agents may be used, including alkaline solutions or waste glass powder, which makes this method more environmentally friendly than other traditional methods. This is because the method involves diluting alkaline solutions and using waste materials, and the resulting products have performance parameters comparable to those of lightweight construction materials like gypsum and light concrete in terms of compressive and flexural strengths (Bernardo et al., 2022). These materials can be described with a dual lifespan, meaning the created geopolymers become construction materials just as well as can be converted into porous glass ceramic foam through heat treatment at the temperature of 950 °C when they are no longer usable. In addition, it is known that low-temperature foaming substances can be used for the creation of ultra-light foams before heat treatment, and after firing, they can be turned into high-performance glass ceramic foam giving good property performance (Bernardo et al., 2022). Sodium hydroxide or potassium hydroxide solutions, along with low-modulus silicates, have also been employed to enhance reactivity. It has been observed that the use of NaOH results in faster reaction rates and higher compressive strength, whereas samples containing KOH exhibit superior thermal stability, showing less than 3% shrinkage after heating to 1000°C. This facilitates the use of these types of geopolymers in construction applications and the manufacture of refractories (Lemougna, Chinje Melo, Delplancke, & Rahier, 2013).

Ceramics construction geopolymers made by means of volcanic ash obtained from Etna (Italy) and Fombat (Cameroon) regions. In the manufacturing process, the ash was crushed, mixed with a dense alkali solution (50

percent sodium hydroxide and 50 percent sodium silicate), and cured at the temperature of 25–400 degrees Celsius. Experimental results indicated that increasing curing temperature to 400 degrees Celsius leads to the substantial increase of strength of the samples as well as reduction of porosity. According to the findings of research, the heat treatment was used as an activation method. The increase of curing temperature to 400 degrees Celsius resulted in a transformation of the initial geopolymers into semi-crystalline and micro-crystalline substances. During this ceramization process, new crystalline phases were formed and the initial dust particles remained undissolved in the substance of the geopolymers that contributed to the increase of strength properties. Although the rate of the volcanic ash is lower than that of metakaolin, the heat treatment in the range of 200–400°C offsets this disadvantage thereby obtaining materials with properties similar to those of ordinary bricks and applicable in construction works and low-temperature fire-resistant conditions (up to 700–800 degrees Celsius) (Kamseu, Leonelli, Perera, Melo, & Lemougna, 2009).

Fortunately, ceramized geopolymers derived from volcanic ash have demonstrated favorable thermal stability and exceptional radiation-shielding capabilities. Consequently, they represent a suitable option for construction applications as well as environments requiring radiation protection (such as nuclear and medical facilities) (Plando, Supnad, & Maquiling, 2025).

2.1.3. KAOLIN AND METAKAOLON

Kaolin and metakaolin materials have been used for making geopolymers historically. Kaolin is an alumino-silicate mineral, and is converted to metakaolin by heating to about 800°c for two hours. Metakaolin is amorphous in nature and much more reactive than kaolin material. Heating causes removal of moisture content and other organic material making the material reactive. Following this stage, metakaolin is mixed with an alkaline activator such as the mix of NaOH and Na_2SiO_3 in correct proportions to make geopolymer paste. The mixtures are compacted and heated at 1100°c for one hour where the processes of sintering, crystallization and densification take place (Al-Buriahi, Kırkbınar, Kucuk, Olarinoye, & Mohammedsaleh Katubi, 2026).

Hollow alumina microspheres have been used as a filling material in potassium geopolymer products for thermal insulation purposes. This geopolymer can perform its functions at high temperatures of 1200 °C (Z. Li, Geng, Jiang, Chen, & Li, 2025). Macroporous ceramics with definite microstructure have been acquired by changing the calcinations conditions. These materials demonstrate appropriate physical properties along with their overall porosity and can be used in filtration, catalysis, and sensing applications (H. Wang, Li, Wang, & Yan, 2015).

The good thing is that the use of a high percentage of pottery waste (up to 80 wt%) in kaolin can be implemented without wasting any thermal and mechanical features of the final material. Through the changing of the alkaline liquid ratio parameters and assuring compatibility of the materials' microstructure one can keep the compressive strength of about 40 MPa after firing at 1000 °C.

The presence of the ceramic waste reduces cracking and shrinkage taking place; at the same time, ceramized geopolymers produced on the basis of metakaolin only at the same firing temperature lose a huge part of their strength (from 50 to 6.5 MPa) and incur a serious linear shrinkage because of the appearance of both newly created liquid and crystalline phases (such as albite and mullite). Therefore, it is possible to use ceramic waste with the needed particle size distribution pattern and crystalline composition (quartz, hematite, and microcline) in order to provide the geopolymers with thermal stability due to the dimensional and phase stabilization processes (Bezerra, Soares, & Morelli, 2023).

In order to improve the polymerization process and eliminate open pores, very minute quantities (about 2.5% by weight) of high-purity nanocrystalline silica are used. In the course of the slow burning process at elevated temperatures (up to 1000°C), new crystalline phases appear, and the density of the material increases. As a result, a significant improvement in its strength properties can be achieved (up to 95 MPa) (Zawrah, Abo Sawan, Khattab, & Abdel-Shafi, 2020). Findings from this study and the previous one indicate that the specific optimal dosage must be determined for each additive; in some cases, the desired outcome is achieved with small quantities, as seen in this study, while in others, larger amounts are required, as demonstrated in the earlier paper.

Various factors influence the properties of the resulting product; one such parameter is the heating rate. It has been established that the heating rate plays a key role independent of the material composition. Slow heating rates (less than 5°C/min) provide sufficient time for atomic diffusion at grain boundaries and surfaces, leading to reduced porosity, controlled grain growth, and increased density. In contrast, high heating rates result in abnormal grain growth and a deterioration of properties (Nur B. Mustapa et al., 2023).

Studies indicate that the optimal values required to achieve the best properties vary. For instance, a nanosilica content of 2.5% has been cited for improving compressive strength (Zawrah et al., 2020), whereas 80 wt% waste content has been identified for enhancing thermal stability (Bezerra et al., 2023). This implies that the optimal filler content depends heavily on particle size, chemical composition, and the specific chemistry of the geopolymer matrix. Even processing parameters,

such as the heating rate, influence the optimal amount (Nur B. Mustapa et al., 2023).

2.1.4. ILLITIC CLAY

Illitic clay is an example of natural aluminosilicate clay which, after calcination, can become the material of geopolymers. The main difficulty connected to this clay is the low reactivity due to its ordered crystal structure, which is why activation is needed. To achieve activation, some methods like mechanical treatment, namely high-speed planetary milling, are used together with calcination to convert clay into a non-crystalline state. This has allowed geopolymers to get good mechanical properties such as compressive strength of 64 MPa after 28 days of curing. As illitic clay is widely distributed all over the world, this process of producing geopolymers from such an affordable material can be regarded as very important for the green construction industry (Zerzouri, Hamzaoui, Ziyani, Yahia, & Alehyen, 2025). Illitic clay causes a shift in the primary crystalline phase from akermanite to ferrian diopside and leads to a linear increase in the amorphous phase content. An optimal content of 30% illitic clay was determined, yielding a density of 2.82 g/cm³ and a flexural strength of 62 MPa, while also resulting in minimal pyroplastic deformation (You et al., 2023).

In certain cases, thermal activation at the temperature of 750°C was used instead of mechanochemical activation. In order to overcome the low reactivity of illitic clay, the activation of clay with metakaolin was utilized. As a result, a slight improvement of thermal conductivity was achieved (0.25 W/m·K) and the product was considered to be appropriate for construction uses that require sufficient thermal behavior (Eliche-Quesada, Bonet-Martínez, Pérez-Villarejo, Castro, & Sánchez-Soto, 2021).

Various types of clay, such as halloysite, palygorskite, and sepiolite, can serve as sustainable alternatives to Portland cement and supplementary cementitious materials; however, their optimal calcination temperatures differ due to variations in crystal structure. This temperature is significant because it brings the clay to its maximum pozzolanic reactivity (Islam, Kafle, & Al-Ameri, 2025).

Alkali activation is sometimes implemented to increase the reactivity of illitic clay. The process of calcination (thermal firing) is completely exempted from this method. Potassium hydroxide at a concentration of 10 M and sodium silicate in liquid form in different solid-to-liquid proportions are used. It has been revealed that the Si/Al molar ratio in the amorphous form is the crucial characteristic for reaching the greatest flexural strength from the microstructural point of view (Vasić, Terzić, Radovanović, Radojević, & Warr, 2022).

2.2. USE OF INDUSTRIAL WASTE

2.2.1. FLY ASH

Fly ash is a byproduct, which is recognized for its amorphous nature and the possibility of being used efficiently in alkaline conditions for making geopolymers. However, sometimes it is necessary to add some additional materials as well. For example, quartz sand (mineral filler) and waste asphalt (organic-mineral filler) have been added to Class F fly ash-based geopolymers. The study showed that the inclusion of quartz sand has improved particle density and resolved the problems of getting good binding to the geopolymer matrix and hence it has led to a density increase that reached nearly 19.5%, 41.2% increase in the flexural strength, and exceptionally low abrasion and water absorption. In contrast, while the use of recycled asphalt (which is made of non-reactive materials like carbonates and organic matter) reduced compressive strength by more than 50%, it nevertheless managed to markedly lower water absorption (to below 5%) due to its hydrophobic properties. The concurrent application of both sand and asphalt in the formulation of ternary composites (such as the mix of 33% ash, 33% sand, and 33% asphalt) ensured the desired equilibrium of mechanical strength properties and durability features when exposed to wet environment (Kozub, 2025). The use of fly ash also requires an alkaline activator; sodium hydroxide (NaOH) has been employed for this purpose. Optimal ranges for the SiO_2/Na_2O and Al_2O_3/Na_2O molar ratios have been identified for producing high-quality geopolymers, as the geopolymerization reaction does not proceed correctly outside these ranges (Ryu, Lee, Koh, & Chung, 2013). Geopolymer made from fly ash is also used to manufacture bricks. Studies indicate that the energy requirement can be substantially lowered using pressure forming technology and that the conventional process of firing ceramics can be eliminated (Mastura et al., 2014). It should be noted that different types of fly ash possess distinct properties. For instance, conventional Class F fly ash from the Skawina power plant (Poland) differs from ultrafine fly ash (RUFA) from China and ash derived from municipal solid waste incineration (MSWI[1]). Consequently, the product obtained from each will also exhibit different properties (Pławecka et al., 2022).

Although ultra-fine fly ash has a similar composition to conventional fly ash, it has a high degree of activation due to its almost completely amorphous nature. In contrast, a phase analysis of municipal solid waste ash shows that the material is composed mainly of calcite (43%), chlorocalcite (35%), and anhydrite (14.4%), with almost no presence of the amorphous phases required for geopolymerization purposes. Thus, municipal solid waste ash has to undergo treatment and activation optimization (Pławecka et al., 2022).

Given that various parameters influence the production of geopolymers from fly ash, some research has focused

on this subject. For instance, one study investigated the simultaneous effects of four key parameters on geopolymer bricks, namely (1) NaOH concentration, (2) the percentage of GGBS [3] replacing fly ash, (3) curing temperature, and (4) curing time, and optimized these values to achieve maximum brick strength (Figure 4).

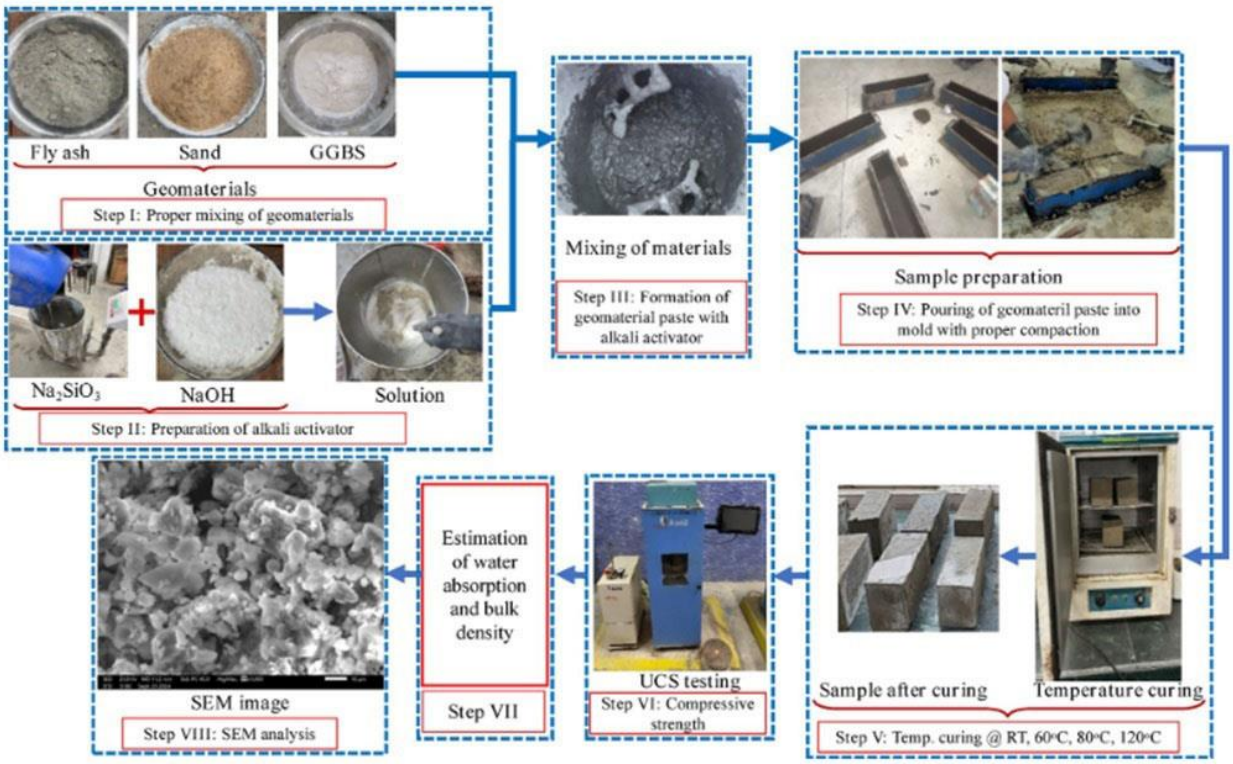

Figure 4. Flowchart and experimental methods for estimating various properties of geopolymer brick preparation (Ansari & Kumar, 2025).

It has been concluded that temperature while curing does not have a momentous impact on strength, but the effect of replacement is more significant. The explanation for this milestone can be found in the fact that the increase of GGBS increases the Ca/Al ratio from 0.037 to 0.635, hence producing calcium hydroxide gels (C-S-H and C-A-S-H) which gives rise to increased strength. Moreover, it was found out that an increase of GGBS leads to a denser structure with lower porosity and smaller voids. What is more, the water absorption of these blocks is much lower compared to ordinary clay bricks and cement-based concrete blocks (Ansari & Kumar, 2025).

A comprehensive analysis of the economic and environmental benefits of fly ash-based geopolymers has shown that for every million tons of fly ash used to replace Portland cement, savings equivalent to one million tons of limestone, 250,000 tons of coal, and 80 million energy units are achieved, while the emission of one million tons of CO_2 is prevented. Furthermore, the production cost of geopolymer concrete is estimated to be 10% to 30% lower than that of cement-based concrete. These materials also exhibit superior corrosion resistance (Sawant & A.N.Hunnabad, 2020).

A comparison among conventional Class F fly ash, ultrafine fly ash (RUFA), and municipal solid waste incineration (MSWI) ash (Pławecka et al., 2022) reveals that, despite similar bulk chemical compositions between conventional and ultrafine fly ash, RUFA produces a denser microstructure due to its finer particle size and higher amorphous content. In contrast, MSWI ash, composed primarily of crystalline calcite, chlorocalcite, and anhydrite with negligible amorphous phases, cannot undergo geopolymerization without pretreatment. This comparison demonstrates that crystallinity and particle size distribution are at least as important as bulk oxide composition in determining geopolymer reactivity.

2.2.2. BLAST FURNACE SLAG

In the process of making ceramized geopolymers, two slag types are utilized - the steel slag which has high iron oxide content and the blast furnace slag high in calcium content. Steel slag and blast furnace slag act not only as fillers but also as reactants. By controlling the calcium-silica ratio, these slags determine the process of hydration and gel formation. The role of steel slag is to provide iron and calcium, while the blast furnace slag gives silica and alumina upon reaction (Bai, Wang, & Fang, 2023).

Porosity and density were mentioned earlier amongst the measures for quality. The capillary absorption coefficient is another measure to determine micro-structural solidity and durability. For example, when a sample with 20 percent steel slag was examined, its capillary absorption coefficient was found to be the least, which means that there were less interconnected capillary pores, which enabled high resistance to liquids from penetrating the sample and also that the use of steel slag improves workability and density as well as reducing the occurrence of cracks (Bai et al., 2023).

Composites based on blast furnace slag can also be made more sustainable through the incorporation of coffee silverskin fibers. It has been shown that using organic lignocellulosic fibers, which include coffee silverskin fiber, as reinforcement for geopolymers produced using slag is successful. These fibers have low in density and have a lignocellulosic structure, enabling them to lower the weight of the composite while improving its toughness and energy absorption. Modification of these fibers' surfaces with sodium hydroxide can eliminate impurities, enhance surface roughness, and improve wettability, leading to noticeable increases in the compressive strength of the composite. Furthermore, surprisingly, the thermal stability of the produced composite improved. This result can be explained by the formation of protective char layer and better interfacial interaction between the fibers and the matrix. However, significant reduction of the surface hardness can be observed because of the enhanced concentration of Na_2O in the matrix and appearance of the softer surface layer. The last result is the decreased porosity and improved interface adhesion achieved due to the alkaline modification of the fibers (Vieira Ramos et al., 2026).

Sometimes, a combination of strategies is employed to achieve superior results. For instance, in a study conducted by Wang et al. (Y. Wang et al., 2024), To reach the desired strength of results of 45 MPa, we performed the experiment based on the mixture of the two industrial waste materials (40% pottery waste and 60% blast furnace slag). In parallel, a bilayer nanocomposite coating (SiO_2-TiO_2) has been applied to give the geopolymer surface the hydrophobic and photocatalytic effect (destruction of methyl orange, oleic acid, and waste from bauxite). In the end, the parameters such as the SiO_2/Na_2O ratio and the amount of ceramics have been analyzed and their influence on the compressive strength and self-cleaning ability of geopolymer has been studied.

A combination of ferronickel slag and blast furnace slag has also been utilized as a raw material for geopolymer production. Durability in aggressive environments (chloride and sulfate) was a key factor evaluated for the material developed in this study. The research demonstrated that adding an optimal amount of ferronickel slag enables the achievement of a 28-day compressive strength of 56–64 MPa. Furthermore, the optimal mixture yields the best performance regarding chloride penetration resistance and excellent dimensional stability in sulfate environments. The results indicated that common admixtures, such as lignosulfonate and polycarboxylate, do not affect the setting time; only increasing the water-to-solid ratio and reducing the blast furnace slag content can extend the setting time to meet standard requirements (exceeding 45 minutes) (Nguyen & Castel, 2023).

As the steel slag content increases, the resulting changes in properties stem from both chemical and physical mechanisms. Physically, C-A-S-H and N-A-S-H gels coat the C-S-H gel and fill micro-cracks, while fine steel slag particles act as reinforcing micro-fillers. Chemically, two phenomena occur: the micro-aggregation of inert components and competitive activation driven by hydrated $Ca(OH)_2$, both of which have a dual nature (potentially positive or negative); however, it has been reported that physical synergy outweighs chemical synergy and serves as the primary driver for performance enhancement in binary geopolymer systems. Additionally, electrochemical impedance spectroscopy has been introduced as a relatively novel method for monitoring microstructure and synergistic mechanisms (S. Wang et al., 2025).

Various properties, specifically compressive strength and resistance to sulfuric acid attack, were investigated using the Central Composite Design (CCD) method. Waste pottery powder was added to a slag-based geopolymer, and an activator was incorporated into the initial mixture; the activator-to-precursor ratio was 0.725. The results demonstrated that the addition of waste The sample without the additive experienced a higher decrease in terms of compressive strength compared to the sample with pottery powder because the latter reduced the acid-induced strength loss by 35.5% and formed a stable aluminosilicate mineral. Secondly, it has been reported that ceramic waste powder not only increases the workability and density of the mixture but also improves its durability. This is achieved when the fluidity of the paste is enhanced (from 135 to 173.5 mm), and the rate of water absorption is lowered to 6.09%. Finally, it has been proved that a mix proportion with an optimized ratio based on advanced statistical analysis can yield a geopolymer with improved durability and high strength that is capable of withstanding the erosive effects of acids and, therefore, suitable for wastewater treatment plants and industrial floors. (Berkouche, Belkadi, Benaddache, Tayebi, & Aggoun, 2025).

Two abundant industrial wastes, fly ash and blast furnace slag (60–90 wt% fly ash and 10–40 wt% blast furnace slag), have been used to produce self-glazed geopolymer tiles that require no secondary glazing process. The firing temperature turned out to be considerably low. A more intensive and denser geopolymerization reaction occurs at the surface due to

the accumulation of alkalis and an excess of material at the bottom of the mold during vibro-casting and high-humidity curing (90-98% RH), resulting in the formation of a smooth, defect-free glassy layer with hardness higher than 4 on the Mohs scale. By using various alkaline activators (such as sodium or potassium hydroxide and sodium silicate) and superplasticizers, a product with a compressive strength of 20-50 MPa, water absorption of 10-25%, and a density of 1.5-2.5 g/cm³ was obtained. Beyond eliminating the costly and energy-intensive glazing stage, which, for traditional tiles, requires temperatures of 850–1250°C and expensive raw materials like frit and zircon, this product generates no CO_2 emissions and aligns perfectly with the circular economy and green construction principles (Kumar, Kumar, Kumar, & Mehrotra, 2007).

Sustainability of composites based on blast furnace slag could be increased by using fibers from coffee silverskin as reinforcement. It has been proven the replacement of organic lignocellulosic fibers (including coffee silverskin fibers) for reinforcement of geopolymer composites made of slag is effective. Low density and lignocellulosic structure of these fibers allow to decrease composite weight and to increase its toughness and the ability to absorb shock and impact loads. Surface treatment of the fibers with sodium hydroxide removes impurities, increases surface roughness and improves matrix wettability, and consequently provides obvious improvements in the composite compressive strength. In addition, surprisingly, the produced composite has improved thermal stability. This can be explained by the formation of protective char layer and better interface interaction between the fibers and the matrix. However, there is a significant reduction in the surface hardness due to improved concentration of Na_2O in the matrix and formation of the softer surface layer. The third result of the alkaline treatment of the fibers is improved interface adhesion due to decreased porosity (Vieira Ramos et al., 2026).

Often, the results are better when we use a combination of the aforementioned strategies. For example, in an investigation carried out by Wang et al. (Y. Wang et al., 2024), In order to achieve the required compressive strength of the specimen of 45 MPa, we conducted the experiment based on the mixture of the two industrial waste materials (40% pottery waste and 60% blast furnace slag). At the same time, a bilayer nanocomposite coating (SiO_2-TiO_2) has been applied to the geopolymer surface in order to obtain the hydrophobic and photocatalytic effect (degradation of methyl orange, oleic acid, and bauxite waste). Finally, based on the results, we examined the parameters such as the SiO_2/Na_2O ratio and the amount of ceramics and their influence on the compressive strength and self-cleaning ability of geopolymer was assessed.

A mixture of ferronickel slag and blast furnace slag has been employed as the raw material for geopolymer production. One of the main characteristics of the developed material was investigated for its durability in aggressive environments (chloride and sulfate). The research showed that addition of suitable amounts of ferronickel slag allowed the mixture to reach a 28 d compressive strength of 56-64 MPa, and this mixture performed optimally for resistance to chloride penetration and showed excellent dimensional stability in sulfate environments. In addition, it was found that most common admixtures (lignosulfonate and polycarboxylate) do not affect setting time; it was rather the need to increase the water / solid ratio and reduce the blast furnace slag that made it possible to increase the setting time to a standard level (more than 45 min) (Nguyen & Castel, 2023).

With the increase of steel slag content, there has been significant changes in properties due to both unique chemical and physical mechanisms. On the one hand, physically, C-A-S-H and N-A-S-H gels encapsulate the C-S-H gel and fill the micro-cracks, while fine steel slag particles affect as a micro-filler gains reinforcement. On the other hand, chemically, micro-aggregation from the inert components and competitive activation via hydrated $Ca(OH)_2$ both occur, which have dual properties (may possibly be positive/negative); yet, it has been reported that physical synergy dominates over chemical synergy and its simultaneously an isolating propagator for strengthening binary geopolymer systems. Furthermore, electrochemical impedance spectroscopy as a relatively novel technique to evaluate microstructure and synergistic mechanisms was presented (S. Wang et al., 2025).

Various properties, specifically compressive strength and resistance to sulfuric acid attack, were investigated using the Central Composite Design (CCD) method. Waste pottery powder was added to a slag-based geopolymer, and an activator was incorporated into the initial mixture; the activator-to-precursor ratio was 0.725. The results demonstrated that the addition of waste The sample without the additive experienced a higher decrease in terms of compressive strength compared to the sample with pottery powder because the latter reduced the acid-induced strength loss by 35.5% and formed a stable aluminosilicate mineral. Secondly, it has been reported that ceramic waste powder not only increases the workability and density of the mixture but also improves its durability. This is achieved when the fluidity of the paste is enhanced (from 135 to 173.5 mm), and the rate of water absorption is lowered to 6.09%. Finally, it has been proved that a mix proportion with an optimized ratio based on advanced statistical analysis can yield a geopolymer with improved durability and high strength that is capable of withstanding the erosive effects of acids and, therefore, suitable for wastewater treatment plants and industrial floors (Berkouche et al., 2025).

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Slag type (steel or blast furnace), mixing ratio, alkali activator modulus, and curing conditions exert varying, and sometimes conflicting, effects on compressive strength, flexural strength, and durability; for instance, blast furnace slag, due to its high CaO content, leads to the formation of C-(N)-A-S-H gel, resulting in rapid setting and high early strength, whereas steel slag, with its high Fe_2O_3 and free CaO content, acts as a weaker pozzolanic material but contributes to improved density and reduced shrinkage by filling pores and generating reinforcing fine particles (Ionescu, Lazarescu, & Hegyi, 2020).

A ternary mixture consisting of 60% fly ash, 30% blast furnace slag, and 10% waste ceramic powder has been used to prepare geopolymers. These self-compacting ternary geopolymers are utilized in applications exposed to moderate heat (such as the food industry, chimneys, or industrial environments with temperatures up to 150°C). Optimal mechanical and microstructural performance was achieved at 150°C with a one-hour exposure time. However, as the temperature exceeded 150°C, the properties gradually deteriorated due to micro-cracking and phase changes in the C-A-S-H and N-A-S-H gels. Interestingly, oven curing (at 80°C for 48 hours) resulted in higher compressive strength compared to ambient-temperature curing (Kaarakainen et al., 2023).

The main challenges associated with using slag in geopolymers are (Ionescu et al., 2020):

1) Fluctuations in the chemical composition of slags (depending on the source and production process);

2) The presence of inert crystalline phases that reduce reactivity;

3) Expansion issues caused by free CaO in steel slag;

Strategies have been devised to address these limitations, including:

1) Pre-oxidation, mechanical milling, and the use of stabilizing additives.

2) Establishing standardized evaluation methods and providing design guidelines for each type of slag based on its specific chemical composition.

2.2.3. USE OF CERAMIC WASTE POWDER

The high annual volume of ceramic waste (such as brick, tile, and pottery scraps) generated by the construction industry and ceramic manufacturing plants constitutes a serious environmental challenge due to the non-biodegradable nature of the material.

Benefits of Using Ceramic Waste

Utilizing this waste in the production of geopolymers, as a partial replacement for aluminosilicate raw materials (such as metakaolin or slag), offers several advantages (Shcherban' et al., 2023):

1. Reduction in the consumption of natural raw materials,
2. Reduction in landfill costs,
3. Reduction in CO_2 emissions due to the elimination of Portland cement, and
4. Improvement of certain mechanical properties, such as compressive and flexural strength, resulting from pore filling and the formation of a denser microstructure.

The main challenges include the following (Shcherban' et al., 2023):

1. Low reactivity of crystalline phases (such as quartz and mullite) in ceramic waste, necessitating intensive milling or alkaline activation;
2. Reduced efficiency upon excessive use (exceeding 20–30%), resulting from a decrease in the geopolymer gel ratio and increased porosity;
3. In addition, matching colors and textures with the restored surface, as well as adhering to various substrates (concrete, brick, ceramic), are practical challenges in restoring building facades.

In most cases, the addition of ceramic waste is accompanied by other additives to overcome the problems described above. For this purpose, for example, finely graded ceramic waste powder (more than 90% of the particles < 70 microns) has been used in combination with polyvinyl acetate (PVA[1]), an organic polymer which hydrolyses into polyvinyl alcohol in the alkaline geopolymer environment. The results show a dense structure with high compressive and flexural strength. Other results of this study are the reduction by 54% of water absorption and the increase by 9% of adhesion to concrete and ceramic substrates (Shcherban' et al., 2023).

A waste material, ceramic waste powder (CWP[2]) and iron blast furnace slag were used as a blend. The product was cured at room temperature without any heat treatment.The five key factors on the product properties, binder content, slag replacement percentage, activator-

to-binder ratio, sodium silicate-to-sodium hydroxide ratio and sodium hydroxide concentration, were studied.The mixture with 40% CWP and 60% slag had better performance, which might be due to the formation of C-A-S-H and N-A-S-H gels (Chokkalingam, El-Hassan, El-Dieb, & El-Mir, 2022).

2.3. ADDITIVES

These materials are added to the mixture to either facilitate the ceramic processing or improve the final properties. Research related to each is discussed below:

2.3.1. WASTE GLASS POWDER

Glass waste includes items such as bottles, fluorescent lamps, and window glass (Rivera, C., Vanegas-Bonilla, & Mejia, 2018). Because of its high amorphous silica and very low alumina content, glass waste cannot itself form a geopolymer network and has to be used in combination with aluminous precursors such as fly ash, metakaolin or slag. In low-calcium systems, the N-A-S-H gel predominates, whereas combinations with slag result in the formation of hybrid N-A-S-H/C-(A)-S-H gels, which significantly influence durability performance (Mohan Kumar, Kinuthia, Oti, & Adeleke, 2026).

The utilization of waste glass powder as a partial replacement of fly ash in the production of geopolymer concrete was examined. The main parameters were replacement percentage and the molar concentration of sodium hydroxide. The increase in waste glass powder and alkaline concentrations showed a negative influence on slump and setting times. On the other hand, increasing the NaOH concentration showed a positive influence on compressive, flexural, and tensile strengths. A mixture with 10% waste glass powder and 13 M NaOH was considered to be the best mix for the production of a high-quality geopolymer (Çelik et al., 2023).

Given that only about 30% of glass waste is currently being reused worldwide, using this particular type of waste in other areas is extremely important. It is possible to use glass waste for production of secondary raw materials. One should note the high content of silica in glass waste, which allows obtaining N-A-S-H gel (hydrated sodium aluminosilicate) through its interaction with an alkaline activator. Specifically, using NaOH as an alkaline activator, geopolymer tiles were obtained with 178 kg/cm^2 compressive strength and 1006 N ultimate load. This success was made possible because of the high amount of silica in the initial glass waste (Rivera et al., 2018).

Bottle glass, with a solubility of 52.92% in an alkaline environment, exhibited the highest strength (56 MPa at 7 days) among the three types of glass. Utilizing waste glass in cement and aggregates resulted in a 27% energy saving and a 37% reduction in greenhouse gas emissions (Rivera et al., 2018).

Potassium activators (potassium hydroxide and silicate) can also be used in the production of ceramic geopolymers from glass waste instead of sodium activators. It has been reported that increasing the SiO_2/Al_2O_3 ratio and the presence of calcium oxide (CaO), which is absent in the glass, increased the compressive strength by 37% to 47% at 28 days. It has also been stated that the use of potassium activators provides compressive strengths of up to 26 MPa, which are higher than the values reported for sodium activators under similar conditions. With this method and without heating, geopolymers have been produced using glass waste as a source of silica (Alvarenga, Sales, Caldas, Cetlin, & Aguilar). Replacing 10–20% of glass waste with suitable fine aggregate can improve resistance to chloride and sulfate penetration by creating a denser microstructure and reducing porosity, but replacing more than 30% without providing sufficient aluminum leads to incomplete gelation and increased connected porosity (Mohan Kumar et al., 2026). Sometimes, porous and foamed geopolymers are also formed from brown glass waste (drinking bottles) using two types of alkaline activators, sodium hydroxide and sodium aluminate solution. The mass reduction and foaming due to the release of gases from dehydration and phase changes in sodium silicates have been reported. The resulting foams are highly desirable for thermal and acoustic insulation applications (AL-Saadi, Abdulnabi, Ismael, Hassan, & Mejbel, 2022).

One of the types of glass that can be used in the production of geopolymer-based ceramics is low-melting ferrite glass. Ferrites, which have a completely amorphous structure, are much more reactive in alkaline media, while allowing to obtain C-A-S-H gels with a dense and honeycomb microstructures, even using low concentrations of sodium hydroxide and without the need for thermal activation (Rezzoug, Leklou, Ayed, & Maryam, 2024). Ferrites are key intermediates for the decontamination and insolubilization of toxic materials. Glass wastes containing lithium, manganese, and hexavalent chromium are also considered new raw materials for the production of valuable glass-ceramics (Almendro-Candel & Jordán Vidal, 2024). In some cases, ferrite glasses have been used in conjunction with other wastes, for example, 50% ferrite and 50% white clay waste mixture, to obtain high compressive strengths. The increased formation of strong chemical bonds between the amorphous ferrite phase and the geopolymer matrix has enhanced the properties (Rezzoug et al., 2024). Sometimes instead of costly sodium silicates soda-lime glass wastes and sodium aluminate activator (NaAlO2) were used. It was found that in the samples with raw glass a crystalline phase of hydrosodalite was formed, while in the samples with glass pre-washed in acid (to remove surface sodium ions) a zeolite phase was formed. The samples made of acid-washed glass, despite the high porosity (44%), formed a more polymerized gel and their

alkali release (which is the reason for glazing and scaling) was significantly reduced. This method, which saved a considerable amount of chemicals, produced products with an attractive appearance and good adhesion between coarse particles and the matrix. This method can be applied not only to soda-lime glass, but also to other difficult-to-recycle glasses (cathode ray tube glass, leaded glass, fiberglass) (Ramteke et al., 2023).

Self-healing geopolymer composites can be produced using transparent glass ferit. For this purpose, it is sufficient to use 50% metakaolin-based potassium geopolymer, 35% transparent glass ferrite (10 to 250 microns in size), and 15% alumina plates (50 × 50 × 10 microns in size). The alumina plates are used to prevent cracking, and the glass ferrite is used to fill microcracks and as a repair agent. The samples are heat treated at 900 o C for 5 to 20 hours. The addition of alumina plates prevents the formation of major microcracks and reduces the linear shrinkage to about 7%. At 900 o C, the glass ferrite melts and fills the microcracks formed by dehydration and crystallization of the geopolymer, thus reducing the open porosity to less than 1% and forming a uniform glaze layer of 250 microns thickness on the surface of the samples. The geopolymer phase is converted to leucite at 900°C, while the glass ferrite and alumina remain chemically unreacted with each other, which ensures the ability to remelt and re-repair the glass in subsequent thermal cycles. Such a product has great potential for application in thermal energy storage vessels with molten salts and highly corrosive environments (P. Keane et al., 2022).

2.3.2. BASALT FIBERS

Crushed basalt fibers are used as a refractory reinforcement. Basalt is also used in the production of "self-healing geopolymers." The best performance has been observed up to 1150°C because, at 1200°C, basalt fibers melt and lose their reinforcing effect (P. F. Keane, Foltz, Chadha, Marsh, & Kriven, 2021).

Basalt fibers are used as a reinforcing agent to increase toughness and flexural strength and improve composite performance at high temperatures. At intermediate temperatures (below 1000°C), the fibers remain intact, while at higher temperatures (around 1200°C), they melt and act as a network filler system. Basalt fibers have been shown to be damaged by alkaline environments; therefore, researchers have modified the surface of the fibers to improve their compatibility with the geopolymer matrix. Physically, the silane layer increases the surface roughness of the fibers, thereby improving mechanical engagement and stress transfer at the fiber-matrix interface. Chemically, this modification prevents the fiber surface from being corroded by hydroxyl ions in the matrix, stabilizes the SiO_4 tetrahedral network of the fibers, and increases the density and chemical adhesion at the interface (T. Zhang, Wang, Lin, & Yao, 2024).

The addition of crushed basalt fibers also increases the flexural strength of the geopolymer. These fibers can even change the failure mechanism of the geopolymer. To achieve a combination of high strength and toughness, basalt fibers should be used in a continuous weave rather than as crushed fibers (Rill, Lowry, & Kriven, 2010). The increased setting time, reduced dry shrinkage, void filling, and bridging of cracks by basalt fibers also improve the mechanical properties and durability of concrete. Basalt fibers are also a sustainable and low-cost solution for producing high-performance geopolymer concretes that are resistant to chemical attack and freeze-thaw cycles (Pantawane & Sharma, 2022).

2.4. ALKALINE ACTIVATORS

The roles of alkaline activators in the production of geopolymer ceramics can be summarized as follows: Providing an alkaline environment for dissolving the aluminosilicate raw material: Alkaline activators (such as sodium and potassium hydroxide) increase the pH of the environment, causing the dissolution of Si^{4+} and Al^{3+} ions from the solid structure of the aluminosilicate raw material and providing the basis for the production of geopolymer gel (S. G. Mohan Kumar et al., 2025).

Creating charge balance and helping to initiate the polymerization process and form a three-dimensional network: Alkali ions (Na^+ or K^+) facilitate the polymerization process and the formation of Si-O-Al covalent bonds by creating a negative charge balance resulting from the substitution of Al^{3+} for Si^{4+} in the tetrahedral network (S. G. Mohan Kumar et al., 2025).

Determining the type of gel formed (N-A-S-H or C-A-S-H): The type of alkali cation and its ratio to calcium determine the predominant gel type. Sodium activators (NaOH and Na_2SiO_3) increase the likelihood of forming N-A-S-H gels with an amorphous network structure, while in the presence of high calcium content (slag), C-A-S-H gels with a semi-crystalline and layered structure are formed (D. Zhang et al., 2023).

Effect on reaction rate and early strength: The use of NaOH compared to KOH results in a faster reaction rate and higher compressive strength in the early stages (Lemougna et al., 2013).

Effect on thermal stability and ceramic behavior: Samples containing potassium activator (KOH) showed higher thermal stability and had a shrinkage of less than 3% after heating to 1000°C, which is very important for refractory applications (Lemougna et al., 2013).

Providing soluble silica to complete polymerization reactions: Sodium and potassium silicates (Na_2SiO_3 and K_2SiO_3), as sources of soluble silica, adjust the Si/Al ratio in the reaction mixture and improve the mechanical properties and durability of the final product by increasing the degree of polymerization (Ryu et al., 2013).

Determining the optimal reaction range through molar ratios: The molar ratios of SiO_2/Na_2O and Al_2O_3/Na_2O play a key role in producing high-quality geopolymers, and the geopolymerization reaction does not proceed properly outside these ranges (Ryu et al., 2013).

Effect on reducing sintering temperature and forming a molten phase: Some activators act as fluxes and reduce the sintering temperature by creating glassy phases during heat treatment (P. Li, Cao, & Ran, 2025).

Possibility of eliminating the calcination step and the effect on the microstructure: The use of alkaline activation in illitic clays allows the complete elimination of the calcination step (thermal firing) and makes the production process more economical. Also, alkaline activation at high concentrations leads to the formation of nanometric zeolite crystals with fibrous morphology in the geopolymer microstructure, which helps to increase the flexural strength (Vasić et al., 2022). Selecting the appropriate type and concentration of alkaline activator, by increasing the degree of polymerization and reducing porosity, leads to an increase in the density of the final samples. For example, using the optimal activator can increase the density to 2.82 g/cm³ (You et al., 2023).

Improving self-healing properties through the formation of a glass phase: In systems containing glass ferrite, alkaline activators, by forming a dense gel, provide the basis for the melting of the ferrite at 815–900°C and the filling of microcracks through a self-healing mechanism (P. Keane et al., 2022).

Role in the production of self-glazing tiles without the need for secondary glazing: Alkaline activators (sodium or potassium hydroxide and sodium silicate) induce a more intense geopolymerization reaction at the surface, enabling the formation of a smooth, flawless glassy layer with a hardness exceeding 4 on the Mohs scale, thereby eliminating the need for a secondary glazing process at temperatures of 850–1250°C (Kumar et al., 2007).

The concentration and type of alkaline activator affect curing time of geopolymers; in particular, in comparing different amounts of the activator, more added leads to quicker setting time as well as faster reactions. To ensure the time of curing (more than 45 min), one can raise the ratio between liquid and solid ingredients or decrease the mass of slag used (Nguyen & Castel, 2023).

Impact on environmental and economic performance: The use of alkaline activators at lower concentrations in conjunction with waste materials helps reduce CO_2 emissions while lowering production costs by up to 30% (Sawant & A.N.Hunnabad, 2020).

The findings from this part reveal that the type of material used has a major impact on the compressive strength. In general, metakaolin geopolymers show much higher strength, as they can reach up to 95 MPa due to their high reactivity. On the other hand, basalt geopolymer applications (for which 80% of metakaolin substitution was carried out) show significantly lower values of strength (around 16.6 MPa), while having the lowest cost (80% of cost-cutting). Despite this, in comparison with metakaolin geopolymers, those based on volcanic ash have superior thermal stability (less than 3% of shrinkage at 1000°C), although the dissolution is much slower. Hence, the type of the raw material can be chosen according to the intended purpose of the geopolymer.

3. Mechanisms of Ceramization and Property Enhancement

Ceramic manufacturing mechanisms can be classified into the following groups:

3.1. Formation mechanism of N-A-S-H gels versus C-A-S-H gels

The formation of N-A-S-H versus C-A-S-H gels in geopolymers produced from multiple sources is controlled by the relative ratio of (Na+Ca)/(Si+Al) and competitive exchange between Ca^{2+} and Na^{+}. At small ratios (≤0.6), the convergence of Na^{+} and Ca^{2+} ions helps to neutralize the Al^{3+} and Si^{4+} ions, favoring the formation of thin C-S-H and N-A-S-H gels. With the increase of the Ca^{2+} in the geopolymers' composition (the ratio of 0.95), the role of the Na^{+} ions in the structure of the C(N)-A-S-H gel lowers leading to the transition of petal-like morphology to larger flake-like C-A-S-H gels while the Na ions occupy the empty positions in the pore solution. Maximum performances of the structure as determined mostly by the amount of C-S-H and C-A-S-H gels occurring at Al/Si ≈ 0.6 and (Na+Ca)/(Si+Al)≈0.95 values indicating the region when Ca^{2+} ions replace the part of Si-O-T and form crosslinks in the structure (D. Zhang et al., 2023).

The N-A-S-H structure's amorphous and interconnected network make it highly permeable, enhance pollutant transportation, achieve uniform photocatalyst distribution, and help achieve high electrical and thermal conductivities, while the C-A-S-H structure, which is layered and semi-crystalline, has stronger-strength Ca^{2+} bonds, more mechanical resistance, but utilizes energy-intensive processes to create porosity that imprisons light and requires service materials such as graphene due to low electricity conductivity (Wilson, Ke, Maskell, & Ball, 2026).

3.2. Sintering process and factors affecting it (temperature, heating rate, and presence of molten phase)

Sintering of geopolymers is a process that takes place at very high temperatures (generally over 1000°C), which causes the matrix to densify, porosity to decrease, and the formation of ceramic-like crystalline phases compensating for some of the lost strength due to heating.

However, the high temperature needed for sintering leads to severe degradation of the geopolymer prior to the activation of this phenomena. A low melting point sintering aid helps in lowering the sintering temperature and viscosity, thus facilitating the process of sintering (P. Li et al., 2025).

3.3. Crystallization mechanism of ceramic phases

Sometimes, the crystallization mechanism of ceramic phases in refractory geopolymers, such as potassium-based geopolymers, is a multi-step process that begins with the initial crystallization of leucite ($KAlSi_2O_6$) from the amorphous geopolymer gel at a temperature of about 1000°C. As temperature rises to up to 1250 °C, kyanite (Al_2SiO_5) acts as a refractory filler and emits alumina and silica, reacting with the rest of the matrix and resulting in the creation of new crystalline phases that include mullite ($3Al_2O_3{\cdot}2SiO_2$), cordierite ($2MgO{\cdot}2Al_2O_3{\cdot}5SiO_2$), enstatite ($MgSiO_3$), and gehlenite ($Ca_2Al_2SiO_7$). This crystallization process is related to the movements of aluminum atoms and their displacement in the structure of SiO_4 tetrahedrons, which is confirmed through changes of the absorption peaks in FT-IR spectra at 1049, 555, and 449 cm^{-1}. Consequently, this results in a denser structure of the matrix with low thermal expansion (below 0.8 %). Fineness of kyanite is a key point of this mechanism since it increases the area of reaction. The occurrence of formed crystalline phases (such as leucite, mullite, cordierite, enstatite, and gehlenite) leads to the formation of strong bonds among the particles, resulting in the production of a dense matrix, which has the ability of being thermally shock resistant and possesses low thermal expansion coefficient, which is useful in its refractory applications at high temperature ranges, which can reach a maximum value of 1250 degrees Celsius (Deutou Nemaleu et al., 2022).

3.4. GLASS PHASE SELF_HEALING MECHANISM

The self-healing mechanism through the glass phase of these composites relies on the addition of low melting glass powder averaging between 815°C and 900°C to the geopolymer matrix. While the temperature is raised to around 900°C, the geopolymer matrix experiences dehydration and microcracks, whereas on the other hand, at the same temperature, the glass particles become liquid and occupy and seal the microcracks via capillary action due to the liquid state. Hence the flexural strength reaches around 6 MPa. At around 1000°C, the geopolymer matrix would be transformed into solid leucite ceramic, while at the same time the basalt fibers would remain intact and the liquid glass would penetrate into the microcracks created by the crystallization and liquid glass that has solidified yet again. The two-step process is responsible for the production of two different varieties of self-healing composites: ASH-C, an amorphous self-healing ceramics at about 1000°C and ASH-G, which is an amorphous self-healing geopolymer. Even though the ideal temperature is 1150°C, anything above 1200°C leads to the melting of basalt fibers thereby losing strength. Moreover, the presence of sufficient amounts of glass particles in the mix (at least 16% by volume) ensures that a smooth surface is formed, and helps achieve open porosity of less than 1% in the final self-healing ceramic.

In this regard, the processes of ceramization heavily rely on the molecular features of raw materials as well as previous technological history. In the case of low-calcium kaolin systems, the main mechanism of ceramization is determined by crystallization of N-A-S-H gel and its conversion into leucite as well as mullite and occurs at over 1000°C (Al-Buriahi et al., 2026; Deutou Nemaleu et al., 2022). In contrast, high-CaO blast furnace slag-based systems undergo C-A-S-H phase formation and liquid-phase sintering at lower temperatures (800–950°C) (D. Zhang et al., 2023).

The primary method of transformation for glass-rich systems (for instance, waste glass and frit-based materials) is viscous flow sintering, which effectively provides the possibility of self-healing for the said systems within temperature values of 815-900°C. (P. Keane et al., 2022; P. Li et al., 2025). Consequently (Al-Buriahi et al., 2026), there is no single optimization strategy applicable to all cases; rather, the dominant mechanism for each class of composition must be identified to guide the selection of processing parameters.

4. DISCUSSION

Table 1 shows a sample of oxide compounds derived from raw materials explained in earlier studies. All the materials presented in the table have silica and alumina in common.

TABLE 1. Examples of oxide compounds from raw materials reported in previous research

	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	SO_3	TiO_2	MnO	Na_2O	Ref
Fly ash	30.78-50.14	17.87-29.08	4.03-15.47	9.66-24.28	0.78-1.53	1.11-6.45	0.47-1.44	-	-	-	(Risdanareni, Puspitasari, & Januarti Jaya, 2017)
kaolin	45.04	39.35	0.05	0.79	1.02	0.22	-	0.16	-	0.1	(Sánchez, de Soto, Casas, Vigil de la Villa, & García-Giménez, 2020)
Blast furnace Slag	31.34-32.09	14.79-16.70	39.51-43.47	-	0.42-0.48	5.97-6.53	1.14-1.34	0.79-2.12	0.43-0.49	0.41-0.46	(Chen, Ou, Lin, Wu, & He, 2026)
Illitic Clay	55.20	9.79	7.69	-	3.49	5.54	-	0.55	-	0.5	(Sedmale, Cimmers, Sedmalis, & Celms, 2009)
Volcanic Ash	44.8-71.6	10.8-16.64	0.42-8.94	3.14-14.70	0.58-3.62	3.57-9.47	0.25-0.04	0.15-3.23	0.07-0.42	3.45-6.1	(Alraddadi & Assaedi, 2020)
Waste glass	20.3-87.46	0.01-4.68	2.68-63.8	-	0.1-8.5	0.4-3.59	-	-	-	-	(Zhou et al., 2025)
ceramic waste	41.45-46.23	5.98-21.02	1.17-5.19	26.31-27.99	2.96-8.56	0-2.09	-	-	-	-	(Mendonça de Souza et al., 2025)
Basalt	40.180-49.85	9.79-13.41	13.34-19.44	6.85-13.30	0.93-2.35	3.99-4.24	-	0.92-2.42	0.13-0.18	0.87-3.26	(Al-Zubaidi, Jasim, & Idan, 2021)

The raw materials used in creating geopolymer ceramics have a diversified chemical composition as shown in Table 1. The kinds and percentages of the oxides may affect the reactivity, process mechanisms, sintering temperature, as well as final properties of the ceramics. For example, kaolin, with the highest Al_2O_3 content (about 39%) and a SiO_2/Al_2O_3 molar ratio of approximately 1.9 (close to the ideal stoichiometric composition), has the highest reactivity in alkaline media and facilitates the formation of pure N-A-S-H gel, while blast furnace slag, with a high CaO content (about 40%) and a low $(SiO_2+Al_2O_3)/CaO$ ratio, contributes to the formation of C-A-S-H gel and, while increasing the initial strength, reduces the sintering temperature through the formation of glass-ceramic phases such as gehlenite and akermaniteVolcanic ash and glass waste differ in that while both exhibit very high SiO_2/Al_2O_3 ratios of 11.2 or higher and 7.5 or higher, respectively; the Alumina content in them is drastically low which can be negated by addition of Alumina sources like Metakaolin. But, because of the total absence of alumina, Glass waste only acts as flux and source of Silica while increasing density and strength of ceramics due to the melting process that fills the pores. Moreover, Basalt deposits, that contain high amounts of Fe_2O_3 (up to 28%) and MgO (up to 9.5%), are known to create Olivine and Pyroxene phases during thermal processing thus contributing to the density but thermal resistance up to 1000°C. This chemical diversity indicates that the selection of the starting material should be based on key ratios (especially the SiO_2/Al_2O_3 ratio and the amount of alkali and alkaline earth oxides) to optimize the polymerization and sintering processes and achieve the desired mechanical and thermal properties for the intended applications.

Based on an analysis of the oxide ratios derived from Table 1, a novel analytical framework is proposed in Table 2. For the first time, this study enables the prediction of the dominant ceramization mechanism and the end-use application.

TABLE 2. Calculation of oxide ratios, phase prediction, and subsequent application.

SiO_2/Al_2O_3 Ratio Range	$(CaO+MgO)/SiO_2$ Ratio Range	Predicted Dominant Mechanism	Optimal Sintering Temperature (°C)	Expected Crystalline Phases	Recommended Application
< 2.5	< 0.1	N-A-S-H gel crystallization	1000 – 1200	Leucite, Mullite	Refractories, fire-resistant panels
2.5 – 4.0	0.1 – 0.5	Hybrid N-A-S-H / C-A-S-H sintering	900 – 1100	Gehlenite, Anorthite	Construction blocks, flooring tiles
> 4.0	< 0.1	Glass-phase melting / Self-healing	815 – 900	Leucite + Amorphous glass phase	Thermal energy storage vessels, self-glazing coatings
Any range	> 0.8	Early C-A-S-H formation with liquid-phase sintering	800 – 950	Akermanite, Diopside	High-early-strength applications (special concretes)

Per Table 2, The framework centers on specific oxide ratios such as SiO_2/Al_2O_3 and $(CaO+MgO)/SiO_2$. With this framework, materials that have an SiO_2/Al_2O_3 ratio of less than 2.5 and low alkaline ratio (like kaolin and

metakaolin) have a tendency of forming the N-A-S-H phases and forming leucite and mullite at temperatures over 1000°C, thus suitable for refractories. Meanwhile, for materials with a $(CaO+MgO)/SiO_2$ ratio higher than 0.8 (such as blast furnace slag), sintering takes place at lower temperatures (800–950°C) and the formation of C-A-S-H gel makes them very good for applications where needed is high early strengths. Furthermore, materials having very high SiO_2/Al_2O_3 ratios (such as waste glass and volcanic ash) and which do not have enough alumina become ceramics at temperatures of 815–900°C without crystallization and thus through the melting of the glass phase and self-healing. The framework can be helpful in choosing the desired raw materials for the process taking into account their chemical composition and the purpose of the use by ease of getting rid of unnecessary trials. A comprehensive summary table has been added as Table 3 in the Discussion section:

TABLE 3. Comparison of advantages, limitations, and typical applications of geopolymer raw materials

Raw Material Category	Specific Material	Advantages	Limitations	Typical Applications
Natural Aluminosilicates	Basalt	Low cost, abundance, and the ability to enhance thermal stability (Mrozek et al., 2025)	Low activity, requires metakaolin (Mrozek et al., 2025)	Fire-resistant materials, fireproof coatings (Ahmadi et al., 2026; Wu et al., 2026)
	Volcanic Ash	High reactivity, good thermal stability, low shrinkage (Lemougna et al., 2013)	Lack of accessibility across different geographical regions, slow dissolution rate (Kamseu et al., 2009)	Radiation shielding materials, construction materials, and refractory materials for low-temperature applications (Plando et al., 2025)
	Kaolin/Metakaolin	High reactivity and compressive strength (Al-Buriahi et al., 2026; Zawrah et al., 2020)	High shrinkage and the need for calcination (Bezerra et al., 2023)	Thermal insulation, High-performance ceramics (Z. Li et al., 2025; H. Wang et al., 2015)
	Illitic Clay	Abundant availability, low cost, high compressive strength (Zerzouri et al., 2025)	Need for mechanochemical or thermal activation due to low reactivity (Eliche-Quesada et al., 2021; Zerzouri et al., 2025)	Use as materials for green construction (Eliche-Quesada et al., 2021; Vasić et al., 2022)
Industrial Wastes	Fly Ash	Abundant and readily available; derived from waste; possesses a completely amorphous structure; low-cost; and reduces CO_2 emissions (Sawant & A.N.Hunnabad, 2020)	Possesses a highly variable composition, requires alkaline activation, and is non-reactive in some cases (Pławecka et al., 2022; Ryu et al., 2013)	Construction Bricks and Concrete (Ansari & Kumar, 2025; Kozub, 2025)
	Blast Furnace Slag	High CaO content: high strength (Nguyen & Castel, 2023)	Expansion problems, variable composition, rapid setting (Ionescu et al., 2020)	High-strength concrete, fire-resistant panels (Cheng & Chiu, 2003; Ionescu et al., 2020)
	Steel Slag	Containing Fe and Ca; improves density and reduces shrinkage (Bai et al., 2023)	Low reactivity; problems caused by the expansion of free CaO (Ionescu et al., 2020)	Durability (Bai et al., 2023; S. Wang et al., 2025)
	Ceramic Waste Powder	Reduction of landfilled waste and environmental problems, reduced water absorption (Shcherban' et al., 2023)	Low reactivity and efficiency (Shcherban' et al., 2023)	Building and construction materials (Berkouche et al., 2025; Shcherban' et al., 2023)
Alkaline Activators	NaOH	High reactivity, high strength (Lemougna et al., 2013)	Lower thermal stability than KOH (Lemougna et al., 2013)	General geopolymer production, construction materials (Lemougna et al., 2013)
	KOH	Low shrinkage and high thermal stability (Lemougna et al., 2013)	Expensive, low reactivity (Lemougna et al., 2013)	High-Temperature and Refractory Applications (Lemougna et al., 2013)
	Sodium Silicate	It produces soluble silica and increases the degree of polymerization (Ryu et al., 2013)	High cost and rapid setting (Ryu et al., 2013)	To adjust the Si/Al ratio and improve mechanical properties (Ryu et al., 2013)

5. UPCOMING CHALLENGES AND FUTURE OUTLOOK

5.1. Challenges

5.1.1. Standardization

One significant difficulty is that there are no universally accepted international standards, inspection procedures, quality control methods, classification systems and regulations to ensure the quality of ceramic geopolymers (Ekinci et al., 2025; Kadhim, Mankhi, & Muslim-AL-Bujasim, 2024; Mohd Mortar et al., 2022).

5.1.2. Durability

Geopolymers' performances, including their responses to external forces of creep, fire resistance, thermal cycling and thermal shock, mechanisms of aging, and temperature alterations, reduces with time due to environmental impacts like freeze-thaw cycles, wet-dry cycles, and chemical assaults. This creates a problem that needs to be resolved (Ekinci et al., 2025; Gailitis, Sprince, Kozlovksis, Pakrastins, & Volkova, IMST 2022; Gailitis, Sprince, Łach, Gavrilovs, & Pakrastins, 2023).

5.1.3. Barriers to Commercialization

Among the main obstacles in the process of making the geopolymer-based ceramics commercially viable are the high price of alkaline activators and the energy necessary for curing, the unreliability of the waste raw materials, and the difference between laboratory conditions and industrial (Alrawashdeh, Zamorano, Alshaaer, & Martín-Morales, 2024; Kadhim et al., 2024).

FUTURE OUTLOOK

Some areas that would be given priority in the research studies would involve developing standard evaluation methods and performance measurement criteria, performing long-term aging tests, altering formulations to make them more energy-efficient, conducting research on new additives, analyzing ecological impacts, and building production facilities on industrial level (Kolade, Ikotun, & Oyejobi, 2025; Martínez & Miller, 2023).

6. CONCLUSION

This piece of writing deals with ceramics based on geopolymer including the raw materials and processes of manufacture and uses. Also, the article discusses the types of aluminosilicate-containing raw materials, their composition, utilization process, and its production. It was found that the chemical composition of the raw materials, especially the SiO_2/Al_2O_3 molar ratio and the amount of alkaline earth oxides, plays a decisive role in the reactivity and final properties of the produced material. For instance, metakaolin exhibits the highest level of reactivity, having a rating of 1.9 and making it possible to achieve compressive strength of around 95 MPa, while blast-furnace slag, which is characterized by rich CaO content (about 40%), facilitates C-A-S-H gel formation and allows decreasing the process of sintering. Four essential modes of ceramic formation have been identified and discussed and include (1) the N-A-S-H versus C-A-S-H gels formation process (characterized by the ratio (Na+Ca)/(Si+Al)), (2) the process of sintering when heating takes place with a temperature of 1000-1200C and the rate of heating of less than 5C per minute, (3) crystallization of the main ceramic phases such as leucite, mullite, cordierite, and gehlenite (which methods are aimed at reducing the coefficient of thermal expansion = 0.8%), and (4) self-healing method, which involves use of the glass phase of processing (which makes it possible to reduce open porosity to less than 1% and fill cracks by melting of glass ferrite at the temperature equal to 815-900C). It was found that using wastes can reduce production costs and energy consumption while also reducing CO_2 emissions. Nonetheless, there are still hurdles such as varying chemical structures of slag and low activity of crystalline bodies of ceramic waste, expansion because of free CaO, and absence of a universal norm preventing the commercial use of this material. Considering the huge possibilities of this ceramic material in many areas such as eco-friendly construction (lightweight blocks, fireproof panels, self-glazing tiles), as well as high-tech industry (thermal energy storage facilities, refractories, radiaition protection materials), research in the future should be aimed at the development of common methods of evaluation, optimization of mixtures for achieving multiple features, and lowering temperature of sintering by using of new fluxes and nanomaterials.

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