sustainability

Review

Geopolymer Cement in Pavement Applications: Bridging Sustainability and Performance

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Abstract: Sustainability and the quest for a more robust construction material cannot be divorced from each other. While Portland cement has revolutionized the construction sector, its environmental toll, particularly in greenhouse gas emissions and global warming, cannot be ignored. Addressing this dilemma requires embracing alternatives like geopolymer cement/geopolymer binder (GPC/GPB). Over the last few decades, considerable strides have been achieved in advancing GPC as a sustainable construction material, including its utilization in pavement construction. Despite these advances, gaps still exist in GPC optimal potential in pavement construction, as most studies have concentrated on specific attributes rather than on a comprehensive evaluation. To bridge this gap, this review adopts a novel, holistic approach by integrating environmental impacts with performance metrics. To set the stage, this review first delves into the geopolymer concept from a chemistry perspective, providing an essential broad overview for exploring GPC's innovations and implications in pavement applications. The findings reveal that GPC not only significantly reduces greenhouse gas emissions and energy consumption compared to Portland cement but also enhances pavement performance. Further, GPC concrete pavement exhibits superior mechanical, durability, and thermal properties to ensure its long-term performance in pavement applications. However, challenges to GPC utilization as a pavement material include the variability of raw materials, the need for suitable hardeners, the lack of standardized codes and procedures, cost competitiveness, and limited field data. Despite these challenges, the process of geopolymerization presents GPC as a sustainable material for pavement construction, aligning with Sustainable Development Goals (SDGs) 3, 9, 11, and 12.

Keywords: geopolymer cement; sustainability; environmental impact; performance metrics; pavement construction

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1. Introduction

The global call for the development of sustainable pavement construction materials such as geocement (also referred to as geopolymer cement (GPC) or geopolymer binder (GPB)) in recent years after a century or more of utilizing Portland cement has brought a significant transformation in the construction industry [1–3]. This development is attributed to the implementation of regulations that will reduce the incidence of the greenhouse effect (GHE) and global warming associated with anthropogenic CO_2 emissions coupled with improvement in the performance properties of cement products [1,2,4–7].

The global demand for GPC/GPB has been investigated and reported to increase geometrically in the Fourth Industrial Revolution (4IR), as revealed by the high number of tons of GPC/GPBs produced and marketed annually [1]. From the global geopolymer (GP) market perspective, USD 6.431 billion was estimated for 2019. The marketed GPC/GPBs were also statistically found to grow at a compound annual growth rate (CAGR) of 29.84%, with a forecast to attain a market size of USD 40.008 billion by 2026. The contributory factors to the CAGR include a rapid rise in construction activities in the present era [5], the sustainability and performance qualities of the geopolymer materials [3,8], the need for reduction of CO_2 emitted from conventional cement or binder materials in controlling global warming effects [2,3,6], rapid infrastructure developments [9], the role of geopolymer materials in waste management [10], and the recovery of construction and mining industries from the impact of COVID-19 pandemic [4,5,11].

From the environmental and industrial chemistry point of view, Portland cement production has been noticed as a significant source of CO_2 emissions globally from the combustion of carbonate materials (mainly $CaCO_3$ and $MgCO_3$) under intense heat in cement kilns at temperatures between 1200 and 1500 °C to yield the clinker (the intermediate nodular cement material or product) and as one of the significant contributors to global warming and climate change [12–14]. In a 5-year study (2015–2020), the emission of CO_2 from each ton of cement produced rises by 1.8% each year, making the cement industry release 4–10% of CO_2 emissions globally [7]. Other air pollutants associated with the cement production process include dust, oxides of nitrogen (as GHGs), and oxides of sulfur, which also need to be reduced alongside the reduction of CO_2 emissions. Figure 1 illustrates the CO_2 emission rates at various stages of ordinary Portland cement manufacturing. Quarrying contributes 7% of the emissions, while pyroprocessing is the most significant source, accounting for 85% due to the high-temperature kiln operations required to produce clinker. Grinding and transportation contribute 5% and 3%, respectively. These percentages highlight the energy-intensive nature of cement production and its substantial environmental impact, particularly during the pyroprocessing stage [14].

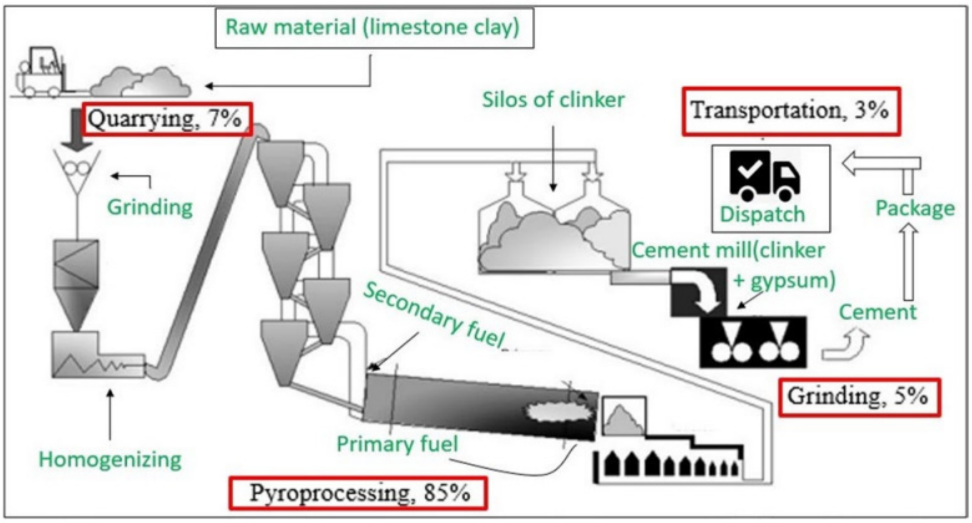


Figure 1. CO_2 emissions across different stages of Portland cement production [14].

Portland cement has been widely used in pavement engineering because of its stable strength and durability [15]. Cement-treated bases are a common choice for high-classified road pavements, offering improved performance and longevity [15]. The incorporation of cement in pavements has been linked to enhanced mechanical properties, making it suitable for various construction applications, including roads, airways, and embankments [15–18]. Research has demonstrated that adding cement as a stabilizing agent in pavement bases can significantly enhance pavement performance, particularly in fatigue cracking resistance [19,20]. Additionally, using cement-stabilized bases in flexible pavements has been a longstanding practice, showcasing the effectiveness of cement in enhancing pavement durability [21]. Furthermore, utilizing cement-treated bases has been shown to reduce construction costs while providing high strength compared to traditional methods [15].

In the realm of sustainable development, exploring alternative materials like fly ash and rice husk ash as partial substitutes for cement in pavement construction has been considered [15]. These efforts aim to reduce CO_2 emissions associated with cement production while maintaining adequate strength in pavement concrete mixes [22]. Additionally, research into developing heat-reflective pavements using cement-based materials has been conducted to mitigate urban heat island effects [23,24]. Building on these efforts to reduce the environmental impact of pavement construction, the construction industry has also begun exploring more radical sustainable alternatives, notably geopolymer cement (GPC) or geopolymer binder (GPB). The GPC, when it reacts with alkaline or acidic solutions, results in the formation of the so-called "Geopolymers", sometimes called "inorganic polymers", which Joseph Davidovits introduced. Geopolymers have superior performance properties compared to Portland cement concrete [25,26]. They offer a sustainable solution for various construction applications, including pavement construction. By integrating geopolymers into pavement design, the industry not only continues the trend of reducing its carbon footprint but also enhances the durability and thermal performance of pavements, thereby addressing broader environmental and urban sustainability development goals [27].

GPC has emerged as a promising alternative to traditional Portland cement, offering a sustainable solution for construction materials. Unlike conventional cement, which relies on the formation of calcium silicate hydrate (C-S-H), GPC, when treated with hardeners (acidic or alkaline solutions), undergoes polymerization to form a three-dimensional network structure called geopolymer [28]. This unique chemical reaction is akin to zeolite synthesis, highlighting the innovative nature of geopolymer technology. The introduction of GPC has paved the way for sustainable development practices in the construction industry [29]. By utilizing industrial byproducts like fly ash, mining tailings, quarry dust, and slag as geocement, geopolymer technology tends to reduce carbon emissions and environmental impacts [30]. Studies have shown that amorphous products from geopolymerization (geopolymer) exhibit superior mechanical properties and durability, making them suitable for various applications, including road base stabilization and pavement construction [31,32]. The reinforcement of geopolymer composites with reinforcement materials such as chopped bamboo fibers further underscores the innovative approaches toward sustainable construction materials [33].

Despite the growing research on geopolymers, significant gaps remain in our understanding of their full potential as pavement construction materials. Most studies have focused on specific aspects, such as the chemical composition or mechanical properties of geopolymer cement. However, more comprehensive evaluations comparing all relevant performance metrics of geopolymer cement (GPC) to those of Portland cement are needed. This review addresses this need by providing a thorough understanding of GPC as a sustainable alternative to Portland cement in pavement construction. This review first sets the stage by comprehensively introducing the geopolymer concept from a chemistry perspective. This broad overview is critical for exploring the science and innovation of geopolymer technology and its implications for pavement applications. By thoroughly examining geopolymers from a chemical standpoint, the paper ensures that readers gain a deep understanding of the material's properties and potential. These insights are crucial for informing the application of geopolymers in pavement construction, where knowledge of chemistry is central to practical implementation.

What further sets this review apart is its unique synthesis of current knowledge by integrating both the environmental impacts and performance metrics of GPC, which have often been examined separately. This holistic approach ensures a comprehensive evaluation of GPC's contributions to sustainability through reduced carbon emissions and energy use during production, alongside its enhanced properties such as durability and mechanical performance. Overall, through these contributions, this study not only advances the understanding of GPC but also promotes its broader application as a sustainable construction material. This aligns with global trends towards sustainable development and the circular economy in construction practices, positioning geopolymers as key components in developing eco-friendly and high-performance infrastructure solutions.

2. Methodology

In this review, the approach taken involves defining precise research goals and crafting efficient search strategies using key terms and Boolean logic (AND, OR, NOT). Select academic repositories including PubMed, IEEE Xplore, Scopus, and Google Scholar were methodically searched, with specific inclusion and exclusion parameters such as publication date, type of source, and pertinence. Preliminary examinations of titles and abstracts led to an in-depth evaluation of chosen papers. The results derived from these articles were then analyzed and presented in a well-organized narrative manner, ensuring accurate citations and acknowledgments.

3. Geopolymer Cement

Geopolymer cement (geocement) is an innovative and sustainable alternative to traditional Portland cement, offering a promising solution to reduce the environmental impact of construction materials [32]. Geocement, as depicted in Figure 2, is a composite binder produced by combining various industrial byproducts, natural sources, or both in appropriate ratios. The formulation considers crucial molar ratios, such as SiO_2/Al_2O_3, SiO_2/Fe_2O_3, and Al/Fe, to achieve optimal performance [26]. Based on the classification of aluminosilicate materials and their combination to produce geocement, three types of geocements exist. These include geocement formed from natural precursor materials, geocement derived from secondary materials, and geocement produced from a mixture of both.

Figure 2. Geocement and geosilicate (hardener) [20].

In the classification of aluminosilicate materials for geopolymer technology, true precursors are defined by their high content of alumina (Al_2O_3) and silica (SiO_2) in a reactive, amorphous form [19]. Examples of these primary precursors include natural minerals like pumice, mullite, zeolite, kaolinite, laterite, and montmorillonite, as well as industrial byproducts such as fly ash, blast furnace slag, fayalite slag, steel slag, mine tailings (copper, bauxite, tungsten, granite, gold, and hematite), palm oil fuel ash, red mud, and basalt [20,27]. These materials are essential for the geopolymerization process due to their composition, which enables the formation of geopolymers with excellent mechanical properties and durability [27]. Conversely, auxiliary components, which have often been misclassified as precursors, include materials like silica fumes, dolomite, quartz, feldspar, vermiculite, tourmaline, and agricultural byproducts such as coconut husk ash, corn cobs ash, and rice husk ash. While these materials may contain alumina and silica, they do so in quantities insufficient to be considered true precursors. Instead, they are critical in enhancing the final composite's mechanical strength, durability, and chemical resistance by acting as hardeners, silicate content adjusters, reinforcement agents, or inert aggregates within the geopolymer matrix [26]. This refined categorization is crucial for advancing geopolymer technology and developing high-performance, environmentally friendly construction materials.

When mixed with alkaline or acidic hardeners, a combination of aluminosilicate precursors (geocement) results in the synthesis of geopolymers, as depicted in Figure 3.

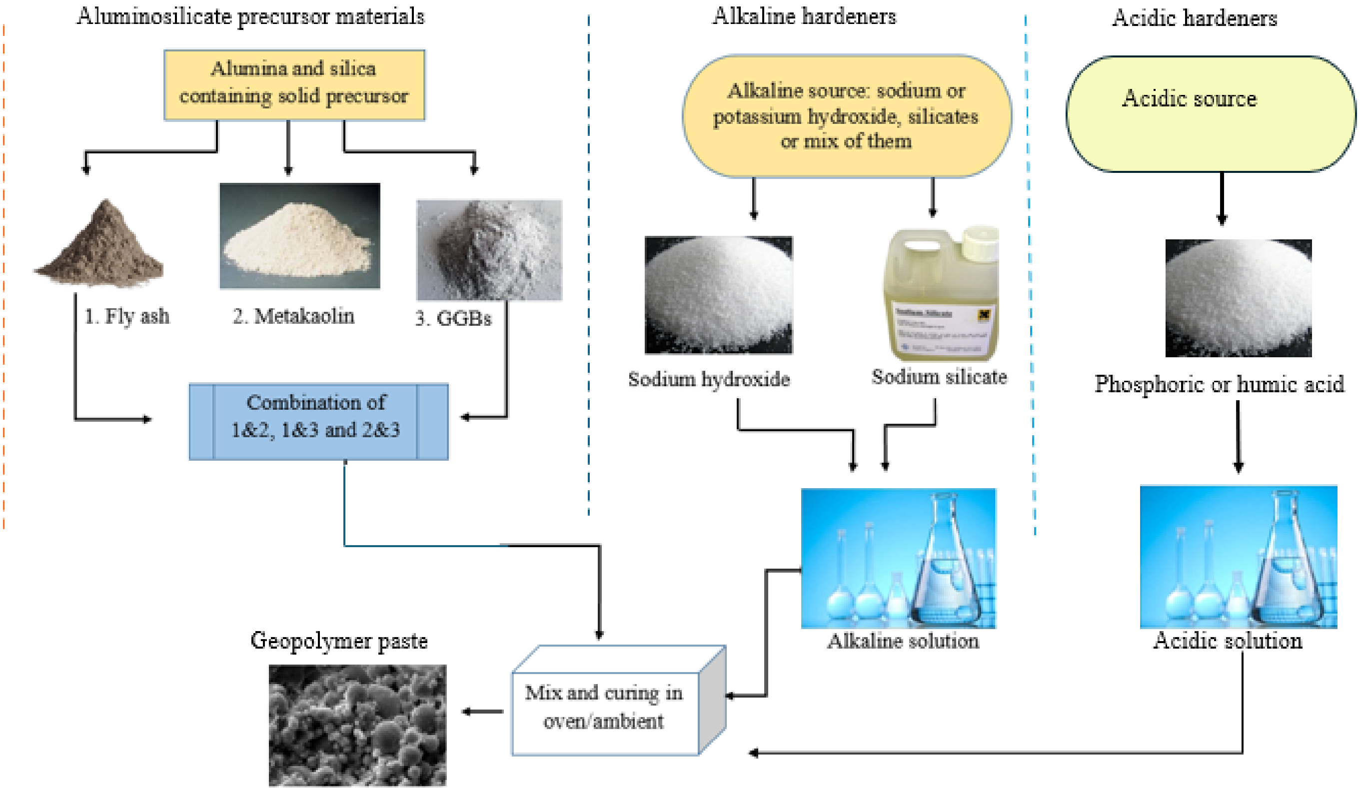


Figure 3. Schematic diagram illustrating the selection and combination of aluminosilicate precursors (geocement) and alkaline/acidic hardeners for geopolymer synthesis [19].

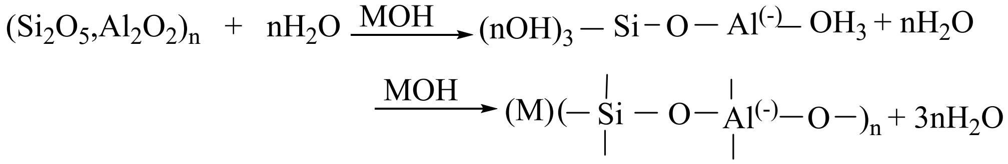
In the realm of geopolymer synthesis, hardeners play a crucial role in transforming geocement into robust geopolymers. These hardeners, which may be alkaline or acidic, play a critical role in promoting the geopolymerization process. Alkaline hardeners, such as hydroxides (NaOH, KOH) and silicates (sodium silicate), dissolve (dissolution) and depolymerize the aluminosilicate precursors and create a high pH environment conducive to polymerization. Dissolution initiates the process by mobilizing silica and alumina from their solid states into solvated forms. Following this, depolymerization occurs, fragmenting these larger molecular structures into smaller, more reactive units essential for the subsequent reassembly phase [20]. Similarly, acidic hardeners such as phosphoric acid interact with aluminosilicate materials using a comparable method to create geopolymer structures with unique properties.

Clarifying the terminology in geopolymer synthesis is crucial. The substances involved are called "activators", suggesting that they trigger a reaction in materials that would otherwise remain inert. This notion, however, is chemically inaccurate. Aluminosilicate precursors are naturally reactive; hardeners do not activate these materials but facilitate and manage the geopolymerization process effectively, such as by raising the pH [20]. Therefore, the term "hardeners" is more accurate, as it reflects their true function in the formation of geopolymers. This distinction is critical for a correct understanding of the underlying chemistry and for advancing the development of sustainable construction materials [26].

Overall, building on the integration of true aluminosilicate precursors, such as fly ash and blast furnace slag, with alkaline or acidic hardeners results in geopolymers that exhibit superior mechanical properties and durability, as discussed earlier. These characteristics are crucial for pavement construction, where materials must withstand heavy traffic loads, environmental exposure, and chemical attack. The refined categorization of primary and auxiliary components in geocement formulations ensures the selection of optimal materials to enhance the performance and longevity of pavements.

3.1. Geopolymer Synthesis

Geopolymers, available as paste, mortar, or concrete, are a class of inorganic polymers synthesized at low temperatures, typically below 100 °C, without emitting CO_2, as depicted in Equations (1) and (2) [25,26,34,35]. This advancement has introduced new opportunities for developing sustainable and environmentally friendly construction materials that could potentially replace conventional cement-based materials [36].



$$(Si_2O_5,Al_2O_2)_n + nH_2O \xrightarrow{MOH} (nOH)_3 - Si - O - Al^{(-)} - OH_3 + nH_2O \xrightarrow{MOH} (M)(-\overset{|}{\underset{|}{Si}} - O - \overset{|}{\underset{|}{Al^{(-)}}} - O -)_n + 3nH_2O \tag{1}$$

where: M = Na or K

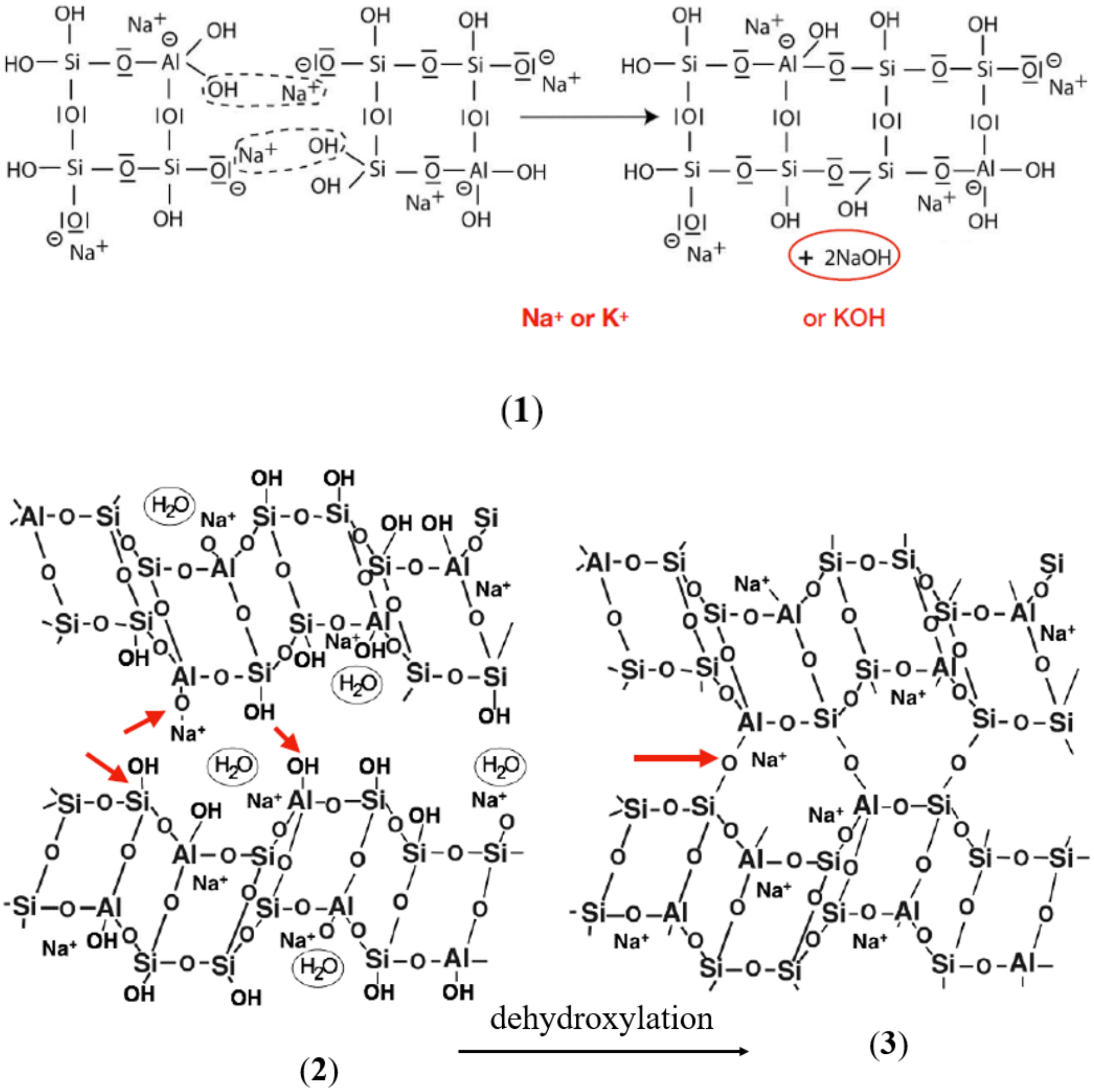
$$Al_2O_3.2SiO_2 + 2H_3PO_4 \longrightarrow Al_2Si_2P_2O_X.H_2O \tag{2}$$

Geopolymers are divided into two categories based on their reaction medium: alkali-aluminosilicate (AAS) geopolymers and aluminosilicate phosphate (ASP) geopolymers. AAS geopolymers are synthesized by reacting aluminosilicate materials with an alkaline hardener, whereas ASP geopolymers are synthesized by reacting aluminosilicate materials with acidic hardeners such as phosphoric acid or phosphate. Both geopolymers utilize natural aluminosilicate minerals like metakaolin and volcanic pumice dust and industrial byproducts like blast furnace slag.

Although the structure of ASP geopolymers is similar to that of AAS geopolymers, in ASP geopolymers, phosphorus partially or completely substitutes aluminum or silicon in the network structure, thus resulting in distinct structures and properties [37]. AAS geopolymers feature -Si-O-Al-O- chains, whereas ASP geopolymers contain -Si-O-Al-O-P-, -Si-O-P-O-Al-, or -Al-O-P- units, forming robust three-dimensional networks that contribute to their exceptional properties [38,39]. Additionally, recent research has shown that iron (Fe) atoms can substitute for some aluminum (Al) atoms, resulting in ferro-sialate structures. The sequence characterizes these structures -Fe-O-Si-O-Al-O- in alkaline or —

Si–O–P–O–Si–O–Fe in acidic mediums. Consequently, iron-containing raw materials are emerging as promising precursors for geopolymers [40–42].

Geopolymer synthesis of alkali-aluminosilicate begins with combining raw aluminosilicate materials, such as fly ash, metakaolin, or slag, with an alkaline hardener, typically composed of sodium or potassium hydroxide and silicate solutions. This mixture undergoes alkalination, leading to the dissolution and depolymerization of the raw materials into smaller monomeric units. These monomers then form a gel of oligo-sialates [40]. The oligo-sialates undergo polycondensation (**1**), reticulation, and networking (**2**), resulting in the solidification (**3**) into a stable three-dimensional network structure characterized by a robust and interconnected molecular framework, as shown in Figure 4.



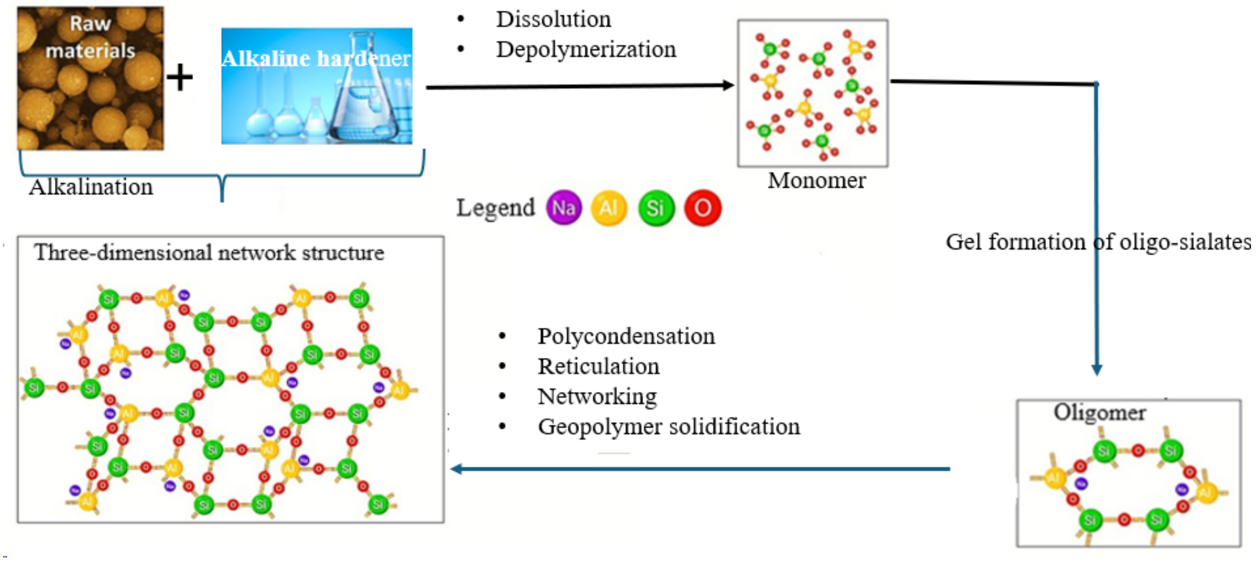


Figure 4. Alkali-aluminosilicate geopolymerization process [20].

For ASP, the first stage of the geopolymerization process involves the dealumination of the aluminosilicate precursor, initiated by phosphoric acid. This stage involves depolymerizing the aluminum–oxygen and silicon–oxygen tetrahedral structures, breaking Al-O-Al and Si-O-Al bonds, and forming -Si-O- units while releasing Al^{3+} ions. In the next stage, polycondensation occurs between PO_4^{3-} ions, Al^{3+} ions, and -Si-O- units, leading to the formation of crystalline phases like $AlPO_4$. Finally, the products from the polycondensation reaction undergo further condensation, forming larger geopolymer chains and establishing diverse three-dimensional geopolymer network structures.

In summary, geopolymers synthesized at low temperatures without CO2 emissions utilize natural minerals and industrial byproducts to form robust three-dimensional networks. Understanding their synthesis with alkaline and acidic hardeners enables the creation of materials designed to withstand heavy traffic and environmental stresses. This knowledge is crucial for developing durable, eco-friendly pavements, reducing environmental impact, and recycling waste materials.

3.2. Key Ratios in Geopolymer Formation and Properties

The SiO_2/Al_2O_3 ratio in geopolymers is a crucial factor that can be precisely tailored by adjusting the molar amounts of SiO_2 and Al_2O_3 in the initial materials. This ratio significantly impacts geopolymers' microstructure and mechanical properties through various mechanisms. Higher SiO_2 concentrations relative to Al_2O_3 lead to a more interconnected network, enhancing structural integrity. Additionally, the balance between SiO_2 and Al_2O_3 influences viscosity, workability, setting time, and strength development. Optimal ratios (SiO_2/Al_2O_3: 3.4 to 3.8) enhance compressive strength and durability, contributing to the material's resistance to environmental degradation [2,3,20].

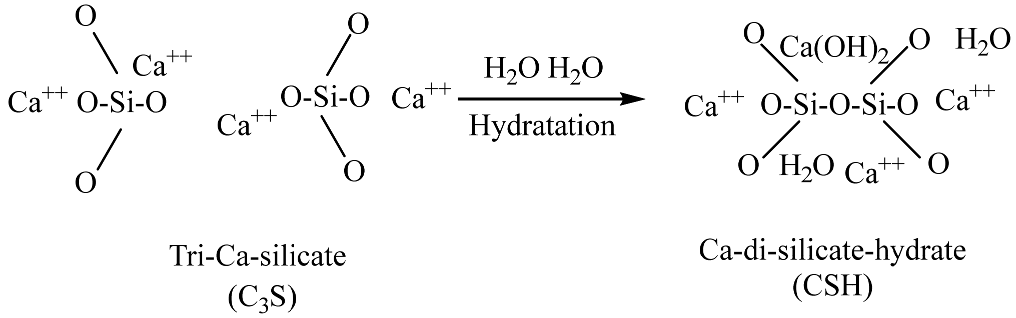
Other important ratios, such as M_2O/SiO_2, M_2O/Al_2O_3, and H_2O/M_2O, also play significant roles in geopolymerization. The SiO_2/Na_2O ratio, for instance, affects mechanical properties and microstructure, while the Na_2O/Al_2O_3 ratio influences the dissolution of silica and alumina species [39,42]. The M_2O/H_2O ratio impacts the dissolution of aluminum and silicate species, thus affecting compressive strength. Optimal ranges for these ratios (M_2O/SiO_2: 0.2 to 0.48, SiO_2/Al_2O_3: 3.3 to 4.5, H_2O/M_2O: 10 to 25, M_2O/Al_2O_3: 0.8 to 1.6) have been identified to ensure successful geopolymerization. Additionally, the SiO_2/Fe_2O_3, Na/Fe, and Al/Fe ratios are pivotal in influencing geopolymers' chemical structure, mechanical properties, and performance. A higher SiO_2/Fe_2O_3 ratio enhances the formation of polymeric Si-O-Si bonds, creating a denser and stronger material [3,20]. Moderate Fe_2O_3 content can improve the compressive strength of the material, but excessive amounts may introduce microstructural defects. The Na/Fe ratio is essential for alkali activation, impacting the microstructure and porosity, while the Al/Fe ratio influences the geopolymer's structural integrity and thermal stability. Balancing these ratios is fundamental to tailoring geopolymer properties for specific applications, ensuring optimal performance and durability [25,26].

In principle, the precise tailoring of ratios such as SiO_2/Al_2O_3, M_2O/SiO_2, and H_2O/M_2O in geopolymers significantly impacts their microstructure and mechanical properties. Optimizing these ratios enhances compressive strength, durability, and resistance to environmental degradation. This knowledge is crucial for pavement applications, where high-performance materials are needed to withstand heavy traffic and environmental stresses. By fine tuning these ratios, geopolymers can be engineered to create durable, eco-friendly pavements that effectively recycle industrial byproducts and reduce environmental impact.

3.3. Key Properties of Geopolymer Cement

Geocement or geopolymer cement is comparable to traditional Portland cement as a binder in construction materials. Unlike Portland cement, which is manufactured by calcining limestone and other materials at high temperatures. This process significantly contributes to CO_2 emissions, and geocement typically involves aluminosilicate materials. When geocement is combined with hardeners like NaOH, it transforms into a geopolymer. This geopolymer can be used in various forms similar to traditional Portland cement. They can be prepared as a paste, mixed with sand to create mortar, or combined with larger aggregates to form concrete. These forms make geopolymers suitable for a wide range of construction applications, offering a sustainable alternative to traditional Portland cement with comparable functionality [19,21]. These geopolymers provide several advantages over conventional cement, such as enhanced durability, reduced environmental impact due to their resistance to chemical attacks and heat, and the sustainability benefits of avoiding limestone calcination and utilizing waste materials [20,42].

Unlike traditional Portland cement, which primarily gains strength through hydration (Equation (3)), geopolymers develop their properties through polycondensation (Equation (4)). This fundamental distinction affects not only their mechanical characteristics but also their environmental impact [43]. This difference in chemical processes allows geopolymers to display unique properties, such as forming X-ray amorphous structures at ambient to medium temperatures. However, they transition to X-ray crystalline structures under higher thermal conditions, occurring above 500 °C for sodium-based species and 1000 °C for potassium-based species [44]. Geopolymers' thermal adaptability and resilience have essential consequences for high-temperature applications.



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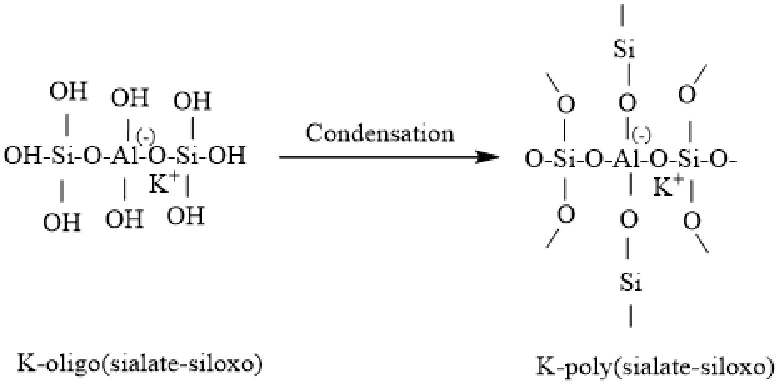


(4)

Building on the advanced properties of geopolymers, they offer a sustainable alternative to traditional Portland cement with significant advantages in construction applications, including pavements. Their exceptional mechanical properties, such as compressive, tensile, and flexural strength, combined with enhanced durability attributes like chemical, fire, freeze–thaw, abrasion, and fatigue resistance, make geopolymers ideal for pavement applications. Additionally, their lower porosity, water absorption, and improved corrosion performance ensure longer-lasting and more resilient pavement structures. By understanding and optimizing these properties, geopolymers can be effectively used to create durable, eco-friendly pavements that reduce environmental impact and recycle industrial waste.

3.3.1. Mechanical Properties

Geopolymers are a distinctive class of inorganic polymers synthesized through the reaction of aluminosilicate materials with alkaline or acidic hardeners. They are highly regarded in the construction industry for their exceptional mechanical properties, which include compressive strength, tensile strength, and flexural strength. These properties make geopolymers suitable for a wide range of applications, providing a sustainable alternative to traditional cement.

The compressive strength of geopolymers is one of their most notable mechanical properties. It generally ranges from 20 MPa to over 80 MPa, depending on the specific formulation and curing conditions [23,45,46]. This strength is primarily influenced by the type of aluminosilicate source used in the geopolymer mix. For example, metakaolin-based geopolymers can achieve higher strengths but require precise control over the curing environment. Fly ash, another common source material offers more flexibility and accessibility but can result in a broader range of mechanical strengths due to its variable chemical composition [47].

Tensile strength in geopolymers, while typically lower than their compressive strength, is crucial for applications where resistance to stretching or pulling forces is required. Geopolymers usually exhibit tensile strengths between 2 and 8 MPa [48]. This property is significant because it affects the material's ability to perform under tensile stress without cracking, which is particularly important in structural applications requiring durability and flexibility. Flexural strength, or the ability to resist bending, further highlights the versatility of geopolymers. This strength typically ranges from 5 to 10 MPa and is tested by subjecting beams or bars of the material to bending forces. Flexural strength is critical for structural elements like beams and slabs that must withstand loads over wide spans without failing [48–50].

The hardeners used in producing geopolymers, such as sodium hydroxide or a combination of sodium silicate and sodium hydroxide, also play a vital role in determining the final mechanical properties. The concentration and ratio of these chemicals are crucial as they drive the polymerization process, affecting everything from setting time and hardness to final mechanical strengths [3]. Curing conditions are equally important in defining the mechanical properties of geopolymers. The temperature and duration of curing influence the rate of chemical reactions and the development of mechanical strengths. Higher temperatures typically speed up the polymerization process, enhancing the material's strength more rapidly, but can also make the material more brittle if not managed correctly [51,52].

Despite these excellent properties, the actual performance of a geopolymer can vary based on its chemical composition, the type of aluminosilicate used, the specifics of the alkaline hardener, and the curing process. These factors must be carefully balanced to optimize the mechanical properties for specific applications, ensuring that the geopolymer meets the required performance standards and remains durable and effective over its intended lifespan [53]. In general, the mechanical properties of geopolymers make them an attractive option for many construction applications. As the construction industry continues to shift towards more sustainable practices, the role of geopolymers is likely to expand, leveraging their mechanical advantages to meet the demands of modern constructions.

Numerous studies have intensively explored advancements in enhancing the mechanical properties of geopolymers. A significant area of research has been fiber-reinforced geopolymer composites, focusing on their material and geometric properties, the interactions between fibers and binders, mechanical characteristics, toughening mechanisms, thermal properties, and environmental durability. The addition of various fibers, including cotton, flax, bamboo shavings, hemp, ramie, and basalt, has been investigated to improve the mechanical properties of geopolymer composites [54,55]. These reinforcements have shown promising results in improving the strength and durability of geopolymer materials. Moreover, the addition of nanomaterials like nano-clay and nano-silica particles has been investigated for their impact on the mechanical properties and durability of geopolymer composites [56,57]. Studies have demonstrated that the inclusion of these nanoparticles can lead to significant enhancements in the mechanical performance of geopolymer materials. Additionally, multi-component supplementary cementitious materials, such as rice husk ash and silica fume, have been shown to promote geopolymerization and improve the mechanical properties of geopolymer composites [58,59]. The mechanical properties of geopolymer composites have been a critical area of interest, with researchers exploring various factors that influence these properties.

3.3.2. Durability Properties

Durability refers to the ability of cement-based materials to withstand disintegration and decay. The final product of geocement, which is a geopolymer, encompasses forms such as paste, mortar, and concrete.

Self-Healing Properties

Self-healing in geopolymers is a captivating area of research that shows promise in enhancing the durability and longevity of infrastructure. Geopolymers with self-healing properties have the potential to reduce repair and maintenance costs while promoting economic and environmental sustainability [60]. The self-healing capability of geopolymers allows them to repair cracks that form due to drying shrinkage over time and under specific environmental conditions, depending on the mix design and ingredients used [61]. This autogenous self-healing ability enables geopolymers to naturally mend themselves from cracks, contributing to their resilience [62]. The self-healing capability of geopolymers allows them to adapt to subsurface stress changes, making them ideal for use as permanent barriers in construction operations [63]. Incorporating self-healing microcapsules into geopolymer cutoff wall backfill has shown promise in enhancing durability and performance, offering a potential solution for improving the longevity of geopolymer-based structures [64]. Furthermore, the use of bio-mineralization techniques in developing eco-sustainable self-healing geopolymer binders has been investigated, demonstrating the potential of incorporating biological processes to enhance the self-healing properties of geopolymers [62]. The self-healing ability of geopolymer paste, mortar, and concrete has been a subject of investigation, with studies comparing different composites and varied curing environments to evaluate their autonomous healing properties and multifunctionality [60,65–67]. Moreover, the development of smart-engineered geopolymer composites with self-healing and self-sensing properties highlights the potential for creating advanced materials with enhanced functionalities [68,69]. Life cycle assessments of self-healing geopolymer concrete have highlighted the environmental implications and sustainability aspects of incorporating self-healing mechanisms into construction materials [70]. The development of self-healing geopolymer composites holds great promise for improving the durability, longevity, and sustainability of infrastructure systems.

Chemical Resistance

Geopolymer cement (GPC) generally provides better resistance to chemical attacks such as acid or base attack, chloride penetration, and sulfate attacks, which are common causes of deterioration in pavement structures [71,72]. The presence of fibers in GPC improves its chemical resistance, but an increase in porosity and pore size of geopolymers subjects them to easy deterioration by chemical attack [40]. This attribute contributes to the long-term durability of geopolymer-based pavements. The chemical resistance of GPC concrete varies with the type and composition [73]. Regarding this, GPC concrete shows higher resistance to the attack by chemicals, such as acids (e.g., H_2SO_4, HNO_3, and HCl), sulfates, chlorides, etc., than Portland cement concrete [74,75].

GPC concrete demonstrates superior compressive strength compared to Portland cement concrete. However, GPC concrete tends to have higher chloride concentrations and lower pH levels than Portland cement concrete, affecting factors like chloride penetration and durability. Studies suggest that GPC concrete, particularly those made with FA, exhibits enhanced durability in harsh conditions and improved resistance to chloride ion penetration, highlighting the importance of FA alkalination and geopolymerization in enhancing GPC concrete's performance [76–79]. Geocement, particularly those made with FA, exhibit resistance to acid degradation based on their mineralogical compositions, showcasing better performance in acidic environments than Portland cement [80–82]. It was found that FA-based geopolymer shows a better resistance to acidic environments than conventional concrete [83]. Thus, a reported result shows that the exposure of GPC concrete to 3% sulfuric acid [84] can only lead to a 0.5% weight reduction. In comparison, a low-calcium FA geopolymer can resist up to 10% sulfuric acid because of its low calcium content [85]. The addition of GGBS with CaO (30–50%), SiO_2 (28–38%), Al_2O_3 (8–24%), and MgO (1–18%) can lead to an increase in the resistance to the aggressive environment of GPC concrete by 10–14% [86].

Fire Resistance

Fire-resistant construction materials with advanced properties, like high fire resistance are currently in high demand [87,88]. The release of water stored in a geopolymer structure during heating contributes significantly to its fire resistance by lowering the temperature and forming a porous microstructure. Geopolymer binders, originating in the late 1970s after significant fires in France, offer improved fire resistance compared to Portland cement, with magnesium-based cement known for its fire resistance and lower CO_2 emissions. GPC concrete's fire resistance depends on various factors such as slag content, binding materials, alkaline liquid hardener type, room temperature, and curing conditions, with GPC concrete exhibiting superior fire resistance due to the absence of hydrate phases like $Ca(OH)_2$ [89]. A separate study revealed that FA- and GGBS-based concrete experiences significantly more shrinkage than 100% FA-based concrete and traditional cement concrete. Moreover, FA-based GPC concrete with slag substitution undergoes a strength decline at temperatures between 200 and 300 °C, followed by strength recovery at 300–400 °C, subsequent strength loss at 500 °C, and further weakening at 800 °C, with GPC concrete generally exhibiting lower fire resistance than regular Portland cement concrete due to varying chemical compositions and mineralogical characteristics [90,91]. Regarding this, GPC is a competitive cement in the infrastructure and construction sectors, guaranteeing long-term durability and offering protection and safety to people’s lives and property.

Freeze–Thaw Resistance

This is the ability of a material to resist the effects of freeze and thaw cycles. The result of the freeze–thaw cycle has been used as an index for evaluating the durability of GPC [71,75]. The presence of fibers in GPC concrete lowers the porosity of concrete and improves the freeze–thaw cycle resistance [71,75]. In addition, due to the low water requirement and coupled with a high concentration electrolyte pore solution, the alkali-activated slag-based GPC concrete can withstand 300–1150 cycles of repeated freezing–thawing. In contrast, typical Portland cement concretes can only withstand less than 300 cycles [3]. Thus, GPC concrete has a greater freeze–thaw resistance advantage over OPC concrete. [44,92].

Abrasion Resistance

This is the ability of the surface of a material surface to resist wearing away by friction or a rubbing effect. It is measured by the weight or mass loss of the material [72]. The abrasion resistance of GPC concrete depends on several factors, such as compactness of the material, fiber content, surface finishing, good curing, aggregate/paste bond, mix proportions, and aggregate hardness [47,93]. Adding fibers, such as polyvinyl alcohol (PVA) fibers, has been shown to improve the abrasion resistance of GPC [94,95]. Hence, GPC concrete generally shows a better abrasion resistance than Portland cement concrete [71].

Fatigue Resistance

The term fatigue resistance of a concrete material is the tendency of the material to withstand the rupturing caused by repetitive static loadings by direct compression, torsion, tension, and bending beyond the strength of the material [84]. Several static fatigue tests conducted on both GPC and Portland cement concrete beams showed better promising results for GPC compared to Portland cement [94,96]. Geopolymer cement concrete has shown superior resistance to fatigue cracking, which is crucial for heavy-loaded pavement applications [97,98].

Porosity and Air Permeability

Porosity is the measure of the number of pores present in a material and it is an intrinsic property of cement-based materials. For a cement material, the porosity is determined as the quantity of the total volume occupied by the pores of the material sample [39]. The air permeability of concrete material is the measure of the volume flow rate of air through the material sample. The volume of the permeable void indicates the permeability-related durability of the geopolymer [99]. Polycondensation, spherical shape, and particle size of the aluminosilicate precursor of FA can reduce permeability by improving the consolidation of geopolymer [100]. The investigation on the geopolymerization with fly ash (FA) and metakaolin (MK) shows an increase in strength by 6% when the FA was used, which accounted for a 34% drop in strength. On the other hand, when MK was used, there was an increase in permeability, allowing the flow of moisture out of the matrix and subsequently a reduction in the amount of damage to the GPC concrete [101]. The addition of nanoparticles may also minimize the gas permeability and flammability of geopolymer by about 20 times [102]. Also, it was found that a higher volume of liquid contributed to a lower compressive strength and improved water permeability [103]. Additionally, it was reported that geocement and other alkaline-activated binders have direct water and air permeability measurements depending highly on the mixed ratios and designs [104]. Thus, GPC has better durability and performance than Portland cement based on the fewer, small-sized pores it possesses [39,40,105].

Water Absorption and Permeability

Water absorption of a material is regarded as the quantity of water absorbed by the material. It is estimated as the ratio of the weight of absorbed water to the dry material weight [39,90]. Water permeability refers to the degree to which water flows through a solid material under pressure [77]. For instance, water absorption and permeability of GPC concrete are influenced by several factors such as pore size and continuity, nature of the cementitious materials, humidity cycle, compactness, curing state, mix proportions, microcracks, and W/C ratio. They also determine the compressive strength of any cementing material [39,77,78,106,107]. Generally, GPC (such as FA-GPC) has lower water absorption and permeability than Portland cement [39,77,107].

Drying Shrinkage

This is regarded as the loss of capillary moisture from the hardened cement mixture matrix during air drying, leading to shrinkage and crack formation within the concrete. It is a crucial durability performance index that provides information on the potential cracks that can result in hardened cementitious materials [71]. Reports have shown that the fiber addition to the GPC matrix on production minimizes the stress in the matrix, making it withstand drying shrinkage better than Portland cement concrete [71,108].

Sorptivity

The term sorptivity of a material is regarded as its ability to absorb and transfer fluid (such as water) through it via capillary action [109,110]. As a measure of concrete material, sorptivity serves as an engineering metric for the microstructure and durability-related attributes of concrete material and as an indicator of the resistance of concrete in unfavorable environments [110]. The optimal physicochemical characteristic of GPC relies on small-sized pores, fiber-reinforced cementitious materials, low humidity cycle, high compactness, better-curing state, fewer microcracks, and low W/C ratio resulting in a lower sorptivity and better performance as a pavement construction material than Portland cement [109].

Corrosion Performance

Geopolymers have been extensively studied for their corrosion performance in various environments. Research indicates that geopolymers generally exhibit low-level corrosion activity but are more prone to corrosion compared to Portland cement concrete [86]. Geopolymers have shown excellent resistance to acid and alkali corrosion, making them superior to common organic concrete protective materials [64]. Studies have also explored the corrosion resistance of geopolymers in different chemical solutions. For instance, the corrosion resistance of fly ash-based geopolymers in hydrochloric and sulfuric acid solutions has been evaluated, emphasizing the importance of understanding their performance in aggressive environments [10]. Geopolymers have been found to exhibit better sulfate corrosion resistance compared to Portland cement adhesive, indicating their potential for use in corrosive environments [64]. Furthermore, the performance of reinforced foam and geopolymer concretes against chloride attack has been assessed, focusing on parameters such as corrosion rate and mechanical performance of reinforcing steel [10]. Overall, the literature suggests that geopolymers offer promising corrosion resistance properties, making them a viable alternative to traditional construction materials in corrosive environments.

3.4. Environmental Impact Assessment of Geopolymer Cement

The Environmental Impact Assessment (EIA) of geopolymer cement/binder involves evaluating the environmental effects of a geopolymer cement/binder throughout its life cycle. Using GPC as an alternative to traditional cement can positively impact the environment due to reduced greenhouse gas (GHG) emissions and lower energy consumption during production. However, there may still be some environmental consequences, especially during the extraction phase of the raw materials. Other valuable EIA evaluation considerations include water usage, waste generation, durability, and end-of-life management. Generally, the assessment should adhere to local regulations and standards, understanding that the environmental impact may vary based on specific formulations, production methods, and regional factors [111–115].

Building on the Environmental Impact Assessment of geopolymer cement, its use in pavement applications offers significant sustainability benefits. Geopolymers reduce greenhouse gas emissions and energy consumption compared to traditional Portland cement, due to lower calcination temperatures and the use of industrial byproducts. These advantages directly translate to more eco-friendly pavement construction. Additionally, the energy efficiency and resource conservation achieved through geopolymer production enhance the sustainability of pavements. By integrating geopolymers into pavement applications, it is possible to create a durable, resilient, and environmentally friendly infrastructure that contributes to reducing the overall carbon footprint and promoting the use of recycled materials.

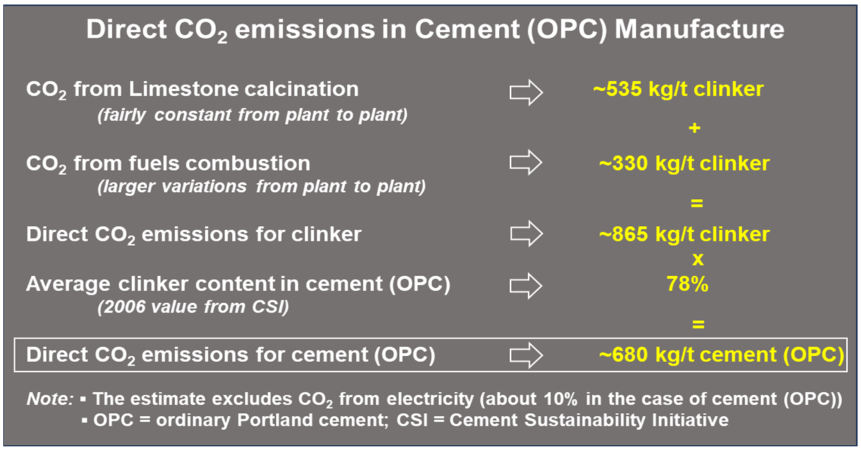
3.4.1. Greenhouse Gas Emissions Reduction

GPC contributes to a reduction in GHG emissions compared to Portland cement through key factors such as the utilization of industrial byproducts, which lowers the demand for traditional raw materials and decreases CO_2 emissions; lower temperatures, which reduce energy consumption and carbon intensity; and the absence of clinker production, which further lowers carbon emissions. However, emissions reduction depends on mixed formulations, production processes, and regional conditions [9,116].

Almutairi et al., 2021 [9] conducted a comparison study between the CO_2-e footprints of concrete with GPC and 100% Portland cement concrete. The study evaluated the carbon dioxide equivalent emissions (CO_2-e) related to sourcing raw materials, producing concretes, and constructing one cubic meter of concrete in metropolitan Melbourne. Surprisingly, the CO_2 footprint of geocement concrete was approximately 9% less than comparable 100% Portland cement concrete. Some factors were suggested to contribute to the result obtained, which included the consideration of emissions from mining, and transporting, considerable energy consumption in the production of alkali activating agents, and the requirement for high temperatures during the curing process of geocement concrete to attain sufficient rigidity [117].

The graphical representation in Figure 5 summarizes the contribution to CO_2-e emissions from various activities involved in producing and constructing one cubic meter of concrete. This comprehensive assessment spans activities from the sourcing of raw materials to the manufacturing and construction phases. It was reported that approximately 0.54 tons (≈540 kg) of CO_2 are directly emitted for every ton of OPC produced at a calcination temperature of 1450 °C and with the addition of 0.33 tons (≈330 kg) of CO_2 released for every carbon-containing fuel burnt to generate the calcination heat at 1450 °C needed [118,119]. It is shocking to release such amounts of CO_2 (a potent GHG) from an OPC industry, producing just 1 ton (1000 kg) of OPC, resulting in detrimental environmental effects, mainly global warming.

The graphical representation in Figure 6 summarizes the contribution to CO_2 emissions from various activities involved in producing and constructing one cubic meter of GPC and OPC concrete. This comprehensive assessment spans activities from the sourcing of raw materials to the manufacturing and construction phases. The figure provides a clear overview of the carbon footprint associated with each stage, offering insights into the environmental impact of the entire concrete production and use lifecycle. Such analyses are essential in understanding and mitigating the ecological consequences of concrete-related activities.

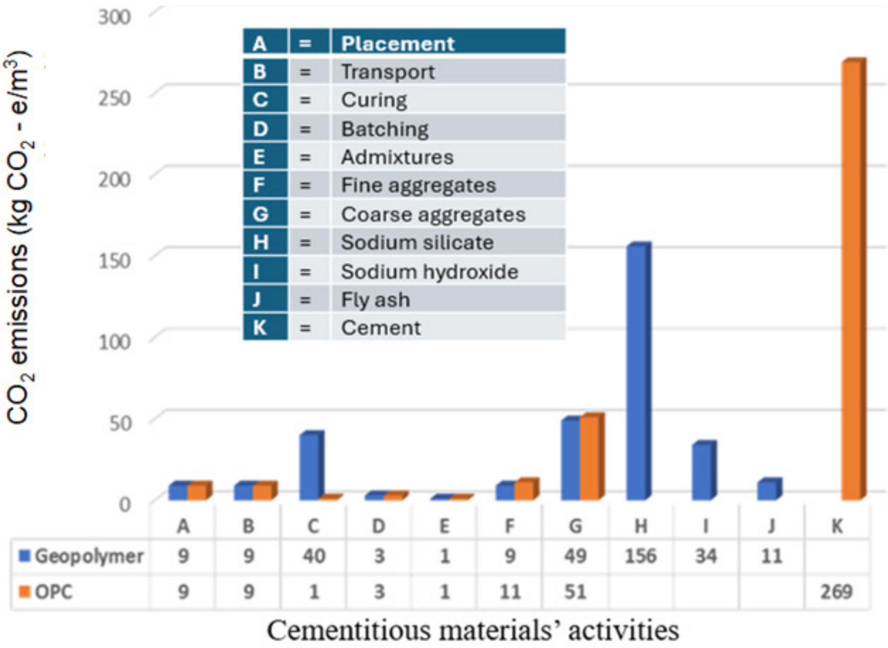


Direct CO_2 emissions in Cement (OPC) Manufacture

CO_2 from Limestone calcination *(fairly constant from plant to plant)*	⇨	~535 kg/t clinker
		+
CO_2 from fuels combustion *(larger variations from plant to plant)*	⇨	~330 kg/t clinker
		=
Direct CO_2 emissions for clinker	⇨	~865 kg/t clinker
		x
Average clinker content in cement (OPC) *(2006 value from CSI)*	⇨	78%
		=
Direct CO_2 emissions for cement (OPC)	⇨	~680 kg/t cement (OPC)

Note: ▪ The estimate excludes CO_2 from electricity (about 10% in the case of cement (OPC))
▪ OPC = ordinary Portland cement; CSI = Cement Sustainability Initiative

Figure 5. Mean weight (in kg) of CO_2 released for every ton of Portland cement produced [119].



A = Placement
B = Transport
C = Curing
D = Batching
E = Admixtures
F = Fine aggregates
G = Coarse aggregates
H = Sodium silicate
I = Sodium hydroxide
J = Fly ash
K = Cement

	A	B	C	D	E	F	G	H	I	J	K
■ Geopolymer	9	9	40	3	1	9	49	156	34	11	
■ OPC	9	9	1	3	1	11	51				269

Figure 6. Illustration of the CO_2-e emissions of concrete mixtures utilizing Portland cement or GPC [120].

3.4.2. Energy Efficiency in Geopolymer Cement Production

In comparison to Portland cement paste, alkali-activated brick powder geopolymers offer benefits in terms of energy efficiency and emission reduction, potentially reducing CO_2 emissions by 40–70% and cutting energy consumption by 20–50% [118]. However, formulations with an 8% alkali dosage in brick powder geopolymers resulted in high energy consumption, primarily due to the extensive use of NaOH and Na_2SiO_3. This highlights the necessity for developing more environmentally friendly alkaline hardeners in future endeavors. An optimal mixture is identified with a 6% alkali dosage, a silicate modulus of 1.6, and a water-to-binder (W/B) ratio of 0.3, considering both functional properties and environmental considerations [121]. Utilizing hardeners derived from waste materials holds the potential to cut down CO_2 emissions by 50–60%, compared to commercially available sodium silicate. Waste materials rich in silica, such as silica fume, rice husk ash (RHA), and waste glass, can activate geopolymers, facilitating additional Si-Al linkages. These alternative hardeners exhibit performance like conventional sodium silicate solutions, albeit with the potential to slightly delay the setting time. Consequently, incorporating waste-derived hardeners in Autoclaved Aerated Concrete (AAC) production has the dual advantage of significantly reducing the environmental impact while maintaining high performance and potentially lowering production costs. Further research is essential to fine tune the utilization of waste materials as hardeners and mitigate any associated drawbacks [122].

3.4.3. Resource Conservation and Waste Reduction

Geopolymers constitute an eco-friendly and resource-efficient approach to waste utilization since it minimizes environmental impact, thereby contributing to a sustainable construction paradigm. From theoretical perspective, most waste materials contains adequate amount of silica and alumina, which can be available for the polymerization process, with alkaline hardeners such as NaOH, KOH, Na_2SiO_3, and K_2SiO_3 commonly used in the geopolymerization phase. It was observed that the type of alkaline hardeners used significantly impacted the properties of the polymerization process [123].

3.4.4. Comparison between Geocement and Portland Cement Based on Their Eco-Friendliness and Sustainability

GPC is globally seen as a greener alternative to Portland cement in various aspects based on the structural and physicochemical properties and sustainability criteria. Some important comparisons between geocement and Portland cement as a construction or building material are presented in Table 1 [111–113].

Table 1. Comparisons between geocement and Portland cement based on their eco-friendliness and sustainability [111–113].

Criteria	Geocement	Portland Cement
CO_2 emissions	Low to none	Extremely high
Sustainability	High	Low
Energy saving	High with no embodied energy	Low with greater embodied energy
Costs (production, sales, etc.)	Low	Extremely high
Eco-friendliness	High	Low
Water requirement	Low	High
Availability of raw materials	Abundant and cheap	Non-abundant and costly
Thermal conductivity	Low	High
Ability to adsorb and immobilize toxic substances	High	Moderate to high
Preparation technique	Simple	Complex
Volume stability	Good	Fair
Setting time	Short (about 10–60 min)	Long (about 30–300 min)
Global warming contribution	Low to none	High

The comparative analysis between geocement and Portland cement as presented in Table 1 underscores significant differences in their environmental impacts and sustainability. Geocement emits low to no CO_2 due to its lack of a high-temperature calcination process required for Portland cement, making it a more environmentally friendly choice. It is highly sustainable, utilizing industrial byproducts like fly ash or slag, which reduces the need for virgin raw materials and minimizes waste. In terms of energy, geocement offers high savings and has no embodied energy, while Portland Cement requires more energy due to intensive processes.

Cost-wise, geocement is generally more economical due to its use of cheaper and more abundant materials, whereas Portland cement involves higher costs associated with resource extraction and processing. Geocement is considered more eco-friendly due to its lower environmental impact and reduced use of water, which conserves resources and reduces its ecological footprint. In contrast, the production of Portland cement consumes a significant amount of water, impacting both the environment and operational costs.

Geocement's raw materials are readily available and inexpensive, often derived from byproducts, making it a cost-effective and sustainable option. This contrasts with the non-abundant and costly materials required for Portland cement. Geocement also has low thermal conductivity, which enhances its utility in building applications by improving thermal insulation. It excels in adsorbing and immobilizing toxic substances, making it ideal for hazardous waste containment, whereas Portland cement has moderate to high capabilities in this regard. Furthermore, the preparation technique for geocement is simpler and less costly compared to the complex processes required for Portland cement, which involves multiple stages of heating and grinding. Geocement also demonstrates good volume stability, minimizing risks of cracking and structural failure, and its setting time is relatively short, which can accelerate construction processes. In contrast, Portland cement takes longer to set, potentially delaying projects.

Overall, geocement contributes minimally to global warming, aligning with goals for environmental sustainability, while the high CO_2 emissions from Portland cement production make it a significant contributor to global warming. This detailed comparison highlights the advantages of geocement in terms of environmental impact, sustainability, and usability in various applications, emphasizing its superiority over traditional Portland cement in eco-friendly construction practices.

4. Geopolymer Cement/Binder as Sustainable Pavement Construction Materials

Pavements are categorized into two types, viz asphalt (flexible) pavements and concrete (rigid) pavements, each consisting of distinct layers such as wearing course or surface, base, subbase, and subgrade [28,29]. The primary purpose of the pavement layers is to distribute the load from the surface to the subgrade, enabling them to endure the applied load from vehicles. The motivation to explore geopolymers in pavement construction stems from their potential to address the environmental imperatives of traditional cement and their better construction performance in terms of mechanical strength and durability for soil stabilization, grouting, fillers, pavers, and airway construction over Portland cement, as shown in Figure 7. In making this possible, GPC is formed through the combination of aluminosilicate materials to offer an environmentally friendly alternative binder by utilizing either natural or industrial byproduct materials such as kaolinite ($Al_2Si_2O_5(OH)_4$), clay, metakaolin, fly ash, red mud, mine tailings, or slag with improved mechanical and durability properties [6–8,14,124].

Researchers have studied the stabilization of pavement and road bases (base, subbase, and subgrade) with different materials based on geopolymerization, as shown in Table 2 [31,60,125–127]. These indicate the possibility of using geopolymers in pavement construction based on their mechanical strength: Unconfined Compressive Strength (UCS) by the aggregate material specifications for road construction in various countries, as shown in Table 3.

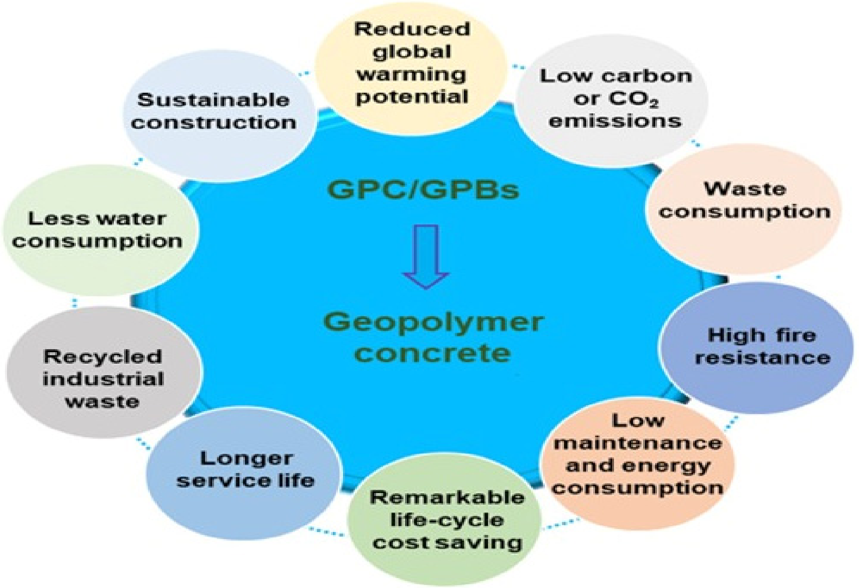


Figure 7. Benefits of GPC as sustainable pavement construction materials [127].

Table 2. Geocement-treated materials are used as stabilizers for road base/subbase.

No	Waste Material (wt.%)	Alkali Hardener	Curing Condition	Test Conducted	UCS (MPa)	Ref.
1	Copper MT (100%)	NaOH (0, 3, 5, 7, and 11 M)	Oven at 35 °C for 7 days	UCS, SEM	5.32 (11 M (NaOH)	[79]
2	Copper MT (100%)	NaOH (0–6%)	Ambient temperature for 7 days	UCS, SEM	2.5 (2% NaOH)	[119]
3	Gold MT (100%)	Na_2SiO_3	8, 14, 21, and 28 days at room temperature	UCS	30 (8% of Na_2SiO_3)	[80]
4	Copper MT	NaOH (5, 10, 15 M)	Ambient temperature for 4 days	UCS	4.4 (10 M)	[31]

Table 3. Conventional cement-treated materials are used as road bases/subbases in different countries.

Country	Stabilizer Portland Cement (%)	7-Day UCS (MPa)–(Base/Subbase)
South Africa	1.5–3.0	1.5–3.0 (base)
United Kingdom (UK)	2–5.0	2.5–4.5 (base)
China	>4 (road-mix method) >5 (central plant mixing)	>2 (subbase), >4 (base)
Spain	3.5–6.0	4.5–6.0 (base)
U.S.A.	3–10	1.03–2.75 (base) [26] 2.06–5.51 (base) [27]

Performance of Geopolymer Cement in Pavement Applications

Geopolymer cement is an emerging material that can find application in pavement construction due to its robust mechanical strengths, enhanced durability, and superior thermal properties, as depicted in Figure 8. A comprehensive review of the comparison of

GPC and Portland cement in concrete pavement applications is given in Table 4, which meticulously tracks the engineering properties and their essential performance indicators. Given the novelty of GPC, standardized testing protocols are still developing; thus, this review adapts existing methods to suit GPC's unique properties. This detailed analysis underscores the potential of geopolymer cement to revolutionize concrete pavement applications, offering a sustainable and efficient alternative to traditional materials.

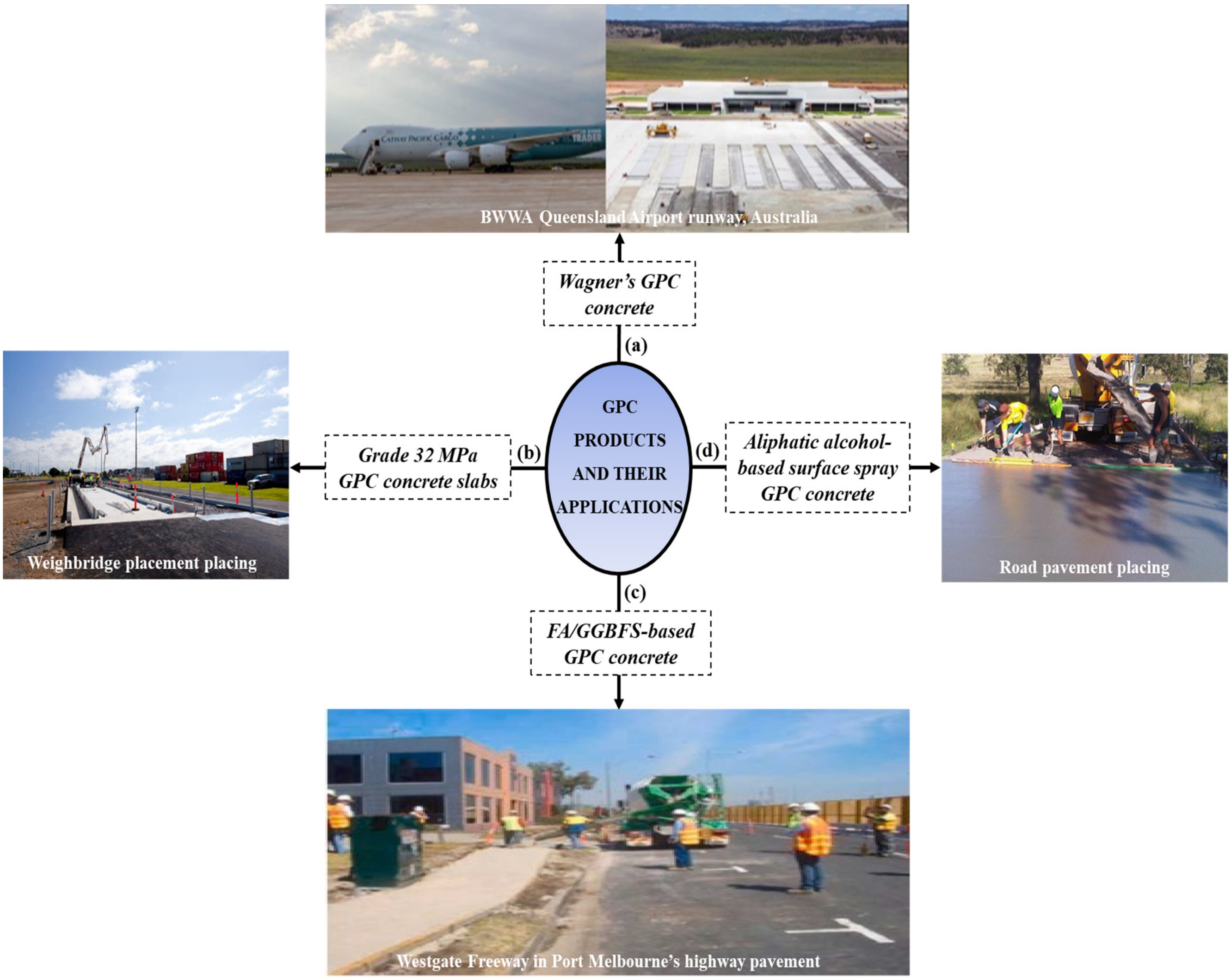


Figure 8. GPC products and their applications: (**a**) Brisbane West Wellcamp Airport (BWWA) runway, Australia, made from Wagner's GPC concrete (an Earth Friendly Concrete (EFC)) [1,2], (**b**) weighbridge GPC concrete slabs at Port of Brisbane [3], (**c**) FA/GGBFS-based GPC concrete highway pavement [4], and (**d**) GPC concrete road pavement placing [5].

Table 4. Comparison of GPC and Portland cement in concrete pavement applications in terms of mechanical, durability, and thermal properties.

1. MECHANICAL	**Descriptions**	**References**
(a) Compressive strength	– Depending on the type and composition, GPC concrete shows higher compressive strength than Portland cement concrete in pavement construction. It is about 1.5 times stronger than that of OPC concrete pavement. – After 7 days of curing, the compressive strength of GPC concrete pavement is 30–120 MPa, while that of Portland cement concrete pavement is 33–53 MPa after 28 days of curing.	[71,112,128,129]

(b)	**Flexural strength**	– The flexural strength of GPC concrete increases as its NaOH solution concentration increases and reinforcement fibers also enhance it. – Fiber-reinforced GPC concrete has a higher bending strength than unreinforced GPC concrete. – GPC concrete has a better flexural strength than Portland cement concrete.	[71,93,130]
(c)	**Fracture toughness**	– GPC concrete showed 20–30% greater fracture toughness in pavement application.	[48,131–133]
(d)	**Elastic modulus**	– The elastic modulus of GPC concrete increases with an increase in compressive strength. – High-strength GPC concrete pavement shows a better comparable elastic modulus than Portland cement concrete over a 28-day test.	[71,91,97,134]
(e)	**Shear strength**	The shear strength of GPC concrete has a better shear strength property for rigid pavement for various fiber mixes and curing conditions. GPC is suitable for road base stabilization.	[71,72,135]
2.	DURABILITY	***Descriptions***	
(a)	**Resistance to chemical attack (based on surface deterioration and mass loss)**	– GPC concrete pavement shows higher resistance to the attack by chemicals such as acids (e.g., H_2SO_4, HNO_3, and HCl), sulfates, chlorides, etc., than OPC. – For instance, GPC (geopolymer mortars) are highly resistant to different concentrations of H_2SO_4 solutions, *unlike* Portland cement mortars (PCMs). – The chemical resistance of GPC concrete pavement varies with the type of precursors.	[111–113]
(b)	**Fire resistance**	GPC concrete pavement can withstand elevated temperatures in the range of 1000–1200 °C with slight deterioration due to its mechanical properties, brittleness, weather tolerance, fiber reinforcement, and thermal stability of GPC concrete, among other factors.	[93,136,137]
(c)	**Resistance to abrasion**	– This indicates the ability of the surface of cement-like material to resist wearing away by friction. – The GPC material's weight loss determines its degree of abrasion resistance. – GPC concrete pavement shows a better abrasion resistance than Portland cement concrete due to its fiber content.	[72,77,94]
(d)	**Freeze–thaw resistance**	– The *freeze–thaw resistance* of cement concrete serves as an evaluation index for assessing the durability of the concrete material. – GPC concrete pavement has excellent *freeze–thaw resistance* compared to Portland cement concrete pavement.	[43,71,75]
(e)	**Fatigue resistance**	– GPC concrete pavement has shown promising results in fatigue resistance compared to Portland cement concrete. – GPC concrete pavement has superior resistance to fatigue cracking, which is crucial for heavy-loaded pavement applications.	[93,94,137,138]
(f)	**Porosity and air permeability**	– *Porosity* measures the quantity of the total volume occupied by the pores of a material sample, while air permeability measures the volume flow rate of air through the material sample.	[33,38,103,139]

	– GPC has lower porosity and air permeability than Portland cement.	
(g) Water absorption and permeability	– Both water absorption and permeability determine the compressive strength of any cementitious material. – They depend on the pore size and continuity, nature of the cementitious materials, fiber content, humidity cycle, compactness, curing state, mix proportions, microcracks, and W/C ratio of any cement materials. – GPC concrete pavement has lower water absorption and permeability than Portland cement concrete.	[38,106,107]
(h) Drying shrinkage	– It is a measure of durability performance index that provides information on the potential cracks that can result in hardened cementitious materials. – Fiber addition improves the drying shrinkage of GPC concrete. – GPC concrete shows a better performance in withstanding drying shrinkage than Portland cement concrete.	[39,108,140]
(i) Sorptivity	– Sorptivity serves as an engineering metric for concrete's microstructure and durability-related attributes and as an indicator of concrete's resistance to unfavorable environments. – GPC possesses lower sorptivity and better performance as a pavement construction material than Portland cement.	[109,110,141]
(j) Corrosion performance	– GPC (such as FA-GPC concrete) can form a protective ferric oxide film on the steel of steel-reinforced GPC concrete, preventing it from corrosion by creating an alkaline environment provided by it. – In doing so, the silicate membrane on the reinforcement bar inserted in GPC concrete is tightly covered, which results in a low corrosion rate, *unlike* Portland cement concrete.	[38,110,142]
3. WORKABILITY, SETTING TIME, AND DENSITY	– Concrete workability measures the ease of working with newly mixed concrete with minimal homogeneity loss. GGBFS-based GPC concrete is more workable than Portland cement concrete. – Depending on the curing temperature, W/C ratio, alkali concentration, etc., GPC concrete setting time is lower than that of Portland cement concrete. – The density of GPC concrete is higher than that of Portland cement concrete.	[93,106,143,144]
4. THERMAL RESISTANCE, INSULATION, AND CONDUCTIVITY	Based on several investigations of GPC's thermal behavior in concrete compared to Portland cement, GPC shows lower thermal conductivity due to its low calcium content, among other factors, but higher thermal resistance, stability, and insulation than Portland cement under the same conditions or parameters (such as density, temperature, and strength).	[71,145,146]

Overall, geopolymer concrete (geocement concrete) significantly surpasses Portland cement concrete in several key aspects, underscoring its suitability for pavement applications. With its markedly superior mechanical properties, including higher compressive and flexural strengths and enhanced fracture toughness, geopolymer concrete is particularly adept at handling the high-load demands typical in pavement construction. Its robust durability features, such as exceptional resistance to chemical attacks, abrasion, and extreme environmental conditions like freeze–thaw cycles, further affirm its readiness for outdoor applications. The material also excels in water resistance and corrosion protection, crucial for maintaining the integrity of reinforced concrete pavements. Additionally, geopolymer concrete's advantageous workability and rapid setting time capabilities facilitate faster construction timelines, while its impressive thermal properties ensure long-term stability and performance under varying temperature conditions. Collectively, these attributes make geopolymer concrete an outstanding material of choice for pavement construction, offering enhanced sustainability and durability that meet the evolving needs of modern infrastructure. This performance solidifies the role of geopolymer cement (geocement) as a pivotal material in advancing the future of sustainable and resilient pavement solutions.

5. Challenges and Future Directions of Geopolymer Cement in Pavement Applications Challenges

1. Material Variability: One of the primary challenges in utilizing geopolymer cement is the variability in raw materials, such as fly ash, slag, and other industrial byproducts. The chemical composition of these materials can vary significantly, affecting the consistency and performance of the final geopolymer product. This variability necessitates rigorous quality control measures and tailored formulations for different applications.
2. Hardeners: The production of geopolymer cement requires hardeners like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), which can be costly and hazardous to handle. The high alkalinity of these hardeners poses safety risks during manufacturing and application, requiring careful management and protective measures.
3. Long-term Durability: While laboratory studies have demonstrated the durability of geopolymer cement, there is limited long-term field data on its performance in pavement applications. Concerns about potential issues such as carbonation, alkali–aggregate reactions, and freeze–thaw resistance in various environmental conditions need to be addressed through extensive field trials.
4. Standardization and Codes: The adoption of geopolymer cement in pavement construction is hindered by the lack of standardized testing methods, design codes, and guidelines. Without established standards, engineers and contractors may be hesitant to use geopolymer cement, despite its potential benefits.
5. Cost Competitiveness: Although geopolymer cement has environmental advantages, its cost competitiveness with traditional Portland cement is still a concern. The production and transportation of alkali hardeners and the need for specialized equipment and curing processes can increase costs.

6. Future Directions

1. Material Optimization: Research should focus on optimizing the raw material composition and alkali hardener ratios to improve the consistency and performance of geopolymer cement. Innovations in using locally available materials and industrial byproducts can enhance sustainability and reduce costs.
2. Development of Hardeners: Developing low-cost, low hardeners that are safer and easier to handle can significantly advance the practical application of geopolymers. This research can include exploring alternative hardeners derived from waste materials.
3. Field Trials and Long-term Studies: Conducting extensive field trials and long-term performance studies of geopolymer pavements in various environmental conditions will provide valuable data on durability, maintenance needs, and overall performance. These studies will help build confidence in the use of geopolymers for pavement applications.
4. Standardization and Codes Development: Establishing standardized testing methods, design codes, and construction guidelines for geopolymer cement will facilitate its broader adoption. Collaboration between industry, academia, and regulatory bodies is essential to develop these standards.

5. Cost Reduction Strategies: Implementing cost reduction strategies, such as using more affordable raw materials, optimizing production processes, and scaling up manufacturing, can make geopolymer cement more economically viable. Additionally, integrating geopolymer production with existing industrial processes can reduce overall costs.
6. Environmental and Life Cycle Assessments: Conducting comprehensive environmental and life cycle assessments will quantify the sustainability benefits of geopolymer cement compared to traditional Portland cement. These assessments can highlight the reduction in greenhouse gas emissions, energy consumption, and resource usage, promoting the environmental advantages of geopolymers.
7. Innovation in Application Techniques: Developing new application techniques and equipment tailored for geopolymer cement can improve its workability and ease of use in pavement construction. Innovations such as rapid-setting formulations and self-healing technologies can further enhance the performance and durability of geopolymer pavements.

By addressing these challenges and pursuing these future directions, geopolymer cement can become a mainstream, sustainable alternative for pavement construction, contributing to more environmentally friendly and durable infrastructure.

7. Conclusions

This paper delves into geopolymer cement in pavement applications with a critical focus on bridging sustainability and performance. The review first sets the stage by exploring the intricate chemistry of geopolymers, providing a detailed understanding of their unique properties and potential applications.

1. Building on this knowledge, GPC stands out as an innovative material for pavement construction, showcasing superior strength, chemical resistance, thermal stability, and durability against freeze–thaw cycles, making it exceptionally suitable for high-load pavement applications. This is in line with SDG 9.
2. GPC's production process significantly reduces greenhouse gas emissions and energy use when compared to Portland cement, supporting global sustainability goals. Through the use of industrial byproducts and reduced high-temperature processing, GPC reduces carbon footprint, encourages waste material recycling, and fosters a circular economy. This is in line with SDG 3, 11, and 12.
3. The integration of GPC in pavement construction not only addresses the urgent need for sustainable development but also ensures the creation of resilient infrastructure capable of withstanding the demands of modern urban environments.
4. As research and technological advancements continue to unfold, the broader adoption of GPC is anticipated, paving the way for a more sustainable and resilient future in pavement engineering.

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