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Review of Self Compacting Geopolymer Concrete Using Slag Sand as Fine Aggregate

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Abstract: The manufacture of ordinary Portland cement produces a lot of CO2s in the atmosphere. The production of cement emits approximately 5% of worlds carbon. Carbon dioxide emissions from the cement industry are a major environmental concern, which is increasing day by day searching for an alternative replacement for cement has become very important.

Self-compacting concrete (SCC) offers advantages in complex formwork and congested reinforcement, but its reliance on Portland cement raises environmental concerns. Geopolymer concrete is an eco-friendly construction material that utilizes industrial by-products such as fly ash, ground granulated blast furnace slag, rice husk ash, and metakaolin as binders. Recycling these waste materials for construction offers a sustainable solution to environmental concerns and presents a cost-effective building alternative.

This review explores the potential of integrating the self-compacting properties of SCC with the sustainability of GPC by using slag sand as a fine aggregate. It examines key aspects such as workability, mechanical strength, durability, and microstructure of SCC-GPC incorporating slag sand. Additionally, it highlights the challenges, existing research gaps, and future research directions in this area.

Developing new construction materials from industrial waste contributes to a more sustainable future by providing an environmentally friendly and resource-efficient alternative in the construction industry.

The literature on geopolymer concrete which is based various industrial wastes such as fly ash, copper slag etc… replaced by natural resource in geopolymer concrete This study provides a review of research era in the field of Self compacting Geo polymer concrete..

Index terms: Self-compacting geopolymer concrete, slag sand, sustainable construction, mechanical properties, durability.

I. Introduction

conventional Concrete is the second most widely used material globally after water, with Portland cement being its primary binder. However, cement production significantly contributes to CO_2 emissions, accounting for approximately 7–8% of global emissions (Rangan, 2008; Habert et al., 2011). Due to environmental concerns, sustainable alternatives like geopolymer concrete (GPC) have gained attention. GPC utilizes industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume to minimize its carbon footprint while maintaining mechanical and durability properties (Davidovits, 1999; Singh, 2018).Self-compacting concrete (SCC) was developed to enhance workability and reduce labor needs, allowing the concrete to flow under its own weight without mechanical vibration (Okamura & Ouchi, 2003). Self-Compacting Concrete (SCC) has gained widespread popularity, particularly in reinforced structures, due to its superior flowability, durability, and ease of placement (De Schutter et al., 2009). Moreover, incorporating industrial by-products such as fly ash, slag, and copper slag into SCC helps reduce cement dependency, thereby lowering CO_2 emissions (Onyelowe & Kontoni, 2023).

With the growing focus on sustainable materials, advancements in Self-Compacting Geopolymer Concrete (SCGC) have combined the benefits of both SCC and Geopolymer Concrete (GPC) (Sherwani et al., 2022). SCGC eliminates the need for cement while utilizing waste materials like fly ash, slag, and recycled aggregates, significantly reducing its environmental footprint (Arunachelam et al., 2022). By polymerizing aluminosilicate materials in an alkaline medium, SCGC forms a highly durable and chemically resistant structure, making it well-suited for harsh environmental conditions (Saloni et al., 2021).

Researchers have also explored the use of alternative aggregates, such as steel slag and copper slag, as sustainable substitutes for natural aggregates. These materials not only enhance the mechanical strength and durability of concrete but also offer carbon sequestration benefits, making them a promising option for construction and pavement applications (Kandhal & Hoffman, 1997; Ahmedzade & Sengoz, 2009). Their effectiveness has been demonstrated in hot-mix asphalt (HMA) and pavement-quality concrete (PQC), contributing to stronger and more sustainable infrastructure while reducing the environmental impact of construction activities (Lye et al., 2015).

SCGC, with its innovative combination of alternative binders and aggregates, represents a promising step toward sustainable construction. However, further research is needed to optimize mix designs, improve curing methods, and facilitate large-scale implementation in infrastructure projects (Sherwani et al., 2022).

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Geopolymer Concrete: Advances in Material Synthesis and Performance

Geopolymers are aluminosilicate-based materials with an amorphous to semi-crystalline structure, synthesized from natural or industrial by-products such as fly ash, red mud, slag, metakaolin, perlite, and rice husk ash (Pawluczuk, 2021; Xu, 2000). The geopolymerization process involves alkaline activation of these materials, with granulated blast furnace slag (GBFS) serving as a non-toxic, high-performance filler, particularly in fire-resistant applications (Cheng, 2003).

Fly ash-based geopolymer concrete (GPC) is characterized by superior sulfate resistance, low creep, and minimal shrinkage (Hardjito, 2004, 2005). The environmental footprint of GPC is notably lower than that of Portland cement concrete, especially when produced with low-calcium fly ash or GBFS, requiring minimal sodium silicate activation (Habert, 2011). The curing regime significantly impacts the strength development of GPC, with optimal curing temperatures ranging from 60°C to 100°C (Chithambaram, 2017).

GPC has demonstrated enhanced mechanical performance in aggressive environments, exhibiting improved strength, durability, and volume stability (Bachhav, 2016). The incorporation of micro silica and calcium carbonate has shown negligible effects on durability (Elchalakani, 2018). Moreover, hybrid fiber reinforcement and ground granulated blast furnace slag (GGBS) contribute to enhanced tensile and compressive strength (Sanjay Kumar, 2018). Complete replacement of cement with GGBS results in high-strength geopolymer concrete with superior early-age performance without heat curing (Zannerni, 2019).

As research advances, geopolymer technology presents a viable alternative to traditional cementitious systems, offering lower CO_2 emissions and improved sustainability in construction (Tempest, 2015)

Geopolymers are synthesized by activating aluminosilicate-rich materials, such as fly ash, slag, and metakaolin, using alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) (Davidovits, 1988). This reaction forms a three-dimensional polymeric network that enhances strength, durability, and resistance to harsh environments (Xu & Van Deventer, 2000).

The geopolymerization process includes three main stages:

1. Dissolution – Silicon (Si) and aluminum (Al) ions dissolve in the alkaline solution.
2. Gel Formation – The dissolved ions undergo condensation, forming a reactive gel.
3. Polymerization and Hardening – The gel reorganizes into a stable aluminosilicate structure, providing strength and durability (Van Jaarsveld et al., 2002).

Unlike Portland cement, which gains strength through calcium silicate hydrate (C-S-H) gels, geopolymer binders develop sodium-aluminosilicate-hydrate (N-A-S-H) and calcium-aluminosilicate-hydrate (C-A-S-H) gels, resulting in enhanced chemical and thermal resistance (Hardjito et al., 2005). Several factors affect the mechanical properties of geopolymer concrete, including NaOH concentration, activator-to-binder ratio, and curing conditions (Meesala et al., 2019). The addition of GGBS as a secondary binder improves early strength development and workability (Ahmed et al., 2022). Moreover, using steel slag aggregates enhances thermal stability, making the material suitable for high-temperature applications (Kumar & Bishnoi, 2020).

Studies indicate that geopolymer concrete can achieve compressive strengths of up to 70 MPa, making it a feasible option for high-performance structural applications (Azad & Samarakoon, 2021). The incorporation of fiber reinforcements, such as glass fibers, further enhances impact resistance, broadening its application in infrastructure and industrial settings (Ganesh & Muthukannan, 2021).

Self-Compacting Concrete: Advances in Workability, Durability, and Sustainability

Self-compacting concrete (SCC) has been extensively studied, with research focusing on its rheological properties and performance (Ozawa, 1989; Okamura, 1993; Maekawa, 1999). A key aspect of SCC is its ability to flow through reinforced sections without external vibration, ensuring homogeneity and ease of placement. The role of viscosity-modifying admixtures (VMA) has been emphasized in enhancing stability by mitigating segregation and surface bleeding across varying water-cement (w/c) ratios (Mukai, 2000).

SCC is formulated through a balance of flowability and stability, incorporating mineral and chemical admixtures such as pozzolans, limestone fillers, superplasticizers (SP), and VMAs (Suksawang, 2006). Mixture design approaches are primarily classified into Japanese and Chinese methods, with the Japanese approach enabling the development of cost-effective SCC achieving 50 MPa at 28 days (Brouwers & Radix, 2005). Comparative studies have evaluated SCC and conventionally compacted concrete (CCC) in heavily reinforced T-beams (Kumar, 2009).

SCC eliminates the need for mechanical compaction, reducing placement costs and improving site conditions, particularly in urban environments (Siddiquea, 2012). However, its durability is influenced by constituent materials, particularly in fire resistance (Seshu, 2013). Optimized SCC mixtures using binary, ternary, and quaternary blends have demonstrated improved mechanical performance, though air-entrained SCC exhibits higher chloride penetration due to increased permeability (El-Chabib, 2013).

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Recent advancements in SCC focus on nano-modification, with nanoparticles (NPs) enhancing microstructural properties (Aslani, 2015). The use of lightweight aggregates such as lightweight expanded clay aggregate (LECA) and feldspar has facilitated the development of sustainable, lightweight SCC (Rampradheep, 2016). The application of high-performance SCC in iconic structures such as the Sagrada Familia underscores its structural advantages (Rodríguez, 2017). Additionally, studies on magnetized water have demonstrated its potential to enhance early-age hydration and long-term strength (Esfahani, 2018).

SCC sustainability has been further improved by incorporating recycled rubber aggregates, leading to self-compacting rubberized concrete (SCRC), which enhances durability while addressing environmental concerns (Aslani, 2019). As SCC technology evolves, integrating novel materials and nanotechnology will continue to drive improvements in structural performance and sustainability.

Steel slag has been extensively utilized as an unbound subbase and backfill material (Prithvi S, 1997). However, with increasing concerns over resource depletion and energy consumption, research has focused on sustainable alternatives to natural sand in concrete (Stewart et al., 2006). Stainless steel slag carbonation has shown potential in solid waste stabilization, effectively reducing heavy metal leaching, particularly chromium (Johnson et al., 2003). Additionally, carbonated ladle slag has been investigated as a fine aggregate, where CO_2 treatment reduces free lime content while stabilizing gaseous CO_2 into solid carbonates (Monkman, 2009).

The concrete industry is a major consumer of natural resources, generating large volumes of demolition waste, much of which is landfilled. The adoption of recycled concrete aggregates (RCA) mitigates this issue, reducing waste and conserving natural aggregates. The integration of RCA with fly ash further enhances sustainability and material performance (Tangchirapat, 2010).

Slag sand

Steel slag aggregates have been recognized as high-quality mineral aggregates in construction, reinforcing their classification as sustainable materials (Sofilic, 2011). Additionally, copper slag has been identified as a viable fine aggregate in pavement quality concrete (PQC) and dry lean concrete (DLC), both essential for subbase layers in pavement applications (Binod Kumar, 2019).

Recent studies have explored the incorporation of metallurgical waste in RCA, either directly or as a fine aggregate replacement. Various approaches include direct addition, integration into rounded RCA, and partial replacement using crushed RCA. These techniques promote waste utilization, concrete recycling, and sustainable construction practices (Pizo, 2020).

Economic and Environmental Benefits

The The use of industrial by-products such as fly ash, slag, and recycled aggregates in geopolymer concrete significantly reduces the demand for virgin raw materials, lowering costs and reducing waste disposal issues (Swanepoel & Strydom, 2002). Additionally, geopolymer technology requires less energy compared to Portland cement, leading to reduced greenhouse gas emissions (Rangan, 2008).

Research has shown that geopolymer concrete can cut CO_2 emissions by up to 80%, making it a sustainable alternative to conventional concrete (Habert et al., 2011). Repurposing industrial waste through geopolymerization not only helps reduce disposal costs but also supports carbon credit incentives, making it an economically viable solution (Gourley, 2003). The development of Self-Compacting Geopolymer Concrete (SCGC) further strengthens sustainability efforts by completely eliminating cement while maintaining excellent mechanical performance (Rahman & Al-Ameri, 2021). The use of high-volume fly ash and slag improves the material’s lifecycle performance, lowers construction-related carbon emissions, and promotes efficient waste management (Mocharla et al., 2022).

Alternative materials such as copper slag and steel slag offer both environmental and economic benefits. Replacing fine aggregates with copper slag enhances abrasion resistance and durability, making it particularly suitable for high-traffic areas (Kumar, 2013). Similarly, steel slag aggregates have been deemed safe for construction, addressing concerns related to radioactivity and environmental impact (Sofilić et al., 2011). From a geo-environmental perspective, steel slag fines have been effectively used to immobilize heavy metals, helping to reduce pollution and contribute to sustainable waste management (Grubb et al., 2011). Additionally, carbonated ladle slag fines improve cementitious properties while lowering CO_2 emissions, making them a promising supplementary cementitious material (SCM) (Monkman et al., 2009).

Structural Performance

Geopolymer concrete (GPC) has demonstrated impressive structural performance, especially in reinforced concrete elements such as beams and columns. Research indicates that the flexural and shear behavior of GPC beams is comparable to traditional OPC concrete, making it a strong alternative for load-bearing structures (Alex et al., 2022). Additionally, GPC exhibits exceptional resistance to acid and sulfate exposure, ensuring long-term durability in harsh environments while minimizing maintenance costs (Wong, 2022).

The compressive strength of GPC largely depends on the concentration of alkaline activators used in its mix. Studies show that increasing the NaOH molarity up to 20M enhances compressive strength; however, exceeding this concentration can lead to shrinkage and reduced workability (Selvan & Ganesan, 2021).

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Optimized mix designs further improve GPC's mechanical performance, making it a dependable material for structural applications (Anand et al., 2017).

Similarly, self-compacting concrete (SCC) has demonstrated exceptional structural efficiency in components such as T-beams, columns, and drilled shafts. Its self-compacting nature ensures uniform compaction, better homogeneity, and a superior surface finish, ultimately enhancing load-bearing capacity and durability (Kumar et al., 2009). Thus, both geopolymer and self-compacting concretes present sustainable, high-performance alternatives to conventional cement-based materials, making them well-suited for structural applications.

Optimizing the mix design of geopolymer concrete (GPC) is crucial for enhancing its strength and durability. Key factors such as the alkaline-to-binder ratio, activator molarity, and curing conditions significantly impact its performance. Recent research has focused on achieving a balance between workability and strength to facilitate large-scale adoption. Further exploration is needed to assess GPC's potential in high-rise buildings, marine environments, and infrastructure exposed to extreme conditions. Additionally, developing cost-effective formulations using locally available materials can promote its widespread use.

For self-compacting concrete (SCC), achieving an optimal mix composition is essential to maintaining flowability without segregation. The use of superplasticizers and viscosity-modifying agents (VMA) improves performance, while lightweight aggregates like expanded clay or vermiculite further enhance its properties. Advanced materials such as nano-silica and nano-clay have also shown promise in boosting mechanical strength and durability. SCC formulated with geopolymer technology offers an eco-friendly alternative by eliminating cement use. Industrial by-products like steel slag and copper slag are increasingly being considered as substitutes for natural aggregates. Proper curing methods can mitigate the volumetric instability of steel slag, making it a viable material for concrete applications. Copper slag, with its high specific gravity and low water absorption, has been successfully used as a fine aggregate replacement, enhancing the strength and durability of pavement-quality concrete.

Sustainable concrete solutions, including slag-based geopolymer concrete (SCGC), integrate industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS). Alkali activators initiate polymerization, forming a durable Si-O-Al network that enhances overall performance. Studies suggest that replacing natural sand with manufactured sand or copper slag by up to 50% improves workability and mechanical properties while supporting environmental sustainability. Additionally, incorporating ultrafine slag enhances microstructural density, improving durability in aggressive environments.

Fresh and Hardened Properties of SCC

Self-compacting concrete (SCC) exhibits superior fresh-state properties, including high deformability, flowability, and passing ability, allowing it to easily move through congested reinforcement without obstruction. Workability and segregation resistance are commonly evaluated using tests such as the slump flow, L-box, and V-funnel (Hodgson et al., 2005). Research has shown that using magnetized water improves flowability while reducing reliance on superplasticizers (Esfahani et al., 2018).

In terms of mechanical performance, SCC achieves early strength comparable to or even higher than conventional concrete, particularly when high-performance admixtures and proper curing methods are employed (Suksawang et al., 2006). Although SCC generally has a lower modulus of elasticity, its tensile strength and durability can be enhanced through optimized mix designs. Replacing fine aggregate with copper slag has been found to improve compressive strength and durability (Gupta & Siddique, 2020), whereas incorporating crumb rubber increases ductility but slightly reduces compressive strength (Aslani & Khan, 2019). Self-compacting geopolymer concrete (SCGC) also exhibits excellent fresh-state properties, including high flowability, passing ability, and segregation resistance, making it ideal for structures with complex reinforcement (Nuruzzaman et al., 2020). Research indicates that replacing 40% of fine aggregate with ferronickel slag results in a compressive strength of 66 MPa at 28 days (Nuruzzaman et al., 2020). Similarly, incorporating up to 50% copper slag as a fine aggregate enhances both strength and durability (Arunachelam et al., 2022). Concrete incorporating steel and copper slag aggregates demonstrates improved workability, strength, and durability compared to conventional mixes. Steel slag has also been found to enhance Marshall stability and rutting resistance in asphalt applications (Ahmedzade & Sengoz, 2009). Additionally, using high-fineness fly ash and recycled aggregates improves slump retention, compressive strength, and elasticity, making it a promising solution for sustainable concrete applications (Tangchirapat et al., 2010). Furthermore, carbonated ladle slag fines have been explored as CO_2-sequestering sand substitutes, further supporting sustainability efforts (Monkman et al., 2009).

Structural Performance and Applications

Self-compacting concrete (SCC) has demonstrated outstanding structural efficiency in various applications, including T-beams, columns, and drilled shafts, due to its superior durability and load-bearing capacity. Its self-leveling ability ensures uniform compaction, reducing defects and improving structural integrity (Kumar et al., 2009). Lightweight self-compacting concrete (LWASCC), which incorporates lightweight aggregates, lowers density while maintaining self-compacting properties, making it ideal for high-rise buildings and precast elements (Papanicolaou & Kaffetzakis, 2011). SCC has been extensively used in projects such as the Temple of Sagrada Familia, where its high flowability facilitated the construction of intricate architectural components (Rodríguez et al., 2017). Additionally, SCC's application in precast concrete, bridge piers, and high-rise structures has reduced labor costs while enhancing construction quality (Rahman & Al-Ameri, 2021). Its self-leveling properties make it suitable for underwater construction and tunnel linings without requiring external compaction (Rampradheep & Sivaraja, 2016). Self-compacting geopolymer concrete (SCGC) is increasingly recognized in infrastructure projects for its strength and resilience.

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SCGC containing copper slag has demonstrated superior resistance to chloride penetration and water absorption, making it a viable option for marine and aggressive environments.

(Sherwani et al., 2022). Notably, SCGC has also been utilized in the Temple of Sagrada Familia due to its workability in intricate structural elements (Rodríguez et al., 2017). The addition of ultrafine slag further improves mechanical properties and sustainability in precast applications (Saloni et al., 2021). The integration of steel slag and copper slag in concrete has also been widely explored in infrastructure projects. Steel slag aggregates have been used extensively in road construction, asphalt pavements, and subbase layers due to their high load-bearing capacity and deformation resistance (Ahmedzade & Sengoz, 2009). Likewise, copper slag has been applied in pavements, precast elements, and marine structures, improving both durability and strength (Lye et al., 2015). Replacing natural sand with copper slag in dry lean concrete (DLC) has been found to improve cohesiveness, reduce segregation, and enhance texturing in pavement applications (Kumar, 2013).

The use of geopolymer concrete with recycled aggregates offers a sustainable alternative to traditional Portland cement concrete. By utilizing industrial by-products, GPC significantly reduces CO_2 emissions and conserves natural resources. Despite its advantages, factors such as raw material variability, curing conditions, and long-term durability require further research to ensure consistent performance. Future studies should focus on improving workability, developing alternative activators, and conducting large-scale field tests to validate its effectiveness in diverse environments.remaining groups depends on the arrival time of mux selection input and the mux delay.

II. Methodology

1.1. Binders: Fly ash and ground granulated blast furnace slag (GGBFS).

1.2. Alkaline Activators: Sodium hydroxide and sodium silicate solutions.

1.3. Fine Aggregate: Slag sand.

1.4. Coarse Aggregate: Recycled concrete aggregates

The study followed a systematic approach

1. Design Preparation: Several SCGC Mix mixtures were developed with varying slag sand proportions.
2. Workability Testing: Fresh properties were assessed using slump flow, L-box, and V-funnel tests.
3. Mechanical Property Analysis: Compressive and flexural strength tests were conducted at different curing periods.
4. Durability Evaluation: Sulfate resistance and chloride penetration tests were performed to analyze long-term stability.
5. Microstructural Assessment: SEM analysis was conducted to study the interfacial bonding between slag sand and the geopolymer matrix. respectively.

III. Conclusion

Geopolymer concrete that integrates recycled aggregates presents an environmentally responsible and sustainable alternative to conventional concrete. The combined advantages of utilizing industrial waste, lowering CO_2 emissions, and enhancing durability make geopolymer technology a promising option for future construction. However, additional research is required to optimize mix proportions, enhance curing methods, and assess long-term performance to facilitate broader implementation within the construction industry.

Geopolymer concrete is a groundbreaking innovation in sustainable construction, offering enhanced durability, reduced environmental impact, and cost efficiency. To promote its widespread use, future research should focus on refining mix designs, improving workability, and exploring large-scale applications.

As a sustainable alternative to Portland cement concrete, geopolymer concrete delivers excellent mechanical strength and durability while significantly reducing carbon emissions. Ongoing advancements in geopolymer technology are crucial for fostering eco-friendly building practices and strengthening infrastructure resilience. Future studies should prioritize optimizing mix compositions, investigating alternative activators, and expanding its application across diverse construction sectors.

Combining high performance with sustainability, geopolymer concrete presents an environmentally responsible alternative to traditional OPC concrete. Its outstanding durability, mechanical properties, and lower carbon footprint make it a practical choice for modern construction. By refining mix formulations and incorporating industrial by-products, the construction industry can reduce its environmental impact while enhancing infrastructure longevity. Continued research and technological innovations will be instrumental in driving the adoption of geopolymer concrete, paving the way for a more sustainable future in civil engineering.

Self-compacting concrete (SCC) is gaining popularity as a preferred material in construction due to its ease of placement, durability, and efficiency. Researchers are working on optimizing mix designs, incorporating innovative admixtures, and expanding its role in sustainable construction.

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SCC addresses many challenges in modern construction by offering effortless placement combined with superior mechanical properties and durability. Its integration into infrastructure projects enhances efficiency, reduces labor costs, and improves structural performance, making it a key material for future developments (Okamura & Ouchi, 2002).

As SCC technology continues to advance, its adoption in upcoming construction projects is expected to grow. Research is focused on optimizing mix compositions, leveraging nanotechnology, and developing carbon-neutral SCC (Onyelowe & Kontoni, 2023).

With its high performance, sustainability, and labor-saving advantages, SCC is well-suited for large-scale infrastructure projects. Innovations in self-curing SCC, fiber-reinforced SCC, and 3D printing applications will further expand its role in modern construction (Rampradheep & Sivaraja, 2016).

Self-Compacting Geopolymer Concrete (SCGC) represents a major breakthrough in sustainable and high-performance construction. Future research should concentrate on refining mix formulations, developing self-healing SCGC, and exploring its potential in 3D printing technology (Nuruzzaman et al., 2020).

SCGC, which incorporates ultrafine slag, copper slag, and recycled aggregates, provides a cost-effective and eco-friendly alternative to traditional concrete. Its superior mechanical strength, durability, and flowability make it an excellent choice for infrastructure, precast concrete, and marine applications (Sherwani et al., 2022).

The adoption of SCGC in the construction industry can significantly lower carbon emissions, enhance resource efficiency, and contribute to global sustainability initiatives (Arunachelam et al., 2022).

The incorporation of steel slag and copper slag in concrete demonstrates an innovative approach to sustainable construction material development. Further research should focus on refining mix designs, improving durability, and broadening applications in high-performance and self-compacting concrete (Lye et al., 2015).

Utilizing slag aggregates enhances mechanical properties and durability while also reducing environmental impact by decreasing landfill waste and sequestering CO_2 (Monkman et al., 2009). By adopting slag-based materials, the construction industry can align with circular economy principles, leading to cost-effective and sustainable infrastructure solutions (Grubb et al., 2011).

The advancement of SCGC technology is expected to drive global sustainable construction practices. Future studies should explore optimizing mix designs, self-healing SCGC, and 3D printing applications to improve both performance and environmental benefits (Sherwani et al., 2022).

By adopting SCGC, the construction industry can achieve cost-effective, high-performance, and sustainable infrastructure solutions, fostering the transition to carbon-neutral construction (Jeyaseela et al., 2024).

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