

CHAPTER II

LITERATURE REVIEWS

2.1 Introduction

This chapter reviews the relevant literature to establish the scientific foundation for this thesis. The review is organized to cover several key areas. First, it explores the use of industrial by-products—specifically fly ash and calcium carbonate sludge as precursor materials for the synthesis of geopolymer mortars. This section analyzes how these materials influence the mortar's mechanical strength and durability. Following this, the chapter examines the critical role of alkaline activator solutions in driving the geopolymerization process and determining the final properties of the mortar. This entire discussion is framed within the broader context of sustainable construction materials. Finally, the review concludes by synthesizing the current research to identify a distinct knowledge gap, which provides the central motivation and justification for this study.

2.2 A Review of Fly Ash and Calcium Carbonate Sludge in Geopolymer Mortars: Impact on Strength and Durability

The demand for sustainable construction materials has driven the exploration of alternative cementitious binders. Geopolymer mortars are promising in this respect, particularly when industrial waste by-products, such as fly ash and calcium carbonate sludge (CCS), are used as partial replacements for traditional materials. This literature review evaluates the use of fly ash and CCS in geopolymer mortars, with a focus on their impact on strength and durability. Fly ash, a by-product of coal combustion, is rich in silica and alumina and is commonly used as a precursor in geopolymer formulations. It is particularly valued for its potential to improve both the mechanical

properties and durability of geopolymer mortars. The high pozzolanic activity of fly ash leads to the formation of strong alumina-silicate bonds when activated with alkaline solutions, such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). For instance, a study by Mohana and Bharathi (2022) demonstrated that pre-treated fly ash geopolymer mortars could reach significant compressive strengths and resist chloride ion penetration, which is crucial for durability in marine environments. Additionally, Ozcelikci et al. (2023) found that geopolymer mortars with a blend of fly ash and slag exhibited enhanced compressive strength and durability, especially under thermal cycling conditions. Calcium carbonate sludge, a by-product of sugarcane processing, has been increasingly explored as an additive in geopolymer mortars. While less reactive than fly ash, CCS contributes to improved workability and may enhance certain mechanical properties. However, it has been observed that adding CaCO_3 can decrease the overall compressive strength when used in large proportions.

Lekshmi et al. (2022) explored the durability of geopolymer mortars incorporating both fly ash and CCS and found that while CaCO_3 increased the setting time, it marginally reduced compressive strength. However, the presence of calcium compounds like CaCO_3 in the matrix improved the resistance to sulfate attack, thus enhancing durability in aggressive environments. Another study indicated that nano-calcium carbonate could improve the microstructure of geopolymer mortars, leading to increased strength and reduced porosity. Combining fly ash and CCS in geopolymer mortars has been shown to yield both positive and negative effects on strength and durability. This mixture also exhibited improved workability, which is beneficial for practical construction applications. Additionally, Ozcelikci et al. (2023) reported that the inclusion of calcium carbonate in geopolymer mortars positively impacted the long-term durability, particularly in terms of resistance to efflorescence, a common issue in fly ash-based mortars.

However, the addition of higher proportions of CCS can negatively impact the overall compressive strength of the geopolymer mortars. For example, an experimental study found that while CaCO_3 improves thermal resistance and

workability, it can lower the strength properties of mortars when used at levels exceeding 30% by weight. Durability is a critical factor in the application of geopolymer mortars. Fly ash-based geopolymers have demonstrated excellent durability properties, particularly in environments where resistance to chemical attacks is crucial. The high alumino-silicate content in fly ash forms a dense matrix that resists the ingress of harmful chemicals like chlorides and sulfates, which can degrade conventional Portland cement-based materials. A study by Qaidi et al. (2022) emphasized that incorporating calcium carbonate can help mitigate efflorescence issues, further enhancing the durability of fly ash-based geopolymer mortars.

The use of industrial by-products like fly ash and CCS not only improves the performance of geopolymer mortars but also contributes significantly to sustainability in construction. Geopolymer mortars reduce the environmental impact of traditional cement production by utilizing waste materials that would otherwise contribute to landfill or pollution. This aligns with global efforts to reduce CO₂ emissions and promote sustainable development. The combination of fly ash and calcium carbonate sludge in geopolymer mortars offers significant benefits for strength and durability, though careful consideration of mixed proportions is required. Fly ash contributes to high compressive strength and chemical resistance, while calcium carbonate improves workability and enhances certain durability aspects like sulfate resistance. Overall, the use of these materials in geopolymer mortars aligns with sustainability goals, providing a low-carbon alternative to conventional cementitious binders.

2.3 Previous Studies Exploring Alkaline Solutions' Role in Geopolymer Mortar Performance

Geopolymers are recognized as sustainable, eco-friendly alternatives to traditional Portland cement, contributing to significant reductions in carbon emissions. The use of geopolymer mortars, which utilize industrial by-products such as fly ash and calcium carbonate sludge, has gained attention for its potential to mitigate

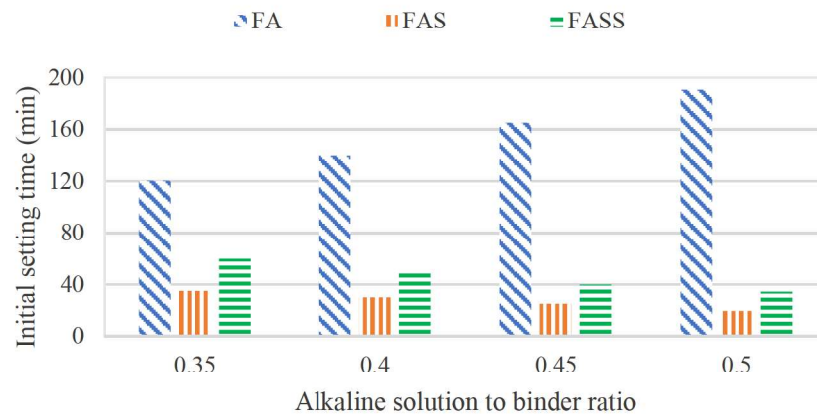
environmental degradation while offering robust mechanical properties, including high compressive strength and chemical resistance. A crucial factor in the performance of geopolymer mortars is the composition and concentration of alkaline solutions, which act as activators to enhance the dissolution and polymerization of aluminosilicate materials. This literature review explores previous studies on the role of different alkaline solutions, particularly sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), in the synthesis and performance of geopolymer mortars.

NaOH is a commonly used activator in geopolymer systems due to its effectiveness in dissolving aluminosilicate sources such as fly ash. Several studies have demonstrated that increasing the molarity of NaOH enhances the compressive strength of geopolymer mortars. For example, an experimental study conducted by Palomo et al. (1999) showed that higher NaOH concentrations (up to 15M) significantly improved the mechanical performance of fly ash-based geopolymer mortars. Similarly, research by Hardjito et al. (2005) found that the optimum molarity of NaOH in geopolymer concrete is between 10M and 15M, depending on the specific mix proportions.

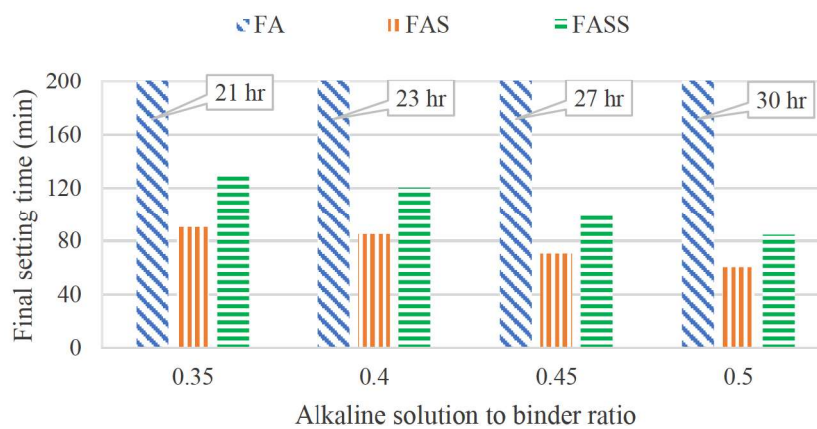
The addition of sodium silicate, commonly referred to as water glass, further boosts the polymerization process in geopolymer systems. The combination of NaOH and Na_2SiO_3 is particularly effective in creating a robust geopolymer matrix. Duxson, Provis, et al. (2007) reported that the ratio of Na_2SiO_3 to NaOH significantly impacts the compressive strength, workability, and setting time of geopolymer mortars. Ratios between 0.5:1 to 2:1 Na_2SiO_3 to NaOH have been explored, with results indicating that a balanced ratio optimizes both mechanical performance and setting time. **Figure 2.1** shows the effect of sodium hydroxide solution molarity on the setting time of geopolymer mortars.

The molarity of NaOH not only influences the compressive strength but also significantly affects the setting time of geopolymer mortars. Research by Samarakoon et al. (2019) observed that lower molarity NaOH solutions result in slower setting times, whereas higher molarity solutions accelerate the setting process, which is desirable in

certain construction applications. However, the balance between compressive strength and workability must be carefully managed, as high NaOH molarity may result in less workable mixes.



(a)



(b)

Figure 2.1 Effect of sodium hydroxide solution molarity on setting time of geopolymers mortar with various binders at ambient temperature and A/B of 0.35 (a) initial setting time (b) final setting time (Elyamany et al., 2018).

Figure 2.2 shows the impact of sodium hydroxide molarity on 7-day compressive strength. The use of fly ash as the primary aluminosilicate source in

geopolymer mortars is well-documented. **Figure 2.3** illustrates the effect of varying NaOH to Na_2SiO_3 ratios on the 7-day compressive strength of geopolymer mortars. However, the integration of calcium carbonate sludge (CCS), a by-product of the sugar industry, presents a novel approach to enhancing the sustainability of geopolymer mortars. Studies by Davidovits (2008) and Rattanasak and Chindaprasirt (2009) suggest that the addition of CCS can influence the setting time, density, and compressive strength of geopolymer mortars.

The performance of geopolymer mortars is highly dependent on the composition and concentration of alkaline activators. Sodium hydroxide and sodium silicate, in various combinations, play critical roles in determining the mechanical properties, setting time, and durability of geopolymer mortars. While higher NaOH molarity generally enhances compressive strength, the addition of sodium silicate improves workability and accelerates the polymerization process. Future research should continue to explore the optimal ratios of these alkaline solutions in combination with supplementary materials like calcium carbonate sludge to further enhance the sustainability and performance of geopolymer mortars.

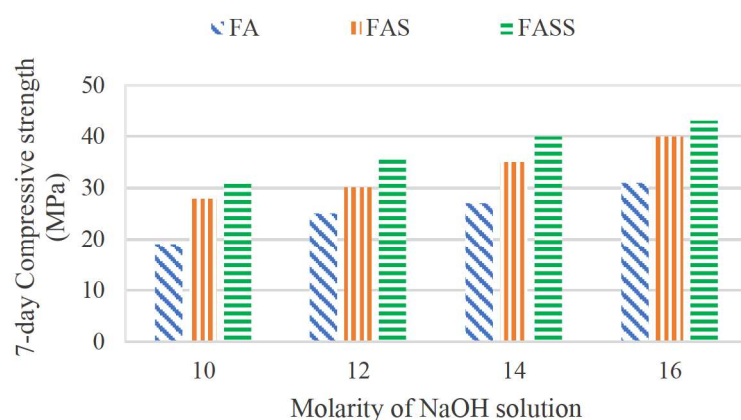


Figure 2.2 Effect of sodium hydroxide solution molarity on 7- day compressive strength of geopolymer mortar with various binders at curing temperature of 60 °C and A/B of 0.35 (Elyamany et al., 2018).

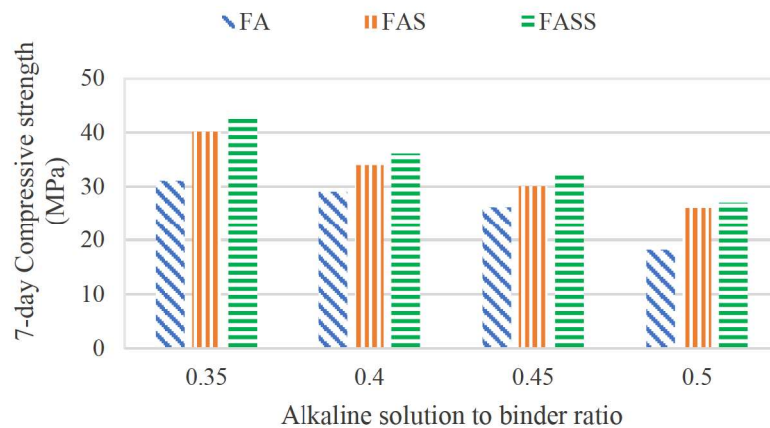


Figure 2.3 Effect of alkaline solution to binder ratio on 7- day compressive strength of geopolymer mortar with various binders at curing temperature of 60 C and NaOH molarity of 16 M (Elyamany et al., 2018).

2.4 Sustainable Alternatives in Construction: A Review of Geopolymer Mortars Using Industrial By-Products

The environmental impact of traditional construction materials, particularly ordinary Portland cement (OPC), has led to an urgent need for sustainable alternatives. Geopolymer mortars, a class of inorganic polymers, have emerged as a promising solution due to their lower carbon footprint, high mechanical performance, and utilization of industrial by-products. These materials are synthesized by activating aluminosilicate materials such as fly ash and ground granulated blast furnace slag (GGBFS) with alkaline solutions, offering enhanced durability and resistance to aggressive environments. This literature review explores the use of industrial by-products, including fly ash and calcium carbonate sludge, in the production of geopolymer mortars, evaluating their mechanical properties, environmental benefits, and potential for large-scale application. Geopolymers have garnered attention due to their potential to replace conventional cement-based materials, which are responsible for approximately 8% of global CO₂ emissions. By utilizing industrial by-products, geopolymers provide a low-energy and low-emission alternative, aligning with global

sustainability goals. Davidovits (2008) pioneered the concept of geopolymers, emphasizing their ability to form stable, inorganic polymeric networks through the activation of aluminosilicate precursors with alkaline solutions such as sodium hydroxide and sodium silicate.

Fly ash, a waste product of coal combustion in thermal power plants, is one of the most used industrial by-products in geopolymer mortar synthesis. Studies have shown that fly ash-based geopolymer mortars exhibit excellent compressive strength, low shrinkage, and resistance to chemical attack. According to Hardjito et al. (2005), fly ash-based geopolymer concrete can achieve compressive strengths exceeding 40 MPa, comparable to traditional OPC concrete, with the added benefit of reducing greenhouse gas emissions by up to 80%.

The primary environmental advantage of geopolymer mortars lies in their ability to significantly reduce CO₂ emissions compared to traditional cement-based materials. A life cycle analysis conducted by Habert et al. (2011) found that geopolymers emit up to 80% less CO₂ than Portland cement, largely due to the avoidance of calcination, which is a major contributor to greenhouse gas emissions in cement production. Fly ash and other industrial by-products used in geopolymer mortars are typically waste materials that would otherwise contribute to environmental pollution. By utilizing these by-products, geopolymer mortars not only reduce carbon footprints but also address the issue of industrial waste disposal. Geopolymer mortars contribute to resource efficiency by replacing conventional cement with industrial waste materials. This reduces the reliance on virgin raw materials such as limestone and clay, which are heavily mined for cement production. Moreover, the lower energy demand for the synthesis of geopolymers compared to the energy-intensive clinker production process in Portland cement further underscores their sustainability.

Several studies have demonstrated that geopolymer mortars can achieve compressive strengths comparable to or even higher than conventional cement

mortars. Research by Palomo et al. (1999) and Nath and Sarker (2014) revealed that the compressive strength of fly ash-based geopolymers could range from 30 MPa to 50 MPa, depending on the type and concentration of the alkaline activator used. The addition of GGBFS or CCS can further enhance the compressive strength, making geopolymer mortars suitable for structural applications. Geopolymer mortars have demonstrated excellent resistance to chemical attack, particularly in aggressive environments such as marine and industrial settings. Studies by T Bakharev (2005) and Fernández-Jiménez et al. (2005) show that geopolymer mortars exhibit superior resistance to sulfate attack, acid exposure, and chloride penetration compared to traditional cement mortars as shown in **Figure 2.4-2.6**. The low permeability of geopolymer mortars, combined with their dense microstructure, makes them ideal for applications where durability is critical. Furthermore, their resistance to high temperatures and fire makes them suitable for fireproofing materials and applications in high temperature environments.

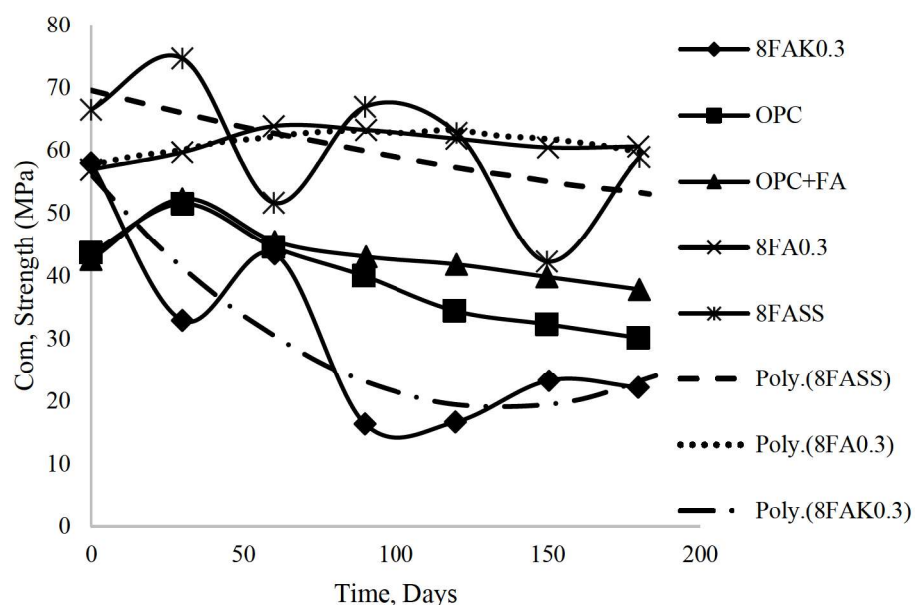


Figure 2.4 Compressive strength evolution of the geopolymer and Portland cement specimens exposed to 5% sodium sulfate solution (T Bakharev, 2005).

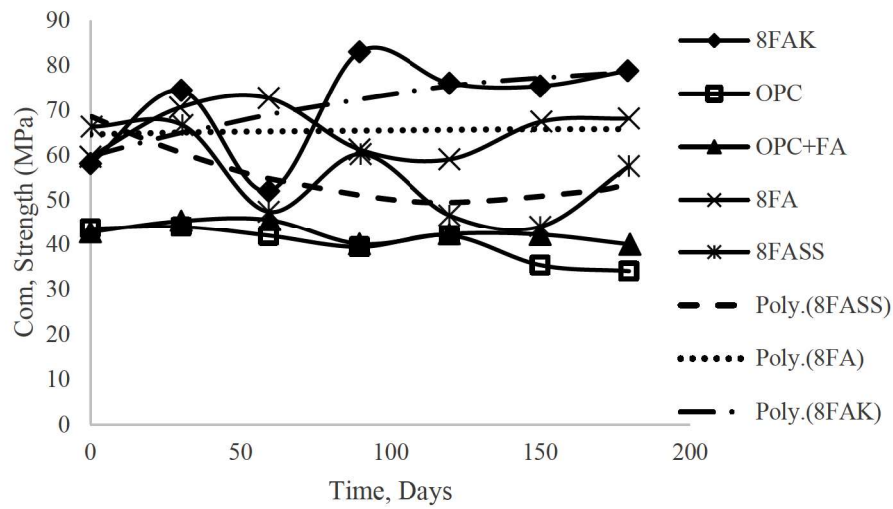


Figure 2.5 Compressive strength evolution of the geopolymer and Portland cement specimens exposed to 5% magnesium sulfate solution (T Bakharev, 2005).

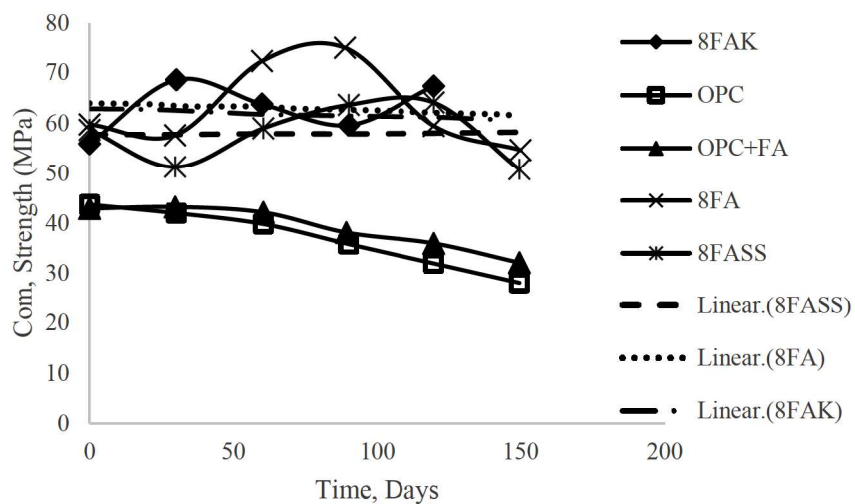


Figure 2.6 Compressive strength evolution of the geopolymer and Portland cement specimens exposed to a solution of 5% sodium sulfate+5% magnesium sulfate (T Bakharev, 2005).

Geopolymer mortars provide a sustainable alternative to conventional cement-based materials by utilizing industrial by-products such as fly ash, GGBFS, and CCS. These materials not only reduce CO₂ emissions but also address waste management issues by repurposing industrial waste. Geopolymers exhibit excellent

mechanical properties, chemical resistance, and durability, making them viable for various construction applications. As research continues to optimize their mix proportions and activator compositions, geopolymer mortars are poised to play a significant role in the future of sustainable construction.

2.5 Identifying Gaps in Geopolymer Mortar Research

Geopolymer mortars have garnered significant attention as eco-friendly alternatives to traditional Portland cement mortars. The utilization of industrial by-products such as fly ash, calcium carbonate sludge (CCS), and other aluminosilicate materials for geopolymer production offers environmental benefits, including reduced carbon emissions and improved waste management. However, despite the numerous studies on geopolymer mortars, there remain several gaps in the existing research, particularly in the areas of material optimization, long-term durability, and the feasibility of large-scale adoption. This literature review identifies key gaps in the current research and suggests areas for further exploration.

While significant research has been conducted on using fly ash, ground granulated blast furnace slag (GGBFS), and other industrial by-products in geopolymer mortars, the role of calcium carbonate sludge (CCS) remains underexplored. CCS is a by-product of the sugar industry and has the potential to enhance the sustainability of geopolymers by reducing the demand for conventional materials and mitigating environmental issues related to its disposal. However, there is limited research on the optimal mix proportions and the long-term performance of geopolymer mortars that incorporate CCS. Existing studies, such as those by Rattanasak and Chindapasirt (2009), have demonstrated that the addition of CCS can improve the workability of geopolymer mortars. However, the specific impact of CCS on the setting time, compressive strength, and durability of geopolymer mortars in various environmental conditions is not well-documented. Further research is needed to fully understand the

role of CCS as a sustainable alternative and its potential to replace or supplement other aluminosilicate materials.

Geopolymer synthesis relies heavily on the activation of aluminosilicate materials with alkaline solutions, typically sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Although various studies have explored the influence of alkaline activators on the performance of geopolymer mortars, there is no clear consensus on the optimal ratios of NaOH and Na_2SiO_3 for different by-products, particularly when new materials like CCS are introduced. For instance, the current research proposal investigates various NaOH-to- Na_2SiO_3 ratios in geopolymer mortars made from fly ash and CCS. However, there is a lack of standardized guidelines on how to determine these ratios for the best mechanical performance, workability, and durability. Studies such as those by Duxson, Provis, et al. (2007) have indicated that the ratios of alkaline solutions play a critical role in the polymerization process, but further research is required to develop tailored solutions for different industrial by-products.

Curing conditions, particularly temperature and humidity, have a significant influence on the performance of geopolymer mortars. Many studies focus on curing geopolymers at elevated temperatures (60°C to 80°C) to enhance early strength development. However, the feasibility of large-scale applications where ambient temperature curing is the norm remains a critical research gap. For example, research by Bernal et al. (2011) indicated that ambient temperature curing results in lower compressive strengths for geopolymer mortars compared to those cured at elevated temperatures. Moreover, the variability in curing practices across different studies has led to inconsistent results, making it difficult to compare performance data across studies. More standardized research on ambient temperature curing, particularly in real-world environments, is necessary to ensure the widespread adoption of geopolymer mortars in construction.

While short-term mechanical properties such as compressive strength are well-documented in geopolymer mortar research, there is a dearth of studies on the long-

term durability of these materials. Factors such as freeze-thaw cycles, sulfate attack, carbonation, and chloride ion penetration can significantly affect the longevity of geopolymer mortars in different environments. For instance, research by Duxson, Provis, et al. (2007) highlighted the importance of durability studies but acknowledged that long-term testing under real environmental conditions is still lacking. There is little information available on how geopolymer mortars incorporating CCS behave over extended periods when exposed to aggressive environments such as marine or wastewater conditions. Long-term studies are essential to ensure that geopolymer mortars can offer the same level of durability as traditional OPC mortars.

Although geopolymer mortars have demonstrated significant promise in laboratory settings, there are considerable challenges associated with scaling up these materials for practical use in large-scale construction projects. Issues such as the availability of raw materials (e.g., fly ash and GGBFS), consistency in material quality, and the economic feasibility of producing alkaline activators on a large scale have not been sufficiently addressed in the literature. Furthermore, the development of standardized manufacturing processes and quality control measures for geopolymer mortars is crucial for their adoption by the construction industry. Currently, the lack of established regulations and industry standards is a significant barrier to the widespread use of geopolymer mortars. Addressing these issues through large-scale pilot projects and collaboration with industry stakeholders will be necessary for the successful implementation of geopolymer technologies in the construction sector.

While geopolymer mortars have been extensively studied as sustainable alternatives to traditional cement-based materials, several gaps remain in the research. The role of CCS in geopolymer mortars, optimal alkaline solution ratios, curing conditions, long-term durability, and large-scale implementation challenges are areas that require further investigation. Addressing these gaps will be critical for advancing geopolymer technology and ensuring its practical adoption in the construction industry.