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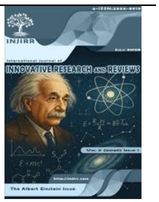

REVIEW ARTICLE

A Comprehensive Review of Nanocomposite Geopolymers: Mechanism, Properties, and Industrial Potential

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ABSTRACT

Geopolymers are inorganic polymers with amorphous or semi-crystalline structures formed by alkali activation of aluminosilicate-based materials. They are presented as a durable alternative to traditional Portland cement because of their low carbon footprint, high mechanical strength, and superior chemical and thermal resistance. However, their limited toughness and crack resistance restrict their application. To address these issues, nanocomposite geopolymers integrated with nanotechnology have been developed. The function of the nanoadditives used in the geopolymer matrix is twofold: (i) a nucleation effect that accelerates polycondensation and increases microstructure density; and (ii) a reinforcement effect that improves load transfer and limits microcrack propagation thanks to the high surface area and strong interface bonds. As a result, these mechanisms lead to significant improvements in compressive and flexural strength, toughness, and wear resistance. Additionally, nano additives enhance durability, particularly against freeze-thaw cycles, sulphate attack, and acid resistance, by reducing porosity. Functional additives, on the other hand, impart properties to geopolymers beyond their role as conventional building materials. For example, carbon nanotubes enhance electrical conductivity, electromagnetic wave attenuation, and piezoresistive sensor capabilities. Consequently, nanocomposite geopolymers are drawing attention not only in the construction industry but also in fields such as electronics, energy storage, catalysis, and advanced insulation. Overall, these materials show great promise due to their multifunctionality, strength, and durability. Future research should focus on adapting these materials to large-scale production processes, ensuring the even distribution of additives, and evaluating their long-term durability from environmental and economic perspectives.

Contents

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1. Introduction

The construction industry is a significant source of carbon dioxide emissions globally. When examining the root causes, the intensive use of Portland cement today stands out as one of the most important reasons why the search for sustainable and environmentally friendly alternative materials should be urgently brought to the agenda [1]. One of the most promising outcomes of these searches was the concept of "geopolymer", introduced by Joseph Davidovits in the late 1970s [2, 3]. Davidovits revealed that by imitating naturally occurring pozzolanic reactions, aluminosilicate-based materials such as fly ash, metakaolin, and blast furnace slag can react with aluminosilicate-based materials, generally sodium or potassium silicate/hydroxide type, to form amorphous or semi-crystalline, three-dimensional silico-aluminate network structures [2, 4]. The polymerisation process, unlike traditional cement hydration, proceeds at relatively low temperatures and is called "polycondensation." Instead of binding water to the chemical structure, polycondensation leaves it largely as a liberated product of the reaction [5, 6]. The resulting geopolymer binders exhibit outstanding properties such as up to 80% lower CO_2 emissions compared to Portland cement, high early-age strength, superior fire and heat resistance, and high resistance to chemical agents such as acids and sulphates [7–9]. These unique properties have made geopolymers extremely attractive not only as a green building material but also for high-tech applications such as fire-resistant coatings, toxic waste immobilisation, and aerospace components [10–12]. Following Davidovits' pioneering work, research on geopolymer chemistry and technology has increased exponentially over the last 20 years. As a result, significant progress has been made in understanding the fundamental reaction mechanisms of materials and optimising their engineering properties [13–15]. The main binder phases that emerge during the geopolymerization process, which occurs when an aluminosilicate source reacts with high pH alkali activators, are generally N-A-S-H (sodium-aluminosilicate hydrate) or K-A-S-H (potassium-equivalent) gels [16, 17]. The resulting N-A-S-H and K-A-S-H-like gel phases have characteristic properties such as nanoscale porosity and high specific surface area. This intrinsic nanostructure makes the geopolymer matrix an ideal platform for homogeneous distribution and efficient interfacial interaction of nano-sized additives [17, 18]. Carbon-based nanoparticles such as graphene, graphene oxide, and carbon nanotubes improve mechanical and electrical performance by bridging microcracks and forming conductive networks within the matrix. Metal oxide nanoparticles, such as nano-SiO_2 and nano-Al_2O_3, on the other hand, compact the microstructure and increase durability through pozzolanic/defining filling effect. Oxides such as TiO_2, ZnO, or Fe_2O_3 tend to impart photocatalytic, magnetic, or radiation-interactive functions [18–21]. 2D materials such as nano-clays and montmorillonite, on the other hand, influence the layering and transform the composite behaviour by supporting ionic and molecular interactions with their large surface areas [18, 20]. This interaction has been sufficiently documented in the literature. Additions such as nano-silica or graphene / graphene oxide (GO) with appropriate structural geometry (≈1–3%) resulted in a dense, pore-free structure and significant increases in mechanical strength between 20% and 80%. Significant improvements have been observed, particularly in fracture toughness. For example, nano-silica additives have been reported to increase compressive strength by approximately 22%, while graphene/GO additives have a more pronounced effect on flexural strength and early-age strength [20, 22, 23]. At the microstructural level, the overall protection of the nano-additives decreases, resulting in a more homogeneous and finer protective network. The resulting compact structure ensures the material's durability by limiting the permeation of water and harmful ions, and consequently, significantly increases its resistance to freeze-thaw, sulfate, and acid attacks [18, 24]. In functional applications, carbon nanotube/graphene additions provide electrical conductivity and piezoresistive behaviour, while magnetic nanoparticles such as Fe_2O_3 provide magnetic properties and oxides such as TiO_2 offer photocatalytic activity. Therefore, nanocomposite geopolymers can be used as building materials for sensing, energy storage, and catalysis [18, 19, 22]. Furthermore, the demonstration of X-ray/γ-ray storage performance of geopolymer composites with optimised density and elemental content and improved photon cooling values with bismuth, yttrium etc. additives has been widely reported, demonstrating the feasibility of new geopolymer-based protection methods [25, 26]. Consequently, this versatile performance portfolio makes nanocomposite geopolymers an attractive candidate not only for high-strength and fire-resistant construction applications, but also for high-technology fields such as toxic waste immobilization, support material for supercapacitor/battery electrodes, photocatalytic environmental process elements and radiation shields; however, practical challenges such as homogeneity of additive distribution, optimum dosing, production scalability and long-term service behavior still remain [18, 21, 24, 26].

2. Fundamentals of Geopolymers

Pressures on the construction industry regarding sustainability and environmental impact have accelerated the search for alternatives to traditional Portland cement (PC). One of the most promising results of this search is the concept of "geopolymer" introduced by Joseph Davidovits in the late 1970s [2]. Davidovits demonstrated that aluminosilicate-based materials such as fly ash, metakaolin, and blast furnace slag can react with an alkaline activator solution such as sodium or potassium silicate/hydroxide to form "amorphous or semi-crystalline, three-dimensional silico-aluminate networks" [3, 4, 17]. This reaction is called "geopolymerization" and is essentially a polycondensation process. Unlike traditional cement hydration, this process proceeds at relatively low temperatures, and water is released as a reaction product; it is not bound to the chemical structure.

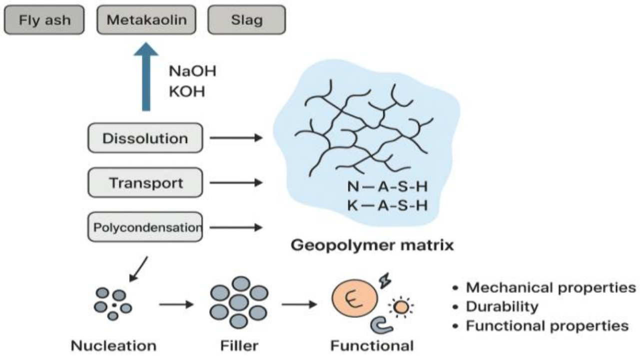

Figure 1 Schematic flow of the geopolymerization process and nano-additive interaction mechanisms [25, 27–31].

The binder phases formed as a result of this process are generally N-A-S-H ($[Na_2O]–Al_2O_3–SiO_2–H_2O$) or K-A-S-H ($[K_2O]–Al_2O_3–SiO_2–H_2O$) gels [4, 28, 29]. These gels have properties such as nanoscale porosity and high specific surface area, making them ideal dispersion and interaction platforms for nanoadditives [17, 32]. The main differences between the two processes are summarised schematically in Figure 1. The binder phases formed as a result of this process are generally N-A-S-H ($[Na_2O]–Al_2O_3–SiO_2–H_2O$) or K-A-S-H ($[K_2O]–Al_2O_3–SiO_2–H_2O$) gels [30, 33].

All these properties make geopolymers suitable for use in high-technology fields such as toxic waste immobilisation, advanced radiation shielding, supercapacitor/electrode supports, and smart structural components, taking them beyond traditional high-performance structural applications. However, major challenges remaining in the literature are large-scale and economically homogeneous dispersion of nanoadditives, optimal dosing, scalability of production processes, and reliable assessment of long-term service behaviour [17, 32, 34].

2.1. Comparison of Geopolymerisation and Portland Cement

There are significant differences between the hydration mechanisms of Portland cement and geopolymerisation. Portland cement is based on a classical hydration process in which clinker phases (specifically C_3S and C_2S) react with water to form a calcium-silicate-hydrate (C-S-H) gel [29]. This process requires clinker production at extremely high temperatures, approximately 1450 °C, resulting in both intensive energy consumption and significant CO_2 emissions [27]. Cement production is reported to account for approximately 7-8% of total global CO_2 emissions [35]. This presents a significant drawback of Portland cement in terms of sustainability [1]. In contrast, geopolymerisation is based on the dissolution of aluminosilicate sources (such as fly ash, metakaolin, blast furnace slag) in alkaline solutions (NaOH, KOH or alkali silicates) and the formation of a three-dimensional aluminosilicate network structure through polycondensation reactions [3]. As a result of this process, N-A-S-H (sodium aluminosilicate hydrate) or, in systems with high Ca content, C-A-S-H (calcium aluminosilicate hydrate) gel phases are formed [36]. As a significant advantage, the geopolymerisation mechanism proceeds at low temperatures in the range of 20-80 °C, unlike Portland cement [4], which reduces both energy requirements and contributes to a significant reduction in the carbon footprint [36]. This fundamental difference is the main reason why geopolymers have emerged as alternative binding materials from environmental and technological perspectives [37].

2.2. Sustainability Advantages

One of the most important advantages of geopolymers is their low carbon footprint. Life cycle analyses show that geopolymer binders result in 40–80% less CO_2 emissions compared to Portland cement [14, 36, 38, 39]. This reduction is particularly related to the elimination of high-temperature clinker production and the utilisation of industrial by-products such as fly ash and blast furnace slag as raw materials. Furthermore, the energy requirements for geopolymer production are significantly lower than for Portland cement [36]. These properties make geopolymers compatible with circular economy principles and contribute to reducing the environmental burden through waste reuse [14]. Recent studies have highlighted the environmental performance of geopolymers, particularly through carbon footprint and energy consumption indicators, and have indicated that they offer sustainable alternatives for infrastructure, building materials, and advanced engineering applications [38, 39]. A comparative summary of the two material groups in terms of production processes, energy consumption, and CO_2 emissions is presented in Table 1.

2.3. Historical Development: From Davidovits to the Present

The pioneering work of Joseph Davidovits in the 1970s laid the scientific and philosophical foundations of the geopolymer concept. Between 1972 and 1979, Davidovits demonstrated that natural aluminosilicates could be hardened by alkali activation, producing durable binders without the need for high temperatures [2]. In the 1980s and 1990s, research focused on material characterisation, reactivity, and mechanism; in particular, the effects of fly ash, kaolin, and silica contents on geopolymerisation were investigated [39, 40]. Since the 2000s, the use of industrial waste components (fly ash, slag), sustainability criteria, economic analyses, and application-oriented research have increased; geopolymer concrete applications, toxic waste immobilisation, and durability studies have come to the fore [40].

In the last 20 years, nanotechnology integration, performance optimisation, curing and additive dosage optimisation, characterisation techniques and standardisation efforts have accelerated [41]. Today, geopolymers find potential use in high-technology applications as well as building materials [38, 40].

Table 1 Comparative analysis of Portland cement and geopolymer production in terms of energy consumption and CO_2 emissions [14, 36, 38, 39].

Parameter	Portland Cement (OPC)	Geopolymer Binders
Production process	High-temperature clinkerization (~1450 °C)	Low-temperature alkali activation (60–80 °C)
Main raw materials	Limestone, clay	Fly ash, slag, metakaolin, industrial by-products
Energy consumption	~3.5–5.0 GJ/ton	~1.5–3.0 GJ/ton
CO_2 emissions	~800–900 kg CO_2/ton	~200–400 kg CO_2/ton
Environmental impact	High – due to calcination and fossil fuel usage	Low utilisation of industrial waste, reduced calcination

3. Rationale for the Nanocomposite Approach

Despite their superior properties, geopolymers have some inherent weaknesses that limit their full potential in structural applications. The most important of these limitations is their brittle behaviour and consequently low tensile strength and fracture toughness [42]. The matrix structure consisting of amorphous N-A-S-H or C-(A)-S-H gels offers limited resistance to microcrack propagation, which can lead to sudden failure of the material [43]. Furthermore, especially in fly ash-based systems, raw material-induced variations lead to microstructural heterogeneities, leading to inconsistencies in mechanical properties and reduced durability performance [44]. From a functional perspective, traditional geopolymers are primarily insulating, non-magnetic, and inert, and are not very functional; this restricts their use in high-technology areas such as sensors, energy storage, or catalysts [45]. Nanomaterials offer a revolutionary solution to overcome these fundamental limitations in composite design. Nanoscale additives, thanks to their high specific surface areas and unique surface chemistry, interact with the geopolymer matrix in multiple ways, fundamentally altering the material's microstructural integrity and macroscale performance [46]. These interactions proceed through three primary mechanisms:

Nucleation Effect: Nanoparticles, particularly nanosilica (nano-SiO_2) and nanoalumina (nano-Al_2O_3), serve as effective nucleation sites during the geopolymerization reaction. These particles aggregate around dissolved aluminosilicate species, accelerating geogel formation and polycondensation reactions. Thus, they promote the formation of a homogeneous and dense microstructure. This mechanism improves pore size distribution and reduces total porosity [47].

Interfacial Interaction and Reinforcement Effect: Nanomaterials with high surface area, such as carbon nanotubes (CNTs), graphene oxide (GO), or clay nanotubes, form a mechanical network within the solidified geopolymer matrix. The strong adhesion forces between these nanostructures and the matrix significantly increase the energy required for crack propagation. As the crack tip encounters these nanoreinforcements during propagation, the crack must expend additional energy to break or detach the nanostructure from the matrix. This process results in significant increases in toughness, flexural strength, and impact resistance [19].

Filler Effect: Spherical or near-spherical nanoparticles (nano-TiO_2, nano-Fe_2O_3, nano-$CaCO_3$, etc.) physically tighten and compact the microstructure by filling existing nano- and micropores within the matrix. This filling effect reduces the permeability of the material, preventing the infiltration of water, chloride ions, and other harmful agents, thereby improving durability properties such as freeze-thaw, sulfate, and acid resistance [48]. A schematic representation of these three primary healing mechanisms in a nanocomposite geopolymer matrix is given in Figure 2.

The nanocomposite approach not only frees geopolymers from their traditional weaknesses but also expands their application boundaries far beyond the traditional construction sector by imparting new and intelligent functions such as conductivity, magnetism, and photocatalytic activity. This transformation has the potential to transform geopolymers from passive building elements into smart and multifunctional materials capable of structural health monitoring, energy storage, and self-cleaning functions [19].

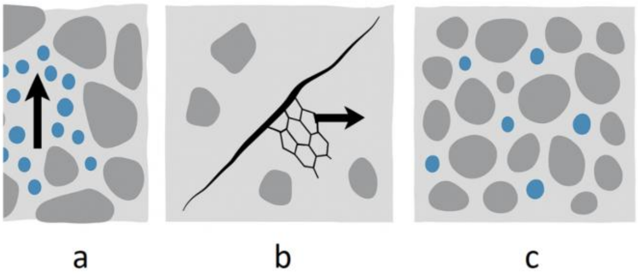

Figure 2 Schematic representation of the basic structure of a nanocomposite geopolymer: (a) Dense matrix formation by nucleation effect, (b) Crack bridging and load transfer by CNT/graphene, (c) Pore-filling effect of nanoparticles.

4. Nano Additive Types and Matrix Interaction Mechanisms

The performance of nanocomposite geopolymers is largely determined by the type of nanoadditive used, its morphology, concentration, and, most importantly, the nature of its interaction with the geopolymer matrix. These interactions shape the final properties of the material at the structural, mechanical, and functional levels. Nanoadditives can be broadly classified into four main categories.

4.1. Carbon-Based Nanomaterials

Carbon nanotubes (CNTs), graphene, and graphene oxide (GO) are among the most studied nanoadditives in geopolymer composites. They are characterised by their high surface area, exceptional mechanical strength, and superior electrical conductivity [21]. CNTs and graphene sheets act via a crack-bridging mechanism by forming a physical network within the geopolymer matrix. As a crack propagates, these nanostructures bridge the crack surfaces, dissipating energy and inhibiting crack propagation (Figure 3), thus leading to dramatic increases in flexural strength and toughness of over 50% [49–51]. In addition, the conductive carbon network in contact with each other confers electrical conductivity to the composite. This property opens the door to innovative applications such as self-sensing concretes for structural health monitoring (SHM), electromagnetic interference (EMI) shields, and electrode materials for energy storage devices [49, 50]. The hydroxyl and carboxyl functional groups on the surface of graphene oxide improve the interfacial bonding by forming stronger chemical bonds, such as hydrogen bonds, with the N-A-S-H gel [52].

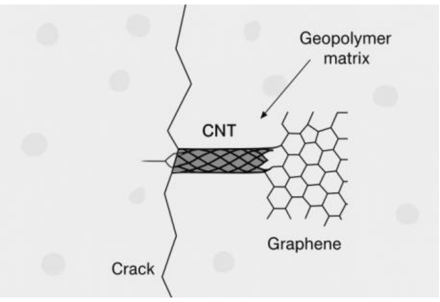

Figure 3 Crack bridging and conductive network formation mechanism of CNT and graphene in geopolymer matrix

In this context, a review of literature studies highlights the work of Tay and Norkhairunnisa [21]. This study examined the mechanical performance of graphene-doped geopolymer nanocomposites in detail. They reported that when graphene layers are well dispersed in the matrix, they reduce pore volume, form a strong interface with the geopolymer gel, and significantly increase compressive and flexural strength. They also emphasised that this additive slows crack propagation and improves fracture toughness. Figure 4 shows microscopic images obtained in the study [21]. This image shows microscopic images of graphene nanoplatelets (GNPs), which are used as a toughening agent to increase the strength of the geopolymer matrix. It was noted that thanks to the high elastic modulus of GNPs, stress is transferred evenly throughout the geopolymer matrix, and the nanocomposite does not deform under tension when loads are applied. It has been reported that when a crack starts to form, it spreads parallel to the loading direction and then reaches the GNP layers, forming a bridge through which the GNP toughness mechanism resists the crack [21].

Kanagaraj et al. [50] investigated the effects of multi-walled carbon nanotubes (MWCNTs) on the flexural behaviour of geopolymer concrete beams. Figure 5 [50] shows SEM images showing changes in the additive ratio. They reported that while low additive ratios provided limited improvement, aggregation occurred when the CNT content exceeded a certain threshold, reducing both strength and negatively impacting workability.

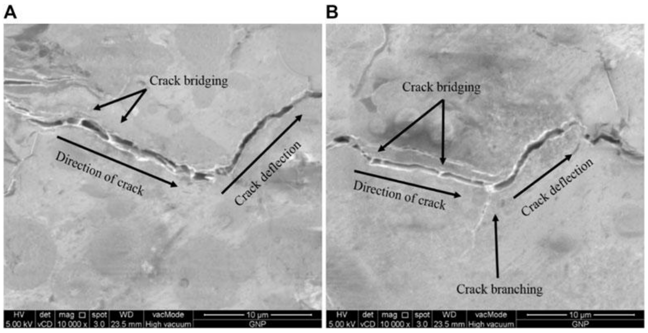

Figure 4 Toughening effects of graphene nanoplatelet (GNP) in geopolymer [21].

The most important point that stands out in both studies is that nanocarbon additives alone do not always provide benefits, and optimum dosage and good dispersion are critical [21, 50].

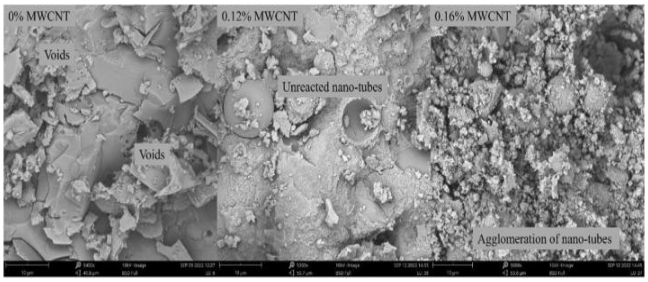

Figure 5 SEM Images of the change of GPC with respect to the amount of reinforcement [50].

4.2. Metal Oxide Nanoparticles

Nanosilica (nano-SiO_2) and nano-alumina (nano-Al_2O_3) are the most commonly used metal oxides in geopolymer composites. These particles exhibit pozzolanic reactivity and dense filling effect due to their high specific surface area. Nano-SiO_2, in particular, dissolves during geopolymerization, providing reactive silica and accelerating the formation of the N-A-S-H gel, thus densifying the microstructure [53]. At the same time, it reduces permeability by filling existing pores, thus significantly improving durability by increasing chloride ion leakage, sulfate attack, and freeze-thaw resistance [53, 54]. Titanium dioxide (nano-TiO_2) and zinc oxide (nano-ZnO) particles are distinguished by their photocatalytic properties. When incorporated into the geopolymer surface, it becomes possible to produce self-cleaning building materials by degrading organic contaminants (VOCs) and harmful microorganisms under UV light [55]. The addition of iron oxide (nano-Fe_2O_3 or Fe_3O_4) nanoparticles confers magnetic properties to the composite. Such composites are potential candidates for heavy metal removal in water treatment through magnetic separation or for magnetic data storage applications [56].

Chiranjeevi and et al. [57] investigated this issue and, upon examining the data obtained, found that the microstructure was significantly tightened when nanosilica was added to fly ash + GGBS-based geopolymer concrete mixtures at doses of 1–6%.

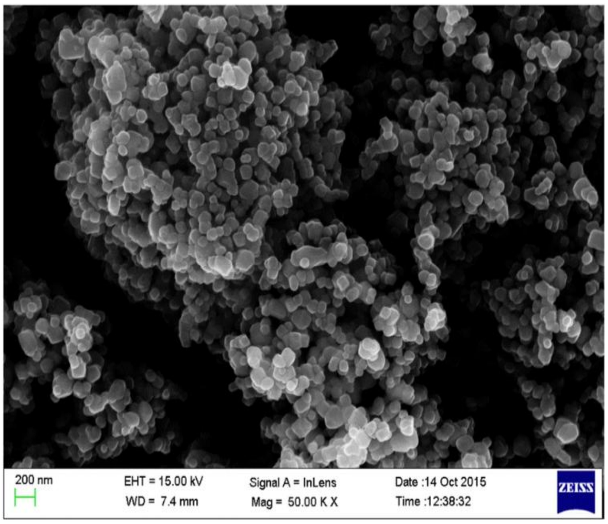

Figure 6 SEM image of nano silica [57].

The SEM image of the nanosilica used in the study is shown in Figure 6. This image shows that the nanosilica particles are very fine, and they tend to fill the pores in the pozzolan + GGBS mixture, creating a denser microstructure. Based on the experimental data, it was determined that geopolymer grain boundaries became clearer and the pore distribution narrowed.

Vanitha and et al. investigated the microstructural properties and thermal stability of phosphate-based geopolymers reinforced with microsilica as an additive [58]. In this study, they found that in metakaolin geopolymers with nanosilica additives (nano-SiO_2), the pore-filling effect was replaced by an increase in aggregation and surface roughness, especially when the additive content exceeded 5%. SEM images showed the formation of small agglomerate clusters instead of pore closure, indicating that this increased water absorption and limited mechanical strength gains [58].

4.3. Nano Clays and 2D Materials

Nanoclays such as montmorillonite (MMT) provide unique reinforcement in the geopolymer matrix with their layered silicate structures. Thanks to their cation exchange capacity, they can participate in the formation of the geopolymer network by interacting with alkali cations (Na^+, K^+), creating a tighter structure that reduces gas/ion permeability [59]. MXenes are a new family of materials consisting of two-dimensional transition metal carbides, nitrides, or carbonitrides. They offer high electrical conductivity, excellent mechanical properties, and modifiable surface chemistry. When combined with geopolymers, MXenes support the development of conductive and fire-resistant composites with high mechanical performance [60].

Table 2 Primary functions and mechanisms of different nano-additives in geopolymer matrices [55, 57, 61, 62]

Nano-additive	**Primary Function**	**Mechanism of Action**
Nano-silica (SiO_2)	Pozzolanic activity & densification	Provides reactive silica during geopolymerization, accelerates N-A-S-H gel formation, and fills micro-pores to reduce permeability.
Nano-alumina (Al_2O_3)	Microstructural refinement	Enhances dissolution of aluminosilicate precursors, promotes gel network cross-linking, and improves strength.
Nano-TiO_2	Photocatalytic activity	Generates reactive oxygen species under UV, degrades VOCs/microorganisms, and enables self-cleaning surfaces.
Montmorillonite (MMT)	Structural reinforcement & barrier effect	Layered silicate structure intercalates alkali cations, reduces ion/gas permeability, and enhances compactness.
MXene	Electrical conductivity & multifunctional properties	High surface conductivity and strong interfacial bonding improve strength, fire resistance, and sensing capability.

Similarly, combinations of MXene and montmorillonite have also been shown to increase fire retardancy and thermal stability [63]. The primary functions and mechanisms of action of different types of nanoadditives in the geopolymer matrix are summarised in Table 2. Alastaira et al. [64] conducted a study on montmorillonite + illite geopolymers. The study found that low Na:Al ratios exhibited a dense gel structure and low porosity. However, they reported that at high Na:Al ratios, mechanical performance decreased due to a significant increase in pore volume and a deterioration in pore distribution [64]. The SEM images in Figure 7 indicate that at low Na:Al ratios, pores were small and evenly distributed, and the gel structure was dense. However, at high Na:Al ratios, deterioration of grain edges, larger pores, and a less dense structure were observed. This indicates a positive effect on mechanical strength and permeability, but also points to the potential for adverse effects if the critical doping level is exceeded [64].

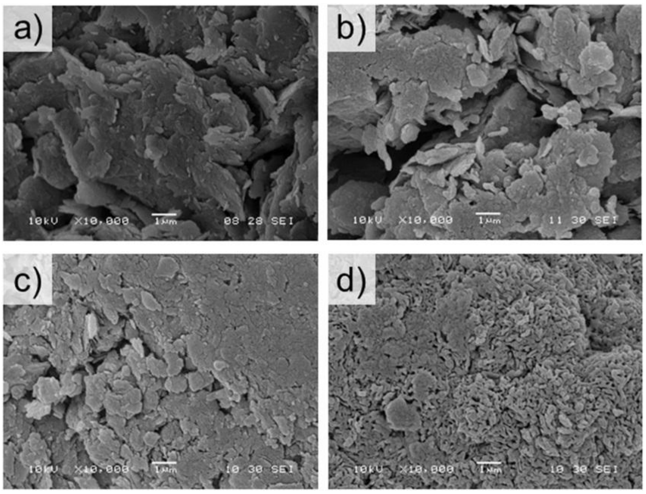

Figure 7 a) The illite precursor, and the cured samples' Na:Al ratios, b) 0.25, c) 0.5, d) 0.75 [64]

On the other hand, Wu et al. [65], in their study on the addition of montmorillonite + illite mixture to geopolymer composites, showed that when the montmorillonite content is high, the porous structure increases, the interfacial bonding weakens, and this leads to a decrease in mechanical behaviour. Krishna et al. [66] conducted a study investigating the electrical properties of graphene oxide-added fly ash-based geopolymer composites. They found that electrical conductivity increased significantly with 0.1–0.4 wt.% GO addition. However, when the GO content exceeded 0.4%, adverse effects such as aggregation and microcrack formation were observed, which limited the increase in conductivity.

4.4. Hybrid Nanocomposite Systems

Hybrid systems are attracting increasing interest to overcome the limitations of individual nanoadditives and to create synergistic effects. For example, the combined use of nano-SiO_2 and CNTs can simultaneously increase microstructure density, toughness, and conductivity [67]. Similarly, the combination of graphene oxide and nano-TiO_2 improves both mechanical properties and photocatalytic activity, enabling the creation of multifunctional composites [68]. This hybrid approach offers the possibility to fine-tune the properties for a specific application by combining the individual advantages of each nanoadditive [69].

Rommozzi and co-workers [70] synthesised graphene oxide (GO) and titanium dioxide (TiO_2) hybrid nanocomposites and comprehensively studied their effects on photocatalytic performance. In their study, significant increases in the degradation efficiency of the methylene blue solution were observed, especially with increasing the GO doping ratio. However, it was reported that at low GO doping ratios, photocatalytic activity and film stability decreased, and undesirable morphological irregularities formed on the surface. The change in the hydrophilic/hydrophobic properties of the surface was evaluated by contact angle measurements, and it was stated that this could have limiting effects on performance in long-term applications. Overall, the study successfully demonstrated the synergistic effects of the hybrid nanocomposites and also emphasised that the doping ratio and the production method are the determining factors in system performance [70].

5. Microstructural and Mechanical Behaviour

The superior performance of nanocomposite geopolymers is directly related to the microstructural properties of the final product and their impact on mechanical behaviour. Nanoadditives radically alter the macroscale response of the material by reorganising the entire microstructure, from the matrix's pore structure to its interfacial interactions.

5.1. Effect of Nano Additives on Pore Structure and Microstructural Densification

The strength and durability properties of the geopolymer matrix are largely determined by the morphology of the internal pore structure. Conventional geopolymers contain micro- and nano-scale pores due to the evaporation of water released during dissolution-polycondensation reactions and the degree of reaction. These pores not only create stress concentration sites for crack initiation but also serve as pathways for the infiltration of harmful ions and liquids, negatively impacting durability [71]. Nano-additives improve this pore structure through two primary mechanisms: (1) Physical filling effect and (2) Chemical/pozzolanic activity. Spherical particles such as nano-SiO_2 and nano-Al_2O_3 physically fill existing capillary pores and voids, reducing total pore volume and connectivity [72]. Furthermore, thanks to their high reactivity, nano-SiO_2 particles dissolve, promoting the formation of additional N-A-S-H or C-A-S-H gels and strengthening the gel phase. This chemical action leads to the coating of pore walls with calcium or sodium aluminosilicate gels, thus reducing the pore size [73].

Mercury Intrusion Porosimetry (MIP) analyses show that the addition of nano-SiO_2 at an optimum dosage (>3%) reduces total porosity by 20–30% and shifts the average pore diameter from macropores (>50 nm) to micro- and nanopores (<50 nm) [71–73]. This finer and less connected pore network increases mechanical strength while also acting as a barrier against the penetration of water and aggressive chemicals [73].

5.2. Mechanical Strength Increase Mechanisms and Literature Data

The mechanical strength increases observed in nanocomposite geopolymers are explained by several complex mechanisms originating from the nano-additive-matrix interface, in addition to microstructural densification. Among these, the following are prominent:

Crack Bridging: High-surface-area nanomaterials such as carbon nanotubes (CNTs), graphene, and GO form a physical bridge between crack surfaces when positioned perpendicularly or at an angle to the crack propagation plane. This bridge requires additional energy to further open the crack and slows the rate of crack propagation. The high tensile strength of CNTs plays a critical role in this process [21, 53].

Load Transfer: The strong adhesion formed between the nanoadditive and the geopolymer matrix allows some of the external load to be transferred to the higher-strength nanoadditive. This increases the overall strength and toughness of the composite. Well-dispersed graphene sheets efficiently distribute the load across large surface areas and contribute to this mechanism [21, 74].

Fracture Toughness: As a result of the above mechanisms, the energy required for crack propagation, i.e., fracture toughness, increases significantly. The crack must either pull the nanoreinforcement out of the matrix, fracture it, or circumvent it. Each process results in additional energy dissipation [75].

Experimental studies in the literature confirm significant mechanical improvements at optimal additive ratios. Table 3 summarises the typical ranges of strength gains reported for different types of nanoadditives [21, 74, 75].

As seen in Table 3, carbon-based nanomaterials such as CNTs and graphene provide a more significant improvement in flexural strength and toughness, while metal oxide nanoparticles are more effective in the increasing compressive strength. This is consistent with the dominant mechanism of each additive type [21, 74, 75].

5.3. Long-Term Durability Performance

The dense and finely porous microstructure of nanocomposite geopolymers also provides significant advantages in terms of durability [76]. The service life of building materials exposed to aggressive environmental conditions is determined by the transport rate of water and harmful ions (Cl^-, SO_4^{2-}) into the material [77].

Freeze-Thaw Resistance: Water within pores expands during freezing, creating hydrostatic pressure and causing internal cracks. Nanoadditives disrupt the interconnected pore network by filling the pores [78]. This reduces the amount of space available to water and the resulting pressure. Experiments have reported that geopolymers containing 2% nano-SiO_2 exhibit significantly lower loss in dynamic modulus of elasticity compared to reference samples [78].

Table 3 Effect of different nanoadditives on mechanical strength in geopolymers [21, 82, 83].

Material	Optimal Dosage (wt%)	Compressive Strength Increase (%)	Flexural Strength Increase (%)	Primary Mechanism of Action
Nano-SiO_2	1.0 - 3.0	15 - 40	10 - 25	Pozzolanic activity, microstructure densification, pore filling
Nano-Al_2O_3	1.0 - 2.0	10 - 30	5 - 20	Interfacial hardening, nucleation
CNT	0.1 - 0.8	10 - 25	20 - 60	Crack bridging, load transfer, fibre reinforcement
Graphene/GO	0.1 - 0.8	15 - 35	25 - 80	Crack bridging, load transfer, and interface modification
Nano-TiO_2	1.0 - 4.0	5 - 20	5 - 15	Filling, nucleation (photocatalytic properties are secondary)

Sulfate Resistance: Sulfate ions can react with calcium or aluminium in the geopolymer matrix, leading to the formation of secondary phases such as ettringite or thaluminite, which cause expansion. The low permeability provided by nanoadditives delays or prevents sulfate ions from seeping in and reaching the reaction sites [76]. Furthermore, a denser and stronger matrix structure results in better resistance to these expansion stresses [76].

Acid Resistance: Geopolymers generally have better acid resistance than Portland cement, but acids can still disrupt the Si-O-Al and Si-O-Si bonds, which are the main network-building blocks. Nanoadditives enhance this resistance in two ways: (1) by physically limiting internal penetration of the acid solution and (2) by increasing the stability and amount of the N-A-S-H gel phase [57].

Nano-SiO_2, in particular, helps replace silica units that are detached from the network during acid exposure, slowing surface degradation [57]. By strengthening the microstructural integrity of geopolymers, nanoadditives radically improve not only mechanical strength but also long-term durability against aggressive environmental agents. This makes them ideal materials not only for high-performance structures but also for harsh conditions such as waste immobilisation, marine structures, and aggressive industrial environments [76, 77].

6. Functional Features and New Applications

The truly revolutionary aspect of nanocomposite geopolymers is that they go beyond improving structural performance to imparting intelligent and multifunctional properties. Functional additives such as carbon-based nanomaterials, magnetic nanoparticles, and photocatalytic oxides hold the potential to transform geopolymers from passive structural elements into active systems that interact with the environment, store energy, or collect data.

6.1. Electrical Conductivity and Piezoresistive Sensors

The geopolymer matrix is inherently insulating. However, by uniformly dispersing conductive nanoadditives, an interconnected conductive network can be created within the matrix [66]. These conductive composites exhibit a measurable change in electrical resistance when subjected to mechanical load, resulting from changes in the distance and contact points between the nanoadditives [66]. The resulting structure is called piezoresistivity, and this property forms the basis of self-sensing materials for structural health monitoring.

Mechanism: When a load is applied to a composite, microcracks form or existing cracks widen. This causes the conductive nanofillers to separate from each other, thus increasing the electrical resistance [79]. The change in resistance is directly related to the strain or damage level to which the material is exposed [66].

Applications: Piezoresistive geopolymer composites can be used to continuously monitor critical infrastructure such as bridges, buildings, and tunnels for stress, crack formation, and overload [66]. By connecting electrodes to elements made from these materials, real-time data on the structure's condition can be obtained through a simple electrical measurement [79]. Figure 8 shows a schematic diagram illustrating the piezoresistive mechanism and the formation of the conductive network.

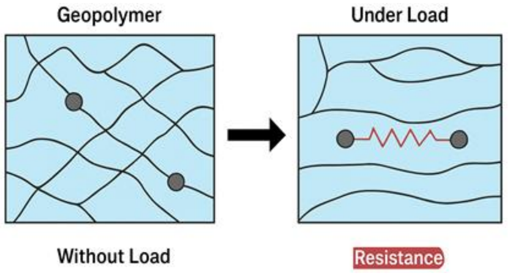

Figure 8 Piezoresistive mechanism and conductive network formation

Literature Findings: Krishna et al. reported a significant increase in the electrical conductivity of fly ash-based geopolymers with 0.4 wt% GO addition and showed that these composites exhibit piezoresistive behaviour [66]. Similarly, reproducible changes in resistance at the 5-10% level were measured in CNT-added geopolymers under compressive loading [80].

6.2. Magnetic Properties and Electromagnetic Wave Attenuation

The incorporation of magnetic nanoparticles (Fe_3O_4, γ-Fe_2O_3, ferrites) into the geopolymer matrix imparts controlled magnetic properties to the composite [81]. Such materials are ideal for magnetic separation, magnetic data storage and especially electromagnetic interference (EMI) shielding applications [19].

EMI Attenuation Mechanism: EMI shielding effectiveness depends on the material's ability to absorb and reflect. Magnetic nanoparticles absorb the energy of incident electromagnetic waves by converting it into heat [82]. At the same time, conductive nanofiller added to the geopolymer matrix reflects the waves [81]. Thus, they act by attenuating through multiple reflections. Hybrid systems exhibit synergistic EMI shielding performance by combining absorption and reflection mechanisms [19].

Applications: They are used to prevent unwanted electromagnetic interactions between electronic devices [83]. Lightweight, fire-resistant, and highly corrosion-resistant geopolymer coatings can provide a superior alternative to traditional polymeric shields in areas requiring critical EMI protection, such as military communication systems, hospitals, and data centres [19]. Figure 9 schematically shows the EMI Shielding Mechanism in Geopolymer Composites.

6.3. Photocatalytic Activity and Environmental Applications

Geopolymers enhanced with photocatalytic materials such as nano-TiO_2 (titanium dioxide) can be used for environmental cleansing by activating under UV or visible light [84]. These composites can serve self-cleaning and air purification functions when used as building exterior cladding, paving stones, or roofing materials [85]. Mechanism: On the photocatalyst surface, stimulated by light energy, water and oxygen molecules are converted into highly reactive radicals such as OH. These radicals break down organic soils and air pollutants that come into contact with the surface into harmless compounds [86].

Applications:

NOx Removal: Nitrogen oxides (NOx) from vehicle emissions can be degraded by photocatalytic geopolymer coatings. They can be used on military fronts or as sound barriers, contributing to the improvement of urban air quality [86].

Wastewater Treatment: Photocatalytic geopolymers can be used as reactor fillers or membrane supports for the treatment of organic dyes and toxic compounds in industrial wastewater. Their high chemical stability provides a long-lasting and efficient photocatalytic system [87].

Case Study: Rommozzi et al. investigated the degradation efficiency of methylene blue dye by GO/TiO_2 hybrid-doped geopolymers and reported a synergistic increase in photocatalytic activity [88].

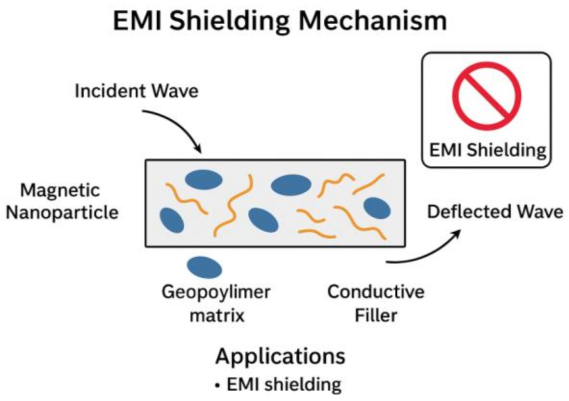

Figure 9 EMI Shielding Mechanism in Geopolymer Composites

6.4. Radiation Shielding

Geopolymers containing high atomic number elements have great potential as shielding materials in high-radiation environments such as nuclear power plants, medical radiology departments, and spacecraft [89]. The addition of these nano-sized materials (nano-Bi_2O_3, nano-WO_3, nano-B_4C) to the geopolymer matrix allows for the production of lighter, more mechanically robust, and more workable shields compared to traditional lead sheets or heavy concrete [83].

Mechanism: The ability to attenuate radiation depends on the density of the material and the atomic number of the elements it contains [89]. Nanodopants provide a more efficient means of absorbing X- and gamma rays by homogeneously dispersing high-Z elements within the geopolymer matrix [90]. Boron-containing nanodopants are effective for neutron absorption [91].

Applications: They can be used as shielding materials for cosmic radiation protection in the construction of radiotherapy rooms, nuclear waste storage containers, and spacecraft [89, 92].

6.5. Energy Storage

The high thermal stability, porous structure and tunable chemistry of geopolymers make them promising support materials for supercapacitor and battery electrodes [93]. In particular, geopolymers modified with conductive carbon nanomaterials (graphene, CNT) or metal oxides (MnO_2, RuO_2) increase the energy storage capacity by offering high surface area and ionic conductivity [94].

Mechanism: The three-dimensional porous network of the geopolymer allows electrolyte ions to easily penetrate and be stored [94]. Conductive nanoadditives increase the electrical conductivity of the composite, reducing charge transfer resistance and thus providing high power density [95].

Applications: They can be used as electrode materials for solid-state supercapacitors and batteries [93]. Geopolymer electrolytes are also under research. They have the potential to be integrated into walls or floors of buildings that can store their own energy [93, 94].

Nanocomposite geopolymers are redefining the boundaries of engineering materials. These multifunctional materials, which can serve not only as structural components but also as intelligent systems that monitor, clean, store energy, and communicate with the environment, have the potential to form the basis of sustainable and future-proof construction, energy, and environmental technologies.

6.6. Advanced Nano scale Design Strategies and Multi scale Modelling Approaches

Recent research trends indicate that the next major leap in nanocomposite geopolymer development will come from the integration of advanced nanoscale design methodologies and multiscale computational modeling. While traditional experimental approaches have successfully revealed the macroscopic benefits of nano-reinforcement, recent studies demonstrate that optimizing the nanoparticle–gel interface, tailoring surface chemistry, and predicting gel network evolution require hybrid experimental–computational frameworks. Molecular dynamics (MD) simulations, for example, have enabled the visualization of nanoparticle-induced gel densification and the rearrangement of Si–O–Al bonds at sub-nanometer resolution, providing insight into how nucleation mechanisms influence long-term performance [96]. Similarly, density functional theory (DFT)–based calculations have contributed to understanding charge transfer, bond energy distribution, and interfacial adhesion between carbon-based nanomaterials and N-A-S-H gels, directly supporting the design of next-generation functional additives [22].

At the mesoscale level, phase-field modeling and finite element simulations are increasingly being used to predict crack initiation, stress redistribution, and load-transfer mechanisms in CNT- and graphene-reinforced matrices. These predictive tools allow the optimization of nanoadditive geometry, aspect ratio, and concentration without excessive trial-and-error in laboratory conditions [16]. In parallel, recent machine-learning frameworks trained on large datasets of mix design parameters and microstructural outputs have shown promising ability to forecast mechanical and durability performance with high accuracy, suggesting that data-driven design will become a key component of future geopolymer optimization strategies [41].

Collectively, these advances highlight a paradigm shift in which nanocomposite geopolymer design moves from purely empirical formulations to a computational–experimental co-design philosophy. This approach is expected to accelerate the development of highly tailored, multi-functional, and application-specific geopolymer systems while significantly reducing development costs and environmental impact.

7. Challenges and Future Perspectives

Although nanocomposite geopolymers offer significant advantages over traditional building materials, such as superior mechanical properties, increased durability, and multifunctionality, significant technical and economic challenges remain in their transition from laboratory scale to industrial applications and commercial maturity [19]. This chapter systematically addresses the main barriers to nanocomposite geopolymer technology and presents future research directions and perspectives to overcome these challenges.

Homogeneous Distribution of Additives and Agglomeration Problem

The performance of nanocomposite geopolymers depends largely on the homogeneous distribution of nanoscale additives within the matrix and the establishment of optimum interfacial interactions without forming agglomerates [19].

Table 4 Summary of Functional Applications of Nanocomposite Geopolymers

Functional Property	Used Nanomaterials	Working Mechanism	Potential Application Areas
Piezoresistivity	CNT, Graphene, GO, MXene	Strain-induced resistance change in the conductive network under load	Structural Health Monitoring (SHM), damage detection
EMI Shielding	CNT, Graphene, MXene, Fe_3O_4	Absorption and reflection of electromagnetic waves	Military electronics, hospitals, data centres
Photocatalytic Activity	Nano-TiO_2, Nano-ZnO, GO/TiO_2	Light activation, generation of reactive oxygen species, degradation of organic matter	Self-cleaning facades, air purification, wastewater treatment
Radiation Shielding	Nano-Bi_2O_3, Nano-WO_3, Nano-B_4C	Photon absorption by high-Z elements, neutron capture by boron	Radiotherapy rooms, nuclear waste containers, spacecraft
Energy Storage	Graphene, CNT, MnO_2	Ion adsorption in porous structures, charge transfer in conductive networks	Supercapacitor electrodes, battery support materials

Carbon nanotubes, graphene, and many metal oxide nanoparticles tend to agglomerate due to their high surface energy and van der Waals forces [19]. These agglomerates not only reduce the mechanical strength of the composite by creating weak bonding sites but also provide stress concentration points for crack initiation. Furthermore, agglomeration in conductive nanoadditives negatively affects functional properties by preventing the formation of a continuous conductive network [19]. Current dispersion methods are energy-intensive and may be inadequate, especially for high-viscosity geopolymer resins [97].

Scalable Manufacturing and Industrial Adaptability

While it is possible to produce consistent and high-performance samples at the gram/kg level at the laboratory scale, scaling these processes up to the industrial scale at the ton level is a major engineering challenge [46]. The main challenges can be listed as ensuring homogeneous distribution of nanoadmixtures in large volumes, preparing and transporting alkali activator solutions safely and efficiently, controlling the workability of the nanocomposite geopolymer mixture, and minimising energy costs for systems requiring heat treatment [46]. Existing concrete plants and mixing equipment may not be sufficient for precise dosing and distribution of nanoadmixtures [46]. In the future, the development of modular and automated admixture dosing systems, prioritising high-performance geopolymer formulations that cure at room temperature, and creating artificial intelligence-based mixing/curing recipes to improve process control will increase industrial adaptability [97].

Life Cycle Analysis (LCA) and Cost Assessment

Although geopolymers are often touted as “green materials,” the environmental sustainability of their nanocomposite versions requires a comprehensive Life Cycle Assessment (LCA) [19]. The analysis should cover the entire process from raw material acquisition (synthesis of nanoadditives) to final product disposal. The synthesis of nanoadditives, particularly carbon nanotubes and graphene, can involve high energy consumption and complex chemical processes, which can increase the overall carbon footprint of the material [19]. Furthermore, the environmental cost of producing alkali activators should be included in the LCA [19]. From an economic perspective, the high cost of nanoadditives can make nanocomposite geopolymers expensive compared to conventional concrete [19]. Therefore, future research should focus on optimising the performance-benefit/cost ratio, obtaining low-cost nanomaterials from industrial byproducts, and developing new chemistries that minimise activator concentration [97].

Lack of Standardisation (Test Methods, Codes)

One of the major obstacles to the commercialisation of nanocomposite geopolymers is the lack of comprehensive standards and design codes to characterise material properties and ensure their performance [19]. ASTM or EN standards used for conventional concrete may not always be suitable for the diverse chemistry of geopolymers and the unique behaviour of nanocomposites [19]. For example, standard protocols for mix design, curing conditions, long-term behaviour (shrinkage, creep), durability testing, and assessment of nanoadditive release risks are urgently needed [97]. This lack of standardisation undermines the confidence of engineers and designers in these materials and slows their acceptance in the construction industry [97]. A table summarising recommended testing and characterisation protocols for different types of nanoadditives would be useful to highlight this need for standardisation.

8. Conclusion and General Evaluation

This comprehensive review demonstrates the transformative role of nanocomposite geopolymers in materials science and construction technology. The study clearly demonstrates that these advanced materials not only offer a sustainable alternative to Portland cement but also expand the scope of engineering applications by exhibiting multifunctionality and intelligent behaviour.

Essentially, the amorphous or semi-crystalline N-A-S-H/C-A-S-H gel structure formed by alkali activation of the geopolymer matrix provides an ideal platform for nanoscale additives. Studies confirm that the interaction of nanoadditives (such as carbon-based nanomaterials, metal oxide nanoparticles, nanoclays, and MXenes) with the geopolymer matrix proceeds through three primary mechanisms: (i) nucleation, which accelerates the polycondensation reaction and densifies the microstructure; (ii) reinforcement and interfacial interaction, which inhibits crack propagation and improves load transfer; and (iii) physical filling, which reduces permeability by filling pores. The synergistic effect of these mechanisms significantly increases the material's mechanical strength and toughness, while also enhancing durability properties such as freeze-thaw, sulfate, and acid resistance.

However, the most striking finding of this review is the potential of nanocomposite geopolymers to transcend their role as mere structural components. The integration of functional nanoadditives has endowed these materials with novel and intelligent functions, such as electrical conductivity and piezoresistive properties, superior EMI shielding, photocatalytic activity, radiation attenuation, and even energy storage. This is poised to make them indispensable in a wide range of applications, from construction and electronics to environmental technologies, defence, and energy.

However, critical obstacles remain before this remarkable potential can be fully realised from the laboratory to industrial scale and commercial applications. The homogeneous distribution and agglomeration of nanoadditives stand out as the biggest technical challenge to material performance. The development of scalable, economical, and safe production processes is a primary requirement for industrial adoption. Furthermore, for nanocomposite geopolymers to be truly "green," comprehensive Life Cycle Assessments (LCA) covering the entire process, from nanoadditive synthesis to final product disposal, must be conducted to clarify the environmental cost-benefit balance of these materials. Finally, to establish material confidence and ensure widespread industry acceptance, guidelines and design codes that standardise mixture design, test methods, and performance criteria are urgently needed.

Future perspectives necessitate an interdisciplinary approach to address these challenges. Innovative research directions such as smart and self-healing geopolymers, hybrid functional systems, and advanced inks suitable for 3D printing are broadening the material landscape. Using predictive models based on artificial intelligence and machine learning to support experimental studies can accelerate optimal blend design and minimise trial-and-error processes.

Nanocomposite geopolymers have the greatest potential to address the sustainable and smart infrastructure needs of the 21st century. With their waste management, low carbon footprint, and superior performance, these materials could become cornerstones of the circular economy. Building on current research, strong collaborations between academia, industry, and standards organisations will transform nanocomposite geopolymers from a laboratory curiosity into a key technology shaping the construction, energy, and environmental technologies of the future. This transition will not only be a technical achievement but also a critical step toward a more sustainable and smarter world.

Future Research Directions

To push the boundaries of nanocomposite geopolymer technology, future research should focus on the following innovative directions:

Smart and Self-Healing Geopolymers: Developing geopolymer composites that take piezoresistive properties a step further, not only detecting damage but also automatically repairing microfissures. Furthermore, studies on shape-memory and self-tuning smart materials that respond to temperature, humidity, or chemical exposure are promising [19].

Hybrid Functional Systems: The synergistic effects of multiple nanoadditives need to be investigated so that a single material can simultaneously fulfil multiple functions. For example, an integrated wall panel that monitors structural health (CNTs), purifies the air (nano-TiO_2), and provides EMI shielding could be developed [19].

3D Printing-Adaptable Nanocomposites: Additive manufacturing (3D printing) has the potential to revolutionise the construction industry. A critical area of research is the development of geopolymer inks whose rheological properties (flowability, viscosity, and green strength) are optimised with nanoadditives, allowing for high-resolution printing and enhancing post-printing structural integrity [98].

Advanced Characterisation and Computational Design: The use of in-situ characterisation techniques is vital for understanding structure-property relationships at the nanoscale. This experimental data, fed by machine learning and artificial intelligence, can lead to the development of predictive models that will enable in-silico design of nanocomposite geopolymers with desired properties [98].

Nanocomposite geopolymers hold a bright future at the intersection of materials science and civil engineering. Current challenges can be overcome through an interdisciplinary approach, industry-academia collaboration, and investment in innovative ideas. By overcoming these hurdles, these materials will offer a sustainable and multifunctional solution with the potential to transform not only the construction industry but also the energy, environmental, and advanced technology fields [19, 46].

Conflict of Interest

The authors have no conflicts of interest to declare.

References

[1] Scrivener KL, John VM, Gartner EM. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cement and Concrete Research* (2018) **114**:2–26. doi:10.1016/j.cemconres.2018.03.015.

[2] Davidovits J. Geopolymers. *Journal of Thermal Analysis* (1991) **37**(8):1633–1656. doi:10.1007/BF01912193.

[3] Davidovits J. *Geopolymer Chemistry and Applications* (2008).

[4] Duxson P, Fernández-Jiménez A, Provis JL, Lukey GC, Palomo A, van Deventer JSJ. Geopolymer technology: the current state of the art. *Journal of Materials Science* (2007) **42**(9):2917–2933. doi:10.1007/s10853-006-0637-z.

[5] Fernández-Jiménez A, Palomo A. Composition and microstructure of alkali activated fly ash binder: Effect of the activator. *Cement and Concrete Research* (2005) **35**(10):1984–1992. doi:10.1016/j.cemconres.2005.03.003.

[6] Provis JL. Alkali-activated materials. *Cement and Concrete Research* (2018) **114**:40–48. doi:10.1016/j.cemconres.2017.02.009.

[7] Rickard WD, Temuujin J, van Riessen A. Thermal analysis of geopolymer pastes synthesised from five fly ashes of variable composition. *Journal of Non-Crystalline Solids* (2012) **358**(15):1830–1839. doi:10.1016/j.jnoncrysol.2012.05.032.

[8] McLellan BC, Williams RP, Lay J, van Riessen A, Corder GD. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of Cleaner Production* (2011) **19**(9-10):1080–1090. doi:10.1016/j.jclepro.2011.02.010.

[9] Allahverdi A, Škvára F. Nitric acid attack on hardened paste of geopolymeric cements. *Ceramics - Silikaty* (2001) **45**(4):143–149.

[10] Adewuyi YG. Recent Advances in Fly-Ash-Based Geopolymers: Potential on the Utilization for Sustainable Environmental Remediation. *ACS Omega* (2021) **6**(24):15532–15542. doi:10.1021/acsomega.1c00662.

[11] Houhou M, Leklou N, Ranaivomanana H, Penot J, Barros S de. Geopolymers in nuclear waste storage and immobilization: mechanisms, applications, and challenges. *Discover Applied Sciences* (2025) **7**(2):126. doi:10.1007/s42452-025-06536-x.

[12] Lyon RE, Balaguru PN, Foden A, Sorathia U, Davidovits J, Davidovics M. Fire-resistant Aluminosilicate Composites. *Fire and Materials* (1997) **21**(2):67–73. doi:10.1002/(SICI)1099-1018(199703)21:2<67:AID-FAM596>3.0.CO;2-N.

[13] Provis JL, Bernal SA. Geopolymers and Related Alkali-Activated Materials. *Annual Review of Materials Research* (2014) **44**(1):299–327. doi:10.1146/annurev-matsci-070813-113515.

[14] Duxson P, Provis JL, Lukey GC, van Deventer JS. The role of inorganic polymer technology in the development of 'green concrete'. *Cement and Concrete Research* (2007) **37**(12):1590–1597. doi:10.1016/j.cemconres.2007.08.018.

[15] Singh B, Ishwarya G, Gupta M, Bhattacharyya SK. Geopolymer concrete: A review of some recent developments. *Construction and Building Materials* (2015) **85**:78–90. doi:10.1016/j.conbuildmat.2015.03.036.

[16] Li Z, Zhang J, Wang M. Structure, Reactivity, and Mechanical Properties of Sustainable Geopolymer Material: A Reactive Molecular Dynamics Study. *Frontiers in Materials* (2020) **7**. doi:10.3389/fmats.2020.00069.

[17] Siyal AA, Radin Mohamed, Radin Maya Saphira, Shamsuddin R, Ridzuan MB. A comprehensive review of synthesis kinetics and formation mechanism of geopolymers. *RSC Advances* (2024) **14**(1):446–462. doi:10.1039/D3RA06205H.

[18] Samuvel Raj R, Prince Arulraj G, Anand N, Kanagaraj B, Lubloy E, Naser MZ. Nanomaterials in geopolymer composites: A review. *Developments in the Built Environment* (2023) **13**:100114. doi:10.1016/j.dibe.2022.100114.

[19] Drabczyk A, Kudłacik-Kramarczyk S, Korniejenko K, Figiela B, Furtos G. Review of Geopolymer Nanocomposites: Novel Materials for Sustainable Development. *Materials* (2023) **16**(9):3478. doi:10.3390/ma16093478.

[20] Rahmawati C, Aprilia S, Saidi T, Aulia TB, Hadi AE. The Effects of Nanosilica on Mechanical Properties and Fracture Toughness of Geopolymer Cement. *Polymers* (2021) **13**(13):2178. doi:10.3390/polym13132178.

[21] Tay CH, Norkhairunnisa M. Mechanical Strength of Graphene Reinforced Geopolymer Nanocomposites: A Review. *Frontiers in Materials* (2021) **8**. doi:10.3389/fmats.2021.661013.

[22] Rathee M, Surendran HK, Thakur A, Narayana C, Lo R, Misra A, et al. Tailoring Functional Graphene-Derived Geopolymer Nanocomposites: Interfacial Interactions and Mechanical Strength Enhancement. *ACS Materials Au* (2025) **5**(4):698–708. doi:10.1021/acsmaterialsau.5c00028.

[23] Althoey F, Zaid O, Martínez-García R, Alsharari F, Ahmed M, Arbili MM. Impact of Nano-silica on the hydration, strength, durability, and microstructural properties of concrete: A state-of-the-art review. *Case Studies in Construction Materials* (2023) **18**:e01997. doi:10.1016/j.cscm.2023.e01997.

[24] Luhar I, Luhar S. A Comprehensive Review on Fly Ash-Based Geopolymer. *Journal of Composites Science* (2022) **6**(8):219. doi:10.3390/jcs6080219.

[25] Alipoor M, Eshghi M, Sever R. Monte Carlo Simulation of Gamma and Neutron Shielding with High-performance Ultra-heavy Cement Composite. *Journal of Medical Physics* (2024) **49**(4):661–672. doi:10.4103/jmp.jmp_91_24.

[26] Al-Buriahi MS, Yılmaz E, Alzahrani JS, Çalışkan F, Alzahrani HS, Alshahrani B, et al. Effects of Bi2O3 and Y2O3 addition on metakaolin-based geopolymers: physical-microstructure properties and shielding performance against ionizing radiation. *Ceramics International* (2026) **52**(1):942–951. doi:10.1016/j.ceramint.2025.11.393.

[27] Cong P, Du R, Gao H, Chen Z. Comparison and assessment of carbon dioxide emissions between alkali-activated materials and OPC cement concrete. *Journal of Traffic and Transportation Engineering (English Edition)* (2024) **11**(5):918–938. doi:10.1016/j.jtte.2023.07.011.

[28] Khasawneh MA. Geopolymer concrete in construction projects: a review. *Discover Civil Engineering* (2025) **2**(1):124. doi:10.1007/s44290-025-00281-1.

[29] Mohan Kumar, Sri Ganesh Kumar, Kinuthia JM, Oti J, Adeleke BO. Geopolymer Chemistry and Composition: A Comprehensive Review of Synthesis, Reaction Mechanisms, and Material Properties—Oriented with Sustainable Construction. *Materials* (2025) **18**(16):3823. doi:10.3390/ma18163823.

[30] Ponomar V, Luukkonen T, Yliniemi J. Revisiting alkali-activated and sodium silicate-based materials in the early works of Glukhovsky. *Construction and Building Materials* (2023) **398**:132474. doi:10.1016/j.conbuildmat.2023.132474.

[31] Xu X, Bao S, Guo Z, Tian X. A clean approach to high-strength fly ash-based geopolymers: Multi-granular screening with NaAlO2 enhancement. *Journal of Cleaner Production* (2024) **464**:142733. doi:10.1016/j.jclepro.2024.142733.

[32] Chen S, Ruan S, Zeng Q, Liu Y, Zhang M, Tian Y, et al. Pore structure of geopolymer materials and its correlations to engineering properties: A review. *Construction and Building Materials* (2022) **328**:127064. doi:10.1016/j.conbuildmat.2022.127064.

[33] Chuewangkam N, Kidkhunthod P, Pinitsoontorn S. Direct evidence for the mechanism of early-stage geopolymerization process. *Case Studies in Construction Materials* (2024) **21**:e03539. doi:10.1016/j.cscm.2024.e03539.

[34] El Alouani M, Saufi H, Aouan B, Bassam R, Alehyen S, Rachdi Y, et al. A comprehensive review of synthesis, characterization, and applications of aluminosilicate materials-based geopolymers. *Environmental Advances* (2024) **16**:100524. doi:10.1016/j.envadv.2024.100524.

[35] Andrew RM. Global CO 2 emissions from cement production. *Earth System Science Data* (2018) **10**(1):195–217. doi:10.5194/essd-10-195-2018.

[36] Provis JL. Geopolymers and other alkali activated materials: why, how, and what? *Materials and Structures* (2014) **47**(1-2):11–25. doi:10.1617/s11527-013-0211-5.

[37] Verma M, Meena RK, Singh I, Gupta N, Saxena KK, Reddy MM, et al. Investigation on the impact of elevated temperature on sustainable geopolymer composite. *Advances in Mechanical Engineering* (2023) **15**(9). doi:10.1177/16878132231196402.

[38] Habert G, d'Espinose de Lacaillerie JB, Roussel N. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of Cleaner Production* (2011) **19**(11):1229–1238. doi:10.1016/j.jclepro.2011.03.012.

[39] Salas DA, Ramirez AD, Ulloa N, Baykara H, Boero AJ. Life cycle assessment of geopolymer concrete. *Construction and Building Materials* (2018) **190**:170–177. doi:10.1016/j.conbuildmat.2018.09.123.

[40] Zhuang XY, Chen L, Komarneni S, Zhou CH, Tong DS, Yang HM, et al. Fly ash-based geopolymer: clean production, properties and applications. *Journal of Cleaner Production* (2016) **125**:253–267. doi:10.1016/j.jclepro.2016.03.019.

[41] Tian Q, Pan Y, Bai Y, Yao S, Sun S. A Bibliometric Analysis of Research Progress and Trends on Fly Ash-Based Geopolymer. *Materials* (2022) **15**(14):4777. doi:10.3390/ma15144777.

[42] Steinerova M, Matulova L, Vermach P, Kotas J. The Brittleness and Chemical Stability of Optimized Geopolymer Composites. *Materials* (2017) **10**(4):396. doi:10.3390/ma10040396.

[43] Trindade ACC, Heravi AA, Curosu I, Liebscher M, Andrade Silva F de, Mechtcherine V. Tensile behavior of strain-hardening geopolymer composites (SHGC) under impact loading. *Cement and Concrete Composites* (2020) **113**:103703. doi:10.1016/j.cemconcomp.2020.103703.

[44] Shilar FA, Ganachari SV, Patil VB, Khan TMY, Almakayeel NM, Alghamdi S. Review on the Relationship between Nano Modifications of Geopolymer Concrete and Their Structural Characteristics. *Polymers* (2022) **14**(7):1421. doi:10.3390/polym14071421.

[45] Paruthi S, Rahman I, Husain A, Hasan MA, Khan AH. Effects of Chemicals Exposure on the Durability of Geopolymer Concrete Incorporated with Silica Fumes and Nano-Sized Silica at Varying Curing Temperatures. *Materials* (2023) **16**(18):6332. doi:10.3390/ma16186332.

[46] Kishore K, Pandey A, Wagri NK, Saxena A, Patel J, Al-Fakih A. Technological challenges in nanoparticle-modified geopolymer concrete: A comprehensive review on nanomaterial dispersion, characterization techniques and its mechanical properties. *Case Studies in Construction Materials* (2023) **19**:e02265. doi:10.1016/j.cscm.2023.e02265.

[47] Jin Q, Zhang P, Wu J, Sha D. Mechanical Properties of Nano-SiO2 Reinforced Geopolymer Concrete under the Coupling Effect of a Wet–Thermal and Chloride Salt Environment. *Polymers* (2022) **14**(11):2298. doi:10.3390/polym14112298.

[48] Rani JJ, Gladston H. Study on durability of fly ash geo-polymer concrete with nano alumina. *Matéria (Rio de Janeiro)* (2024) **29**(4). doi:10.1590/1517-7076-rmat-2024-0412.

[49] Górski M, Czulkin P, Wielgus N, Boncel S, Kuziel AW, Kolanowska A, et al. Electrical Properties of the Carbon Nanotube-Reinforced Geopolymer Studied by Impedance Spectroscopy. *Materials* (2022) **15**(10):3543. doi:10.3390/ma15103543.

[50] Kanagaraj B, Anand N, Lubloy E, Andrushia A D. Influence of Multi-walled Carbon Nanotube (MWCNT) on flexural behavior and microstructure characteristics of geopolymer concrete beams. *Case Studies in Construction Materials* (2024) **20**:e03317. doi:10.1016/j.cscm.2024.e03317.

[51] Saafi M, Andrew K, Tang PL, McGhon D, Taylor S, Rahman M, et al. Multifunctional properties of carbon nanotube/fly ash geopolymeric nanocomposites. *Construction and Building Materials* (2013) **49**:46–55. doi:10.1016/j.conbuildmat.2013.08.007.

[52] Yan S, He P, Jia D, Duan X, Yang Z, Wang S, et al. Effects of graphene oxide on the geopolymerization mechanism determined by quenching the reaction at intermediate states. *RSC Advances* (2017) **7**(22):13498–13508. doi:10.1039/C6RA26340B.

[53] Muhammad Rashid Naveed Umm e Habiba, Aqsa Nisar Muhammad Yousaf Raza Taseer. *IMPACT OF NANO-SILICA ON THE MECHANICAL BEHAVIOR OF GEOPOLYMER CONCRETE*: Zenodo (2025). doi:10.5281/zenodo.16719163.

[54] Nanthini M, Ganesan R, Jaganathan V. Nano-Silica integration for superior properties in potassium feldspar-based phosphoric acid activated geopolymers: A sustainable approach. *Turkish Journal of Engineering* (2025) **9**(2):211–221. doi:10.31127/tuje.1536718.

[55] Ambikakumari Sanalkumar KU, Yang E-H. Self-cleaning performance of nano-TiO2 modified metakaolin-based geopolymers. *Cement and Concrete Composites* (2021) **115**:103847. doi:10.1016/j.cemconcomp.2020.103847.

[56] Shi G, Cui B, Ong SK, Wang K. Magnetic fly-ash geopolymer for heavy metal removal in aqueous solutions. *Water Science & Technology* (2025) **91**(12):1330–1344. doi:10.2166/wst.2025.077.

[57] Chiranjeevi K, Abraham M, Rath B, Praveenkumar TR. Enhancing the properties of geopolymer concrete using nano-silica and microstructure assessment: a sustainable approach. *Scientific Reports* (2023) **13**(1):17302. doi:10.1038/s41598-023-44491-y.

[58] Vanitha N, Thanigaiselvan R, Manivannan M, Jeyalakshmi R, Megha SN, Kesavan M. Expounding the application of nano and micro silica as a complementary additive in metakaolin phosphate geopolymer for ceramic applications—micro and nanoscale structural investigation. *Journal of Materials Science: Materials in Engineering* (2024) **19**(1):32. doi:10.1186/s40712-024-00176-6.

[59] Assaedi H, Shaikh F, Low IM. Effect of nano-clay on mechanical and thermal properties of geopolymer. *Journal of Asian Ceramic Societies* (2016) **4**(1):19–28. doi:10.1016/j.jascer.2015.10.004.

[60] Jia X-T, Xing H-W, Cheng X-W, Zhang Z-H, Wang Q, Zhou J-Z, et al. Two-Dimensional Nanostructured Ti3C2Tx MXene for Ceramic Materials: Preparation and Applications. *Nanomaterials* (2025) **15**(3):204. doi:10.3390/nano15030204.

[61] Xu S, Zhao C, Li G, Shi Z, Liu B. In situ oxidized TiO 2 /MXene ultrafiltration membrane with photocatalytic self-cleaning and antibacterial properties. *RSC Advances* (2023) **13**(23):15843–15855. doi:10.1039/D3RA02230G.

[62] Dong B, Liu C, Shumuye ED, Zhang Y, Zhong H, Fang G. Effect of nano-silica on mechanical properties and microstructure of engineered geopolymer composites. *Cement and Concrete Composites* (2025) **156**:105849. doi:10.1016/j.cemconcomp.2024.105849.

[63] Nazarlou Z, Hosseini SF, Seyed Dorraji MS, Rasoulifard MH, Aydemir U. Ti 3 C 2 MXene/Polyaniline/Montmorillonite Nanostructures toward Solvent-Free Powder Coatings with Enhanced Corrosion Resistance and Mechanical Properties. *ACS Applied Nano Materials* (2023) **6**(10):8804–8818. doi:10.1021/acsanm.3c01214.

[64] Marsh A, Heath A, Patureau P, Evernden M, Walker P. Alkali activation behaviour of un-calcined montmorillonite and illite clay minerals. *Applied Clay Science* (2018) **166**:250–261. doi:10.1016/j.clay.2018.09.011.

[65] Wu D, Cao K, Chen K, Mao N. Interfacial characteristics and mechanical behavior of geopolymer stabilizers with clay mineral: A molecular dynamics study. *Applied Clay Science* (2024) **250**:107286. doi:10.1016/j.clay.2024.107286.

[66] Krishna RS, Saha S, Korniejenko K, Qureshi TS, Mustakim SM. Investigation of the Electrical Properties of Graphene-Reinforced Geopolymer Composites. In: *10th MATBUD'2023 Scientific-Technical Conference*. Basel Switzerland: MDPI (2023). p. 34.

[67] Li S, Shen P, Zhou H, Du S, Zhang Y, Yan J. Synergistic effects of CNTs/SiO 2 composite fillers on mechanical properties of cement composites. *RSC Advances* (2022) **12**(42):27253–27266. doi:10.1039/D2RA04127H.

[68] Štengl V, Bakardjieva S, Grygar TM, Bludská J, Kormunda M. TiO2-graphene oxide nanocomposite as advanced photocatalytic materials. *Chemistry Central Journal* (2013) **7**(1):41. doi:10.1186/1752-153X-7-41.

[69] Bajpai A, Carlotti S. The Effect of Hybridized Carbon Nanotubes, Silica Nanoparticles, and Core-Shell Rubber on Tensile, Fracture Mechanics and Electrical Properties of Epoxy Nanocomposites. *Nanomaterials* (2019) **9**(7):1057. doi:10.3390/nano9071057.

[70] Rommozzi E, Zannotti M, Giovannetti R, D'Amato CA, Ferraro S, Minicucci M, et al. Reduced Graphene Oxide/TiO2 Nanocomposite: From Synthesis to Characterization for Efficient Visible Light Photocatalytic Applications. *Catalysts* (2018) **8**(12):598. doi:10.3390/catal8120598.

[71] Zidi Z, Ltifi M, Ben Ayadi Z, El Mir L. Synthesis of nano-alumina and their effect on structure, mechanical and thermal properties of geopolymer. *Journal of Asian Ceramic Societies* (2019) **7**(4):524–535. doi:10.1080/21870764.2019.1676498.

[72] Han Q, Zhang P, Wu J, Jing Y, Zhang D, Zhang T. Comprehensive review of the properties of fly ash-based geopolymer with additive of nano-SiO 2. *Nanotechnology Reviews* (2022) **11**(1):1478–1498. doi:10.1515/ntrev-2022-0092.

[73] Gao K, Lin K-L, Wang D, Shiu H-S, Hwang C-L, Cheng T-W. Effects of Nano-SiO2 on Setting Time and Compressive Strength of Alkaliactivated Metakaolin-based Geopolymer. *The Open Civil Engineering Journal* (2013) **7**(1):84–92. doi:10.2174/1874149501307010084.

[74] Alvee AR, Malinda R, Akbar AM, Ashar RD, Rahmawati C, Alomayri T, et al. Experimental study of the mechanical properties and microstructure of geopolymer paste containing nano-silica from agricultural waste and crystalline admixtures. *Case Studies in Construction Materials* (2022) **16**:e00792. doi:10.1016/j.cscm.2021.e00792.

[75] Sekkal W, Zaoui A. Residual water and interfacial bonding effects on the mechanical performance of CNT /fly ash geopolymer binder. *Structural Concrete* (2024) **25**(5):3648–3661. doi:10.1002/suco.202301055.

[76] Zhang P, Shi B, Dai X, Chen C, Lai C. A State-of-the-Art Review on the Freeze–Thaw Resistance of Sustainable Geopolymer Gel Composites: Mechanisms, Determinants, and Models. *Gels* (2025) **11**(7):537. doi:10.3390/gels11070537.

[77] Paruthi S, Rahman I, Husain A, Khan AH, Manea-Saghin A-M, Sabi E. A comprehensive review of nano materials in geopolymer concrete: Impact on properties and performance. *Developments in the Built Environment* (2023) **16**:100287. doi:10.1016/j.dibe.2023.100287.

[78] Wan L, Zhao Y, Yu M, Tian Y, Wang Y. Durability and Mechanical Properties of Nano-SiO2 and Polyvinyl Alcohol Fiber-Reinforced Cementitious Composites Subjected to Saline Freeze–Thaw Cycles. *Materials* (2024) **17**(11):2542. doi:10.3390/ma17112542.

[79] Buasiri T, Habermehl-Cwirzen K, Krzeminski L, Cwirzen A. Role of Carbon Nanofiber on the Electrical Resistivity of Mortar under Compressive Load. *Transportation Research Record: Journal of the Transportation Research Board* (2021) **2675**(9):32–37. doi:10.1177/0361198120947417.

[80] Ahmadi H, Khalaj G, Najafi A, Abbasi SM, Safari M. Metakaolin-red mud/carbon nanotubes geopolymer nanocomposite: mechanical properties and structural studies. *Materials Research Express* (2022) **9**(2):25011. doi:10.1088/2053-1591/ac54d6.

[81] Lesbayev A, Akalim D, Kalauov B, Yerezhep D. An Investigation into Fe3O4 Nanoparticle-Based Composites for Enhanced Electromagnetic Radiation Shielding. *Journal of Composites Science* (2025) **9**(5):226. doi:10.3390/jcs9050226.

[82] Sharma R, Clower W, Amritphale S, Alam S, Matthews J, Radadia AD. Development of geopolymer composites for EMI shielding from steel industry waste. *Journal of Materials Science: Materials in Electronics* (2022) **33**(8):4847–4861. doi:10.1007/s10854-021-07674-9.

[83] Sharma R, Hussain S, Seetala N, Matthews J, Edwards R, Amritphale S, et al. Simultaneous use of bismuth trioxide and mill scale for ternary blended geopolymer composite in radiation shielding applications. *Progress in Nuclear Energy* (2024) **172**:105213. doi:10.1016/j.pnucene.2024.105213.

[84] Jaramillo-Fierro X, Gaona S, Ramón J, Valarezo E. Porous Geopolymer/ZnTiO3/TiO2 Composite for Adsorption and Photocatalytic Degradation of Methylene Blue Dye. *Polymers* (2023) **15**(12):2697. doi:10.3390/polym15122697.

[85] Ahmed DA, Aly AA, El-Apasery MA. Sustainable construction: development of self-cleaning geopolymer composite with fly ash, and bentonite incorporated with nano-ZnO. *Sustainable Environment Research* (2025) **35**(1):20. doi:10.1186/s42834-025-00256-y.

[86] Ma H, Li Y, Wang C, Li Y, Zhang X. TiO2-Based Photocatalysts for Removal of Low-Concentration NOx Contamination. *Catalysts* (2025) **15**(2):103. doi:10.3390/catal15020103.

[87] Peturai P, Sanguanpak S, Chiemchaisri C, Chiemchaisri W, Lu MC. Photocatalytic removals of imidacloprid insecticide in TiO2- and Fe2O3-immobilized porous geopolymer granules. *Chemosphere* (2024) **362**:142940. doi:10.1016/j.chemosphere.2024.142940.

[88] Jaramillo-Fierro X, Cuenca G. Enhancing Methylene Blue Removal through Adsorption and Photocatalysis—A Study on the GO/ZnTiO3/TiO2 Composite. *International Journal of Molecular Sciences* (2024) **25**(8):4367. doi:10.3390/ijms25084367.

[89] Al-Buriahi MS, Alzahrani JS, Owoeye SS, Yılmaz E, Çalıskan F. Fabrication, physical properties and radiation shielding performance of geopolymers reinforced by B2O3: Eco-friendly building material. *Radiation Physics and Chemistry* (2025) **237**:112982. doi:10.1016/j.radphyschem.2025.112982.

[90] Mokhtari Dorostkar M, Abdi Saray A. Development of PMMA based polymer composite incorporating WO3 for gamma radiation shielding using synthesis and Monte Carlo simulation. *Scientific Reports* (2025) **15**(1):27346. doi:10.1038/s41598-025-11155-y.

[91] Alomayrah N, Alrowaili ZA, Alalawi A, Al-Buriahi MS. Gamma and neutron attenuation of ASM geopolymers for radiation shielding applications: Theoretical study. *Journal of Radiation Research and Applied Sciences* (2024) **17**(2):100876. doi:10.1016/j.jrras.2024.100876.

[92] Maestre CV, Santos GN. Effect of bismuth oxide nanoparticle on the electromagnetic interference shielding and thermal stability of industrial waste based-geopolymer composites. *Scientific Reports* (2023) **13**(1):1787. doi:10.1038/s41598-023-27623-2.

[93] Liu J-H, Yang J-L, Yang F, Feng J, Yuan X-Y, Zhou J, et al. A renewable bifunctional structural supercapacitor using the recycled geopolymer membrane and MnO2/CNTs electrode. *Journal of Energy Storage* (2024) **102**:114203. doi:10.1016/j.est.2024.114203.

[94] Jeon IK, Gan Y, Wei C, Kim Y-R, Wu C. Biochar-geopolymer composite for structural capacitors. *Materials Letters* (2024) **371**:136856. doi:10.1016/j.matlet.2024.136856.

[95] Pour GB, Ashourifar H, Aval LF, Solaymani S. CNTs-Supercapacitors: A Review of Electrode Nanocomposites Based on CNTs, Graphene, Metals, and Polymers. *Symmetry* (2023) **15**(6):1179. doi:10.3390/sym15061179.

[96] Hou D, Zhang J, Pan W, Zhang Y, Zhang Z. Nanoscale mechanism of ions immobilized by the geopolymer: A molecular dynamics study. *Journal of Nuclear Materials* (2020) **528**:151841. doi:10.1016/j.jnucmat.2019.151841.

[97] Balina K, Gailitis R, Sinka M, Argalis PP, Radina L, Sprince A. Prospective LCA for 3D-Printed Foamed Geopolymer Composites Using Construction Waste as Additives. *Sustainability* (2025) **17**(14):1–21.

[98] Krishna RS, Rehman AU, Mishra J, Saha S, Korniejenko K, Rehman RU, et al. Additive manufacturing of geopolymer composites for sustainable construction: critical factors, advancements, challenges, and future directions. *Progress in Additive Manufacturing* (2025) **10**(2):1003–1061. doi:10.1007/s40964-024-00703-z.