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Advanced Binders for Sustainable Self-Compacting Geopolymer Concrete: A Review of Mechanical Performance and Curing Strategies

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Abstract- The construction sector has been facing pressure to integrate sustainable approaches due to the use Ordinary Portland Cement (OPC) which greatly contributes to carbon emissions and energy consumption. In this regard, Self-Compacting Geopolymer Concrete (SCGC) turns out to be a geopolymer concrete that utilizes industrial and agricultural by-products as a more environmentally-friendly option. This review aims to study the mechanical behavior of SCGC with blended FA, GGBFS, RHA, graphene-based materials under different curing conditions and contains notable gaps in previous literature. The combination of FA with GGBFS improves upon their individual compressive and tensile strength because of the further enhancement of the geopolymerization process due to synergistic effects. Amorphous silica-rich RHA partially substituting for FA and GGBFS exerts some microstructural improvement, but overly high content tends towards low strength due to excessive unreacted silica. GO behaving as a nano-filler with its high specific surface area and functional groups tremendously aids matrix densification, interfacial bonding, durability, and overall structural bolsterment-strengthening properties. Literature corroborates experimental data supporting 60-70 °C elevated temperature curing yields stronger performance over standard ambient cured long-term structures given optimal RHA/GO contents. Furthermore, GO imparted improvement was also noted for chemical attack resistance alongside reduced pores along with greater durability indicators. In this review, recent experimental findings are examined to determine the best binder combinations and curing methods predicted to maximize the performance of SCGC. Incorporating FA, GGBFS, RHA, and GO enhances circular economy principles by reconciling the use of industrial byproducts with sustainability objectives in contemporary construction. The results reinforce the exceptional performance attributes that make SCGC an innovative eco-friendly substitute for conventional cement-based concrete.

Keywords- Self-Compacting Geopolymer Concrete (SCGC), Fly Ash (FA), Granulated Blast Furnace Slag (GGBFS), Rice Husk Ash (RHA), and Graphene Oxide (GO)

INTRODUCTION

Portland Cement is among the most important and critical building materials Portland cement has a very high energy consumption and CO2 emissions in its production process.[1] The production of Ordinary Portland Cement needs to be curtailed in the interest of achieving goals for reducing CO2 emissions. To reduce the cement waste by-products, supplementary cementitious materials such as GGBFS (ground granulated blast furnace slag), fly ash, Wollastonite, and even Graphene have been utilized [2]. Fly Ash is rich in silica and alumina. Wollastonite, also known as calcium meta-silicate, is a naturally occurring fine-grained mineral used in concrete as a partial substitute for cement. Geopolymer concrete also has good performance against many environmental conditions [3]. The use of geopolymer binders will greatly decrease greenhouse gas emissions and fossil fuel consumption. Also, there is a need to minimize the amount of waste materials that are dumped into landfills. This can be done by using industrial by-products transforming them into useful products instead. Thus these types of concrete with geopolymers are called 'Green Concrete' due to their numerous benefits towards green construction and preserving nature. Geopolymer binders also strengthen concretes making it more durable which aids its performance [4]. It is plausible to state that since fly ash exists widely, everything containing aluminosilicates could theoretically be transformed into geopolymer when treated with alkali stimuli. Like many, geopolymer concrete allows for high early strength and resistance to a variety of assaults, chemical or otherwise [5]. Due to the advantages that geopolymer technology brings along combined with the rise of self compacting concrete (SCC), there is an emerging trend in construction towards development of a new hybrid concrete that amalgamates advantages from both categories. SCGC can be produced using fly ash as the raw material without any need for portland cement which alleviates the necessity of compaction work ease. Few studies are aimed towards examining the characteristics of SCGC. In one case rubberlike superplasticizers were used to improve workability at lower temperatures with careful control over other parameters including sodium hydroxide molarity, curing temperature, and time.[6]. These days graphene is recognized as the new creation of skilled materials scientists. Graphene is one of the most active research material frontiers in recent years [7]. Every type of graphitic materials has graphene as its basic building block, which is a two-dimensional planar with thickness 0.335nm honeycomb structure consisting of carbon atoms. Graphene can be transformed into 3D graphite, rolled into one-dimensional nanotubes, or wrapped into OD fullerenes. As previously mentioned in figure 1.[8]. While utilizing graphene as a raw material for self-compacting geopolymer concrete (SCGC), it was evident that ultra lightweight graphene enhanced the materials mechanical properties such as its strength to weight ratio when compared to traditional components. Moreover, it possesses a high surface area which allows for better bonding with the concrete matrix. Its incorporation enhances the concrete's workability, durability, resistance to cracking while maintaining excellent mechanical properties Furthermore, the incorporation of SCGC aids performance significantly while working towards developing eco-friendly advanced construction materials. GO is recognized as a precursor for large-scale inexpensive manufacturing of graphene-based products due to oxidized graphite’s lower cost relative to its oxidized form. Hydroxyl, epoxide, carboxyl and carbonyl functional groups have dominate presence on GO sheets [9]. Due to these polar groups hydroxyl and epoxide Group’s functionalization makes GO highly soluble in water aiding the overall reaction mechanism making it easier to process through liquid channels via dispersion enhancing synthesis (DES). These reinforcing composites enhances the tensile strength and elastic modulus attributed by the increased specific surface area provided. Utilizing GO as fillers improves organic epoxy resins along with plastic composites aiding in enhancing materials composites mechanical characteristics allowing attributing strong intermolecular forces between them. Considering all of these astonishing features, polymers enriched with graphene display tremendous promise within geopolymers enabling them to self-monitor their own conditions[10].

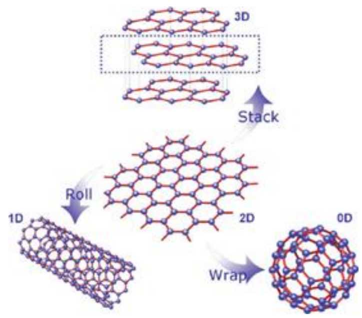


Fig.1

Amorphous RHA, another type of supplementary material, comes from agro-industrial waste generated by rice mills and is available throughout India, an agricultural country. India produces approximately 30 million tons of rice husk waste every year. Over 83 to 90% of RHA contains amorphous silicon oxide. Prior research showed that partially replacing FA, GGBFS, and Red Mud with RHA resulted in enhanced mechanical and microstructural properties of geopolymer concrete. [11]. Mechanically graded GGBFS composites can also have the new characteristic feature under SCGC influenced by RHA inclusion. Therefore, geo-incorporation of RHA into SCGC modified with GGBFS remains unexplored.[12]. A large body of research has studied the mechanical properties of Rice Husk Ash (RHA) and Graphene-based Self-Compacting Geopolymer Concrete (SCGC) incorporating Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) under varying curing regimens. The consolidation offered by the synergistic action between FA and GGBFS accelerates the geopolymerization process which enhances strength development along with durability and workability. Additionally, the incorporation of RHA improves pore structure while increasing compressive, tensile, and flexural strengths due to enhanced bonding at nanoscale levels alongside graphene-derived materials. In several studies, various curing conditions including ambient curing, steam curing, and elevated temperature curing were found to significantly affect the rate of strength gain as well as the overall performance. While ambient curing aids in long-term durability, it lags behind others when it comes to early-age strengths geopolymerization which is accelerated with elevated temperature curing. The combination of FA with GGBFS, graphene as well RHA proves to have great promise for modern construction needing high-performance concrete due to the SCGC's sustainable nature. Separately focusing on FA and analyzing its performance with GGBFS, RHA and GO under different kinds of curings enabling sustainable construction solutions led to this review article.

LITERATURE REVIEW

The compressive strengths of SCGC mixes with 100\% FA, 100\% GGBFS and 5-25\% RHA are illustrated. Increased unreactive silica gives rise to decreased strength with increased RHA. The exception is at 5\% RHA where mixes have lower room temperature cured strength. Strength is significantly enhanced at higher curing temperatures (60 - 70 °C), particularly with 15\% RHA due to faster Si and Al release. Activated bGGBFS enhances geopolymer gel quality therefore improves mechanical properties as noted by Yamini J patel & Niraj Shah [8]. Figures 2 to 4 illustrate the findings of Ramamohana R. B. et al. [7], who studied the compressive strength of geopolymer concrete incorporating fly ash and GGBFS alongside 1 to 4 percent graphene oxide (GO). The addition of GO positively impacted strength at every age of curing (3, 7, 28, and 60 days). Mechanically, the increase in filler GO's weak scaffolding contributed to improved strengthening of the geopolymer concrete matrix both explicitly as a structure ameliorator and implicitly as a matrix filler leading to denseness enhancement. Thus, significant improvements in both duration-dependent ambient curing aging and consistent strength were observed. According to Ahmed M. et al. [13], the presence of graphene oxide (GO) improves the compressive strength of geopolymer concrete over time. This enhancement results from strong physical and chemical interactions between GO and the matrix. The mechanical interlocking and filler functions of GO's wrinkled structure aid in early-stage dense microstructural strengthening. Ezzatollah et al. [8] worked on GO-doped cement and reported a rise in compressive strength from 14.3 ± 0.2 MPa to 19.4 ± 0.9 MPa with the addition of 0.5% GO. Other curing approaches such as water curing and microwave curing also improved strength further. Blended with microwave cured geo-polymeric cement paste, GO was found to substantially accelerate the hydration process resulting in improved compressive strength due to enhanced microstructural density predominately observed at early stages of setting prior to hardening being underway within a densely packed structural arrangement coupled with increased intermolecular forces as a result of intense heat exposure activated by microwaves. According to the study by Balamurali Kanagaraj et al. [14], the strength of SCGC composites was 3.07 to 4.56 MPa for room temperature cured specimens, while it was 4.68 to 6.63 MPa for elevated temperature cured specimens. In this case, room temperature curing was adequate because the bonds formed with geopolymeric gels and filler materials were strong enough to achieve composite strength. The observed strength development in the composites is due to formation of CASH and NASH gels. As stated by Yamini J Patel et al. [12], The highest split tensile strength of 3.4 MPa was recorded in S4 (15% RHA) at 70°C while lowest value of 1.4 MPa was recorded in mix S1 containing FA (100% FA) under ambient conditions. There is a noted decline in strength with drop in curing temperatures and increase in RHA content. Improvement seen from S1 in Mix S2 (100% GGBFS) indicates remarkable mid-grade performance of these blends over other low-grade mixes containing sole Fly Ash/ RHA on their own without any cementing binder blend support structurally as suggested even for compressive strength patterns. Bellum et al. [15] showed that fly ash-based geopolymer concrete's compressive strength, modulus of elasticity, and chloride permeability were improved by 3% graphene oxide and 30% GGBFS addition by 38.51%, 28% and 65.44% respectively. SEM analysis revealed the microstructure was more dense with reduced porosity. The interdependence between strength, elasticity, and durability validates the additive's benefits—GO and GGBFS indeed enhance performance further corrobored by strong interdependencies. From prior research applying advanced nanomaterials to concrete technologies such as geopolymer concrete, Nanthini et al. [16] concluded that using 0.3% graphene oxide accompanied with 0.3% nanozirconia yields a increase of 50 % in compressive strength along with significant improvements in flexural/tensile strength, microstructural endurance and durability. N.A Sayed & Muhd Kureshi [17] noted the advantages of incorporating GGBFS into SCC containing FA through improved compressive strength when compared to conventional SCC particularly at the later stage (90days). Also noted was GGBFS based SCC being superior to FA based SCC due to its greater pozzolanic activity which improves microstructural densification resulting in greater structural funneling of porosity. This trend was confirmed through bar chart analyses presented (Figs 5-7). Increased substitutive replacement coupled with prolonged curing time up until 30%,enhanced compressive strength while overall displaying better effectiveness FA especially at lower substitution levels enhanced Strength/Durability proved superior performance than FA [17]. As Sayed & Muhd. Kureshi [17] showed, SCC with GGBFS and FA performed better than normal SCC during splitting tensile strength tests performed according to ASTM C496/C496M-17. The peak strength was observed for a 30% supplement of GGBFS and FA to cement after 90 days of curing. GGBFS's greater pozzolanic activity enlarged its efficaciousness over FA, particularly at lower substitution levels, and superior pore refinement markedly improved concrete durability. Strength improvements correlated with replacement levels and elongating time, clearly depicted in Figs. 8–10, showcasing enhanced performance even in aggressive conditions.

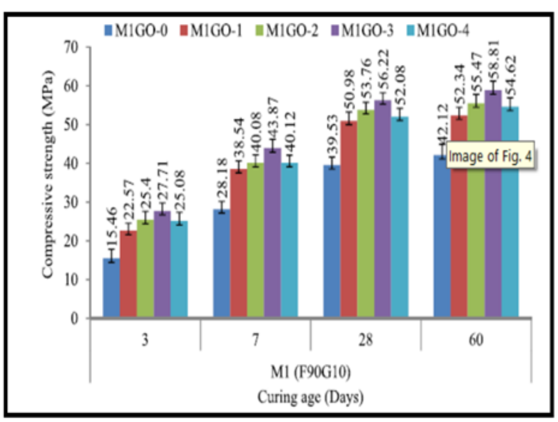


Fig. 2

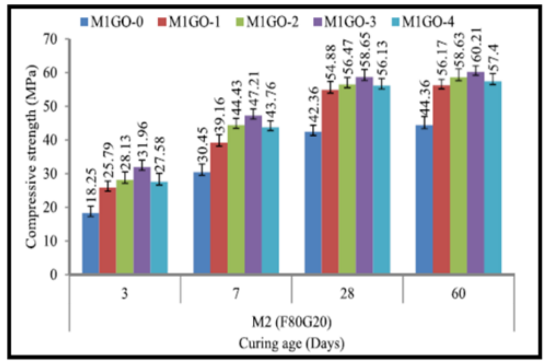


Fig. 3

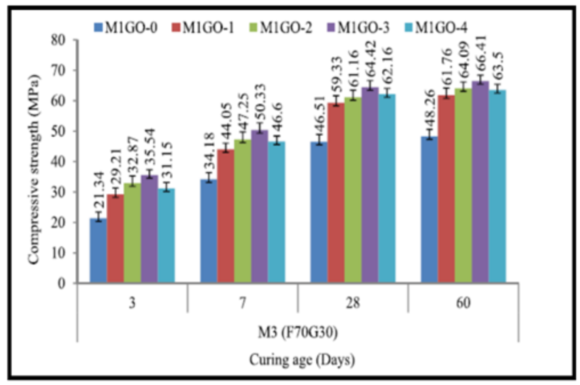
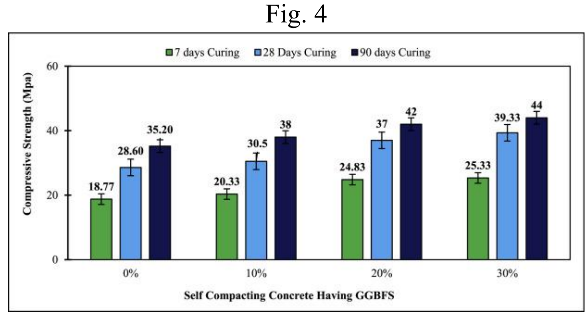


Fig. 4



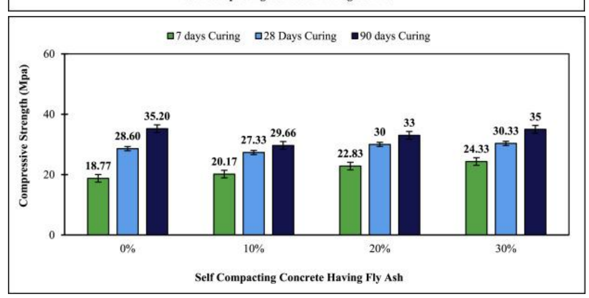
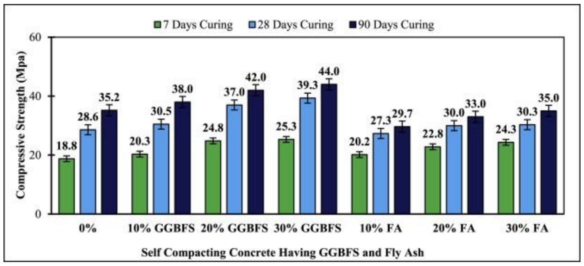


Figure 5. Change in compressive strength of SCC incorporating GGBFS after various curing durations.

Fig. 6. SCC with FA compressive strength after various curing periods.



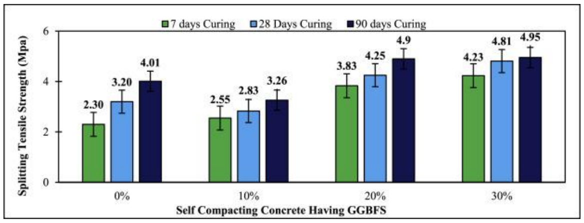
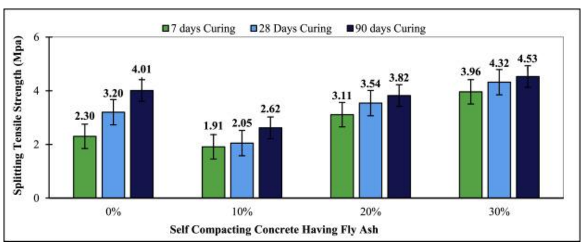


Fig. 7 Compression Testing and Analysis of SCC Incorporating GGBFS and FA with Respect to Varying Curing Times.

Fig. 8. Outcomes of the Splitting tensile strength test on SCC containing GGBFS with varying curing durations.



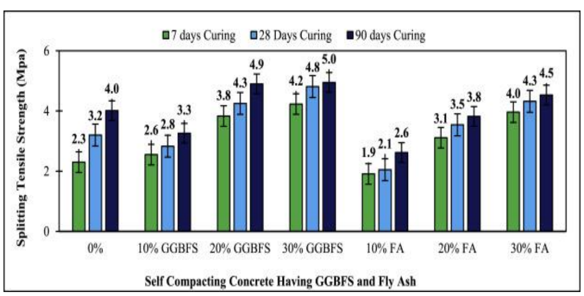


Figure 9 illustrates the splitting tensile strength of self-compacting concrete with fly ash over various curing durations.

Fig. 10. The Impact of Curing Time on the Splitting Tensile Strength of SCC Containing GGBFS and FA

METHODOLOGY

This review examines the performance of Rice Husk Ash (RHA) and Graphene Reinforced Self-Compacting Geopolymer Concrete (SCGC) in relation to its compressive and tensile strength with varying ratios of Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), along with different curing conditions. The focus of this study encompasses a literature search on the experimental investigations concerning the compressive and splitting tensile strengths of SCGC containing FA, GGBFS, RHA as an aluminosilicate constituent. The impact of graphene nanoparticles on the geopolymer microstructure and mechanical properties is evaluated in detail. Curing conditions like ambient, thermal, or steam are analyzed for their impact on geopolymerization kinetics and strength progression. A blend design is evaluated based on the concentration ratio of FA, GGBFS, RHA, and graphene incorporated into the mix for optimal performance.

FINDINGS

This paper has demonstrated the promising potential of Self-Compacting Geopolymer Concrete (SCGC) with certain graphene-based materials, Fly Ash (FA), Rice Husk Ash (RHA), and Ground Granulated Blast Furnace Slag (GGBFS). The mechanical properties, including compressive and tensile strength, are improved by the synergistic interaction of FA and GGBFS which accelerates the geopolymerization process, especially under elevated temperature curing. RHA ash adds amorphous silica to enhance microstructural refinement when partially replacing FA or GGBFS; however stronger silica may contribute to a reduction in strength too. Graphene oxide (GO) augments the strength and durability by improving matrix densification and bonding at the nano-scale due to GO's high surface area and functional groups. SCGC with optimized RHA and GO performed best between 60–70 °C. Temperature during curing had a critical impact on performance: ambient provided long-lasting reliability while heated applied faster strength gain due to scaffolding acceleration supported by heat. This approach combines industrial waste resources with advanced nanomaterials while achieving sustainable construction goals, positioning it as an alternative for Portland Cement concrete providing high-performance eco-friendly structures SCGC surpasses dependability gaps. This review focuses on RHA/GO strengthened SCGC bound use with emphasis on improving mechanical and enduring resistances.

CONCLUSION

This review showcases the combined impact of incorporating Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), Rice Husk Ash (RHA), and graphene-based materials into Self Compacting Geopolymer Concrete SCGC) with an aim at optimizing a high performing sustainable concrete in place of Portland cement based concrete. The results indicate that the synergy obtained from the combination of FA and GGBFS contributes positively toward geopolymerization, granting greater compressive and tensile strength, especially under high temperature curing. RHA helps refine microstructure enhancement and gain improved strength due to its high amorphous silica content but limits performance if used excessively due to silicas lack of reactivity. Graphene oxide (GO) as a nanofiller improves matrix densification, bonds interfaces, enhances resistance to chemical attacks which strengthens the mechanical as well as durable properties of SCGC further. Out of all the curing techniques investigated, elevated temperature curing (60-70°C) was best for improving early-age strength while ambient curing aided long-term durability strategies. Enhanced environmental sustainability through reduced OPC dependency alongside improved by integrating specialized industrial and agricultural waste products fulfills dual purpose while simultaneously improving SCGC's performance. This review identifies useful combinations of materials and approaches to curing them which aim towards the development of next-generation concrete that follows the circular economy principles. The results obtained thus far support SCGC's viability as an environmentally friendly, long-lasting, and structurally reliable construction material for contemporary structures, thereby offering one of many possible solutions towards achieving a reduction in the carbon footprint of the construction industry while advancing sustainable infrastructure.

DISCUSSION

The utilization of FA, GGBFS, RHA, and graphene-based materials in SCGC marks a notable innovation towards eco-friendly and high-performance concrete. The synergistic interaction between fly ash (FA) and ground granulated blast furnace slag (GGBFS) enhances geopolymerization and strongly improves mechanical properties particularly with curing at elevated temperatures. Rice husk ash (RHA), as a silicious material containing amorphous silica, contributes significantly toward microstructural refinement but needs to be controlled to prevent the detrimental effects of unreacted silca on strength. GO does much more at the nano scale regarding the effectiveness towards densification, interfacial bonding, chemical resistance, and thus durability that increases considerably enhanced durability. Performance is significantly affected by curing conditions where ambient curing augments long term durability while increased temperature curing supports rapid strength gain. Through this holistic technique, not only does SCGC's structure and durability are strengthened but also sustainable construction is further advanced due to using industrial or agricultural byproducts. The research data emphasize once again that SCGC has good potential as an environmentally friendly alternative to OPC concrete for use in infrastructure projects.

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