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Self- Geopolymer Composites for Sustainable Development: A Compacting Review

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ABSTRACT

Concrete, the second most widely used material after water, heavily relies on Portland cement production, which generates substantial carbon dioxide and other greenhouse gases, demanding high energy inputs. The urgent need for alternatives has led to the development of sustainable geopolymer concrete (GPC), which eliminates the use of Portland cement. GPC reduces carbon emissions, enhances durability, and is environmentally friendly due to its reliance on natural or industrial resources like silica fume, GGBFS, and fly ash, known for their silica and alumina content. This approach not only addresses the disposal of industrial pollutants but also reduces the carbon footprint. GPC's composite binders are activated using alkali solutions like NaOH and Na_2SiO_4 or KOH and K_2SiO_3. Self-compacting eco-friendly GPC concrete (SCG) has been developed to overcome compaction issues, relying solely on its weight for compaction without additional operations. This study thoroughly investigates the influence of various factors such as curing temperature, superplasticizer, molarity, binding materials, and fibers on SCG's fresh and mechanical properties, highlighting potential outcomes and knowledge gaps. Existing literature supports SCG as an environmentally superior alternative to conventional concrete, promoting waste utilization and resource conservation. This publication also addresses global acceptability factors influencing SCG production and its characteristics.

KEYWORDS: Compressive strength; geopolymer; curing conditions; C-S-H; Scanning electron microscopy

1. INTRODUCTION

Cement remains crucial in constructing and maintaining structures prone to water and fire due to its increasing demand and versatility [1, 2]. However, the industry struggles to meet this demand due to slow production, limited limestone storage, and the substantial CO_2 emissions associated with Ordinary Portland Cement (OPC) production. OPC production releases 1.35 billion tons of greenhouse gases annually through fuel combustion, limestone decarbonization, and electricity consumption [3, 4]. It requires 1500 kg of raw materials and 80 kWh of energy per ton [5]. Efforts to substitute OPC with eco-friendly alternatives like waste pozzolan, alkali-activated and super sulfated cementitious composites, magnesium oxy carbonate, and calcium sulpho-aluminate cement have been made [6]. Geopolymer concrete (GPC) has gained attention for its lower CO2 emissions and its potential as a sustainable alternative to OPC [7]. This study aims to comprehensively analyze self-compacting geopolymer concrete (SCG) by creating a database of crucial parameters affecting its production and properties, including binder content, molarity, superplasticizer, alkaline activators, curing environment, aggregates, C-S-H phase, extra water, and AAS-binder ratio. While the demand for GPC is rising, limited literature covers SCG's production and properties. Unlike GPC, SCG does not require additional compaction energy, leading to favorable characteristics like improved microstructure and durability. This study seeks to fill the gap by examining various factors impacting SCG comprehensively. Additionally, it explores different geopolymerization procedures, binders, and fabrication methods for SCG. The study utilized databases like ScienceDirect, Google Scholar, Taylor and Francis, ResearchGate, MDPI, Hindawi, SpringerLink, Web of Science, and Scopus, using keywords such as 'self-compacting geopolymer, geopolymer, cementitious composites, green composites' to gather relevant works. The main goal is to provide a comprehensive overview of current research and the applicability of SCG in green concrete applications.

2. CHEMISTRY OF GEOPOLYMERS

Following OPC and lime concrete, GPC concrete is regarded as the third generation of concrete [7]. While GPC generally refers to amorphous alumino-silicates, the term encompasses various materials like geo-cements, inorganic polymers, alkali-bonded ceramics, alkali-activated cement, silico-aluminophosphate, and hydro-ceramics [7, 16]. GPC's three-dimensional network of alumino-silicates achieves similar or superior strength to OPC through the consolidation of alumina and silica-rich materials with a concentrated alkali solution, which dissolves SiO_2 and Al_2O_3 via geopolymerization [17]. This reaction (as shown below) occurs when aluminosilicates encounter an alkaline solution, forming a 3-D polymeric chain network of Si–O–Al–O bonds [18]. The process involves dissolution, positioning, transport, and polycondensation [19]. Different types of alumino-silicate-based GPC materials form their structure through complex and energy-efficient procedures at ambient temperature.

$$n(Si_2O_5, Al_2O_2) + 2nSiO_2 + 4nH_2O + NaOH/KOH \rightarrow Na^+, K^+ + n(OH)_3 - \underset{(OH)_2}{\overset{Si}{|}} - O - Al^- - O - Si - (OH)_3$$

$$n(OH)_3 - Si - O - \underset{(OH)_2}{\overset{Al^-}{|}} - O - Si - (OH)_3 + NaOH/KOH \rightarrow (Na^+, K^+) - \left[-\underset{O}{\overset{|}{Si}} - O - \underset{O}{\overset{|}{Al^-}} - O - \underset{O}{\overset{|}{Si}} - O - \right]_n + 4nH_2O$$

3. EFFECT OF DIFFERENT PARAMETERS

3.1.Influence of alkaline Activators

GPC and SCG rely on alkaline activators, which, when in contact with alkali-aluminosilicates in an alkaline solution, form the binders for these concretes. Commonly used activators include potassium hydroxide (KOH) and sodium hydroxide (NaOH), often combined with potassium water glass ($nSiO_2K_2O$) or sodium water glass ($nSiO_2Na_2O$). Increasing the content of activating agents like slag and alkaline-activated metakaolin significantly enhances the mix's mechanical strength [20][21]. However, using free water glass alkaline agents as activators can reduce the strength of SCG and GPC [22]. Water glass promotes polymerization, producing a stronger, silicon-rich by-product with improved strength [23]. The molar ratio between water glass and NaOH directly affects compression strength [24], and alkali-activated mixes require a specific molar ratio of H_2O to SiO_2 [25]. This study suggests that KOH or NaOH dissolved in water glass/silicate can serve as alkaline activating agents, but their proportion impacts the mechanical properties and geopolymerization of SCG and GPC.

3.2.Influence of Curing Condition

The curing environment significantly influences the durability and mechanical properties of fresh SCG specimens. Different studies have used various curing environments. Ahmed et al. [26] found that prolonged curing improves geopolymerization, leading to increased compression strength. Specimens cured at 60°C, 70°C, and 90°C showed the highest strength at 70°C after 96 hours. Palomo et al. [22] discovered that alkali-activated concrete cured at 85°C for 24 hours exhibited higher strength than those cured for longer durations at the same temperature. Another study [27] investigated SCG specimens modified with different binder concentrations (RHA, FA, and GGBFS) under ambient curing conditions. SEM analysis revealed a uniform particle network in GGBFS with 5% RHA under ambient curing and GGBFS with 15% RHA under elevated temperature curing. SEM images in Figure 1 provide morphological details such as particle size and shape. Parashar [28] observed reduced workability in SCG when waste foundry sand (WFS) replaced fine sand, as seen in the SEM image in Figure 1. Jerônimo [29] used SEM to study the morphology of ground clay brick waste (GCBW) and its binding capacity to SCG. Despite not being spherical, GCBW showed good shape and was found to aid in compacted SCC formation.
The effect of different temperatures on the strength of GPC specimens was examined. Figure 2 shows that the specimen with 15% RHA achieved the highest compression strength at 70°C curing. Ambient curing was not effective for FA and RHA-modified SCG specimens, while the GGBFS-modified GPC specimen had 15% lower strength than at 70°C. Compared to FA-modified SCG specimens, GGBFS-modified SCG specimens achieved higher early-age strength in an ambient curing environment.

3.3.Influence of binder Content

The development of SSGC depends largely on the types and proportions of binders used. Studies have analyzed various binder proportions, such as Liu et al. [30], who examined the substitution of POFA in an FA-based binder and found that 20% substitution yielded the highest strength. Another study [31] used VPD as the primary binder and observed that substituting VPD with CKD or OPC by 30% reduced workability but enhanced compression strength. Another study [27] investigated GGBFS binders in SCG, finding that adding 5% RHA improved split tensile, compression, and flexural strength, while 15% RHA was recommended for enhanced strength at 70°C curing. Sole FA as a binder did not achieve the desired strength under ambient curing [32].

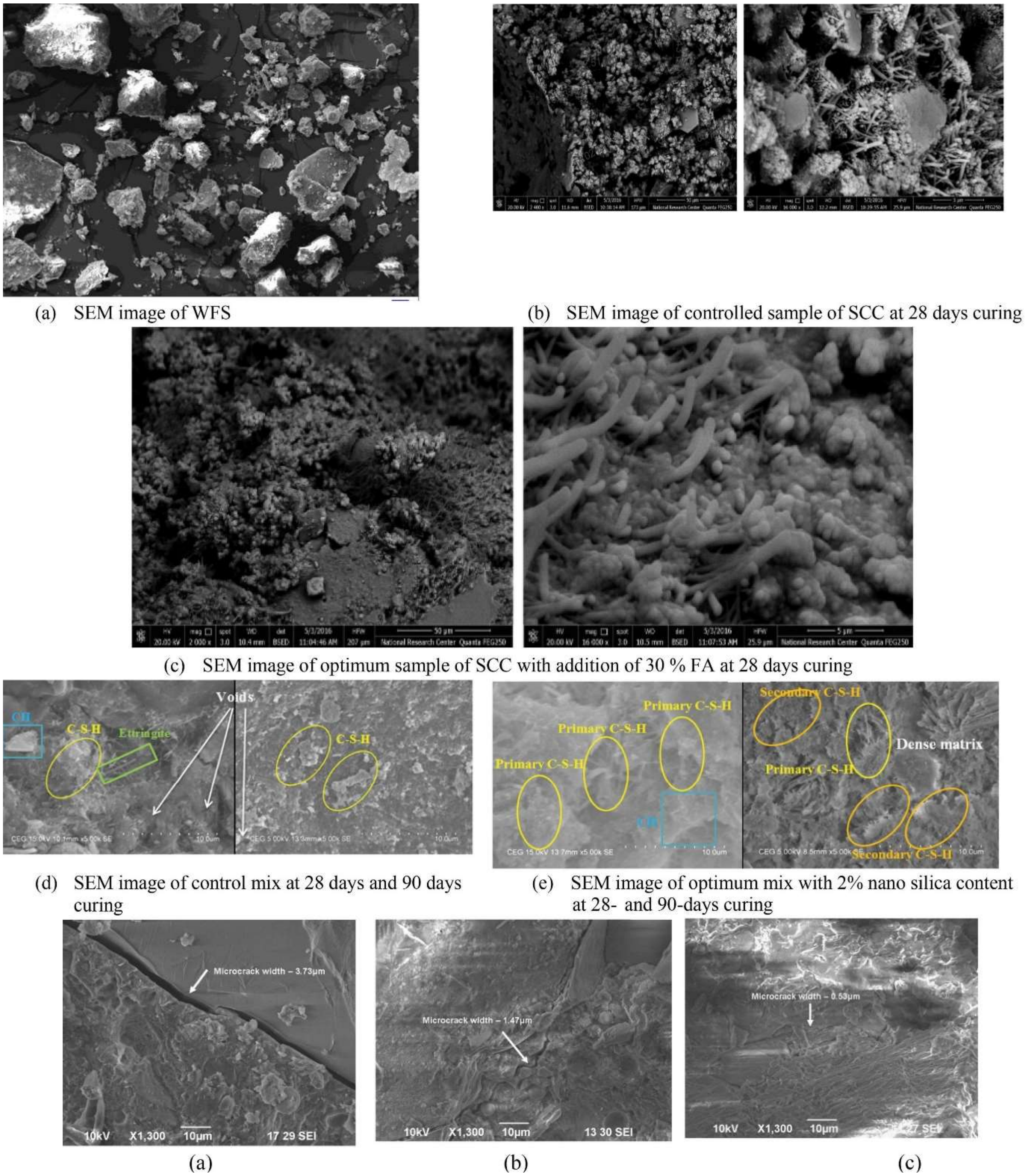

Figure 1. Microstructural analysis of SCG specimens [28, 29].

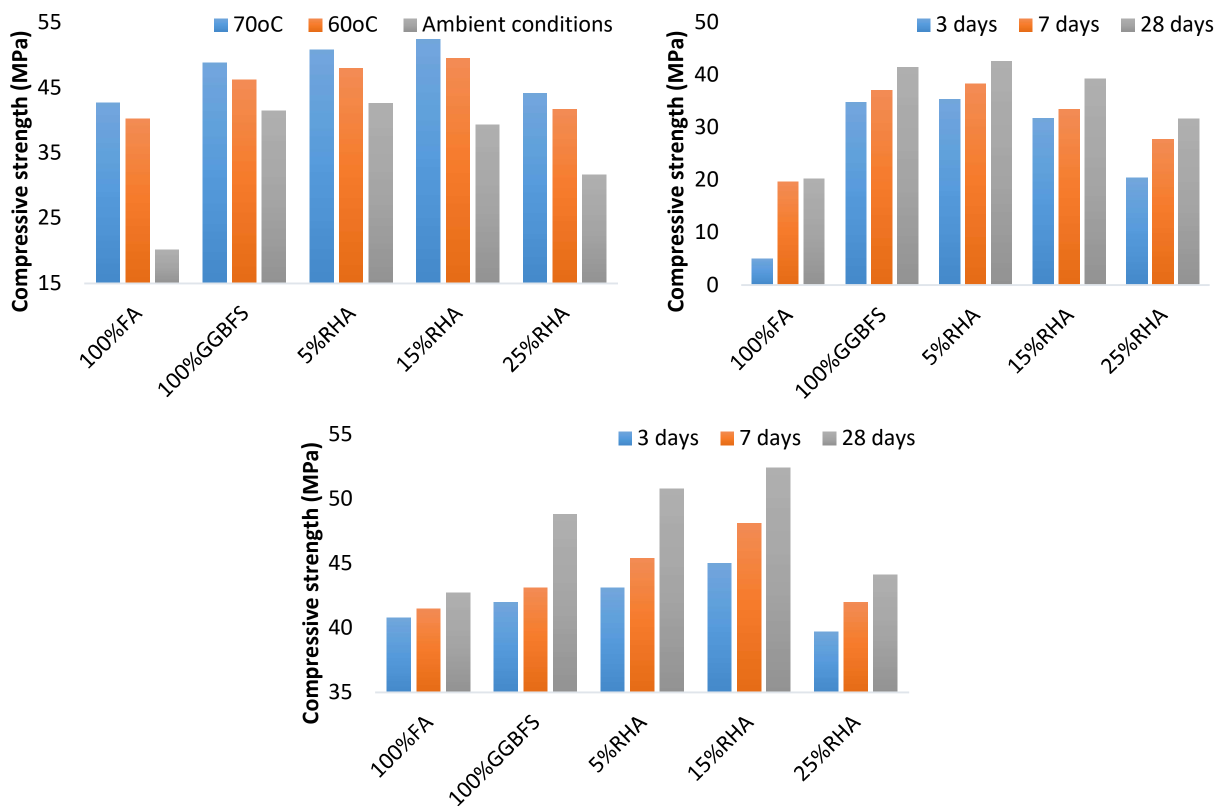

Figure 2. The compression strength of various SCG mixes at discrete curing conditions [27].

Al-Rawi and Taysi [32] found that increasing GGBFS proportion in FA-based SCG reduced workability but improved compression strength. Srishaila [33] observed that GGBFS binders provided better strengths than FA in SCG, with increased water demand. Overall, different binders and their proportions influence both fresh and hardened properties, with GGBFS showing effectiveness in enhancing strength even under ambient curing. Partial substitution of RHA and BRHA in GGBFS is recommended for better strength, along with substitutions of VPD with CKD and FA with POFA. However, an entirely FA-based mix is not suitable for ambient curing, and both FA and GGBFS are beneficial for improved strength under ambient and heat-curing conditions.

3.4.Influence of Molarity

Several studies have investigated the impact of NaOH molarity on SCG. It was found that increasing the molarity from 8 M to 12 M improved compression strength but a further increase to 14 M led to a decline [34, 35]. This decrease was attributed to slower polymerization at higher molarities. Compared to 18 M, 12 M NaOH performed better, and 8 M NaOH showed improved Interfacial Transition Zone and reduced porosity compared to 10 M and 12 M [35]. While increasing NaOH molarity from 8 M to 12 M reduced fresh state features, it notably improved viscosity and compression strength [36-38]. Ultrasonic pulse velocity testing confirmed that higher NaOH molarity improved compression strength [39]. Additionally, using 16 M NaOH with 400 kg/m3 FA provided optimal results for GPC, but beyond 16 M, characteristics declined, reducing porosity and water absorption at 18 M [40, 41]. Overall, higher NaOH concentrations decrease workability but improve mechanical strength and quality. Using 12 M NaOH with silica fume and 16 M for FA-sourced GPC are recommended for enhanced microstructure, strength, and durability. Compressive strength with varying fly ash content and molarity is shown in Figure 3.

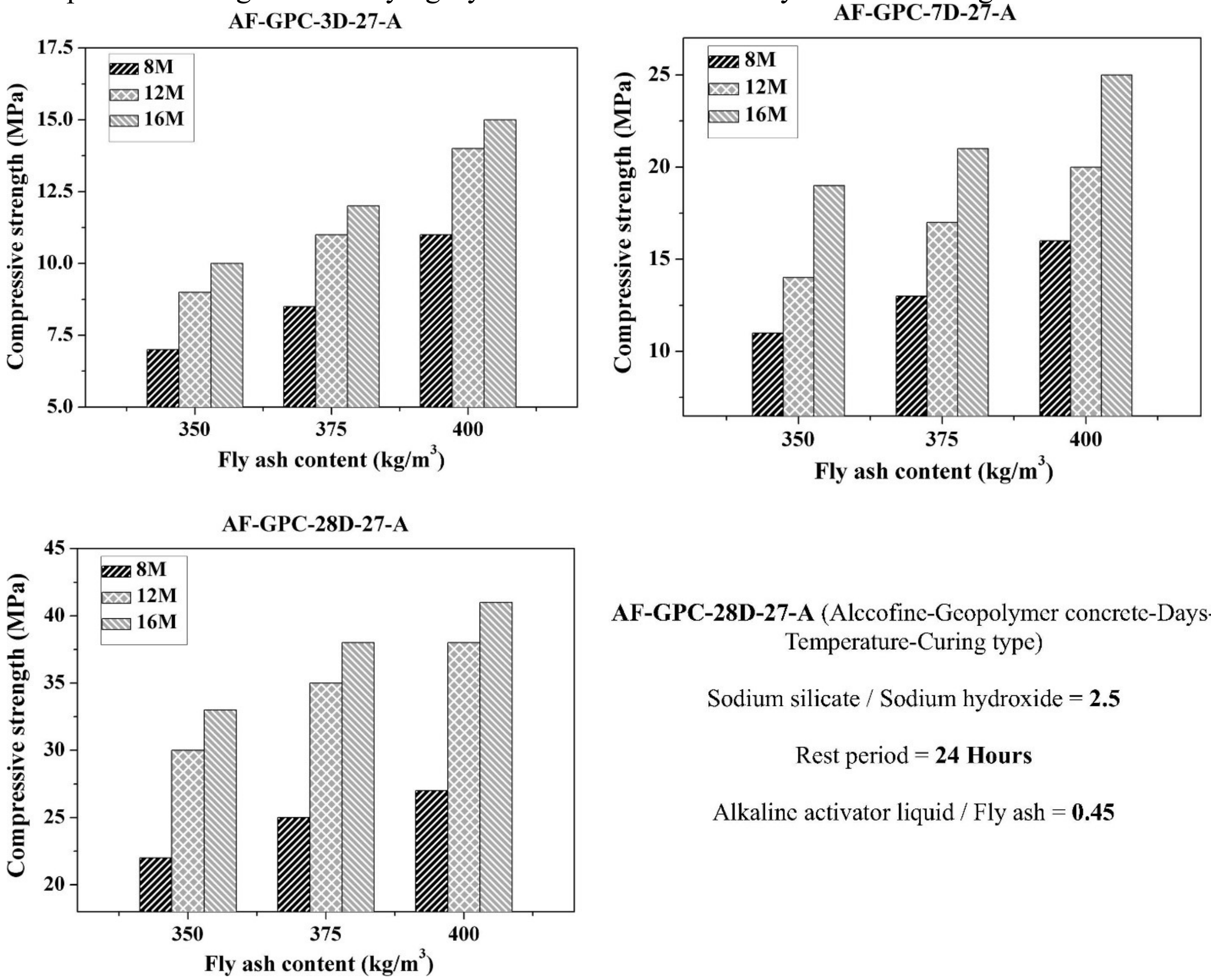

Figure 3. Compressive strength with varying fly ash content and molarity at 27 °C curing temperature [40].

4. ENVIRONMENTAL ASPECTS

Improving conventional concrete materials is crucial for environmental and economic reasons. Creating efficient SGC can lead to more eco-friendly construction practices. SCG utilizes waste materials like fly ash (FA), blast furnace slag (BR), ground wastepaper (GWP), and ground granulated blast furnace slag (GGBS), providing a sustainable alternative to traditional Portland cement concrete. SCG reduces the need for natural resource extraction and offers economic benefits, early strength, durability, reduced carbon emissions, decreased reliance on sodium silicate solutions, and improved structural performance. However, SCG production requires careful handling due to the alkali-activated polymerization process, which can pose challenges such as increased alkalinity, energy consumption, and greenhouse gas emissions. Factors like curing conditions and material characteristics significantly affect SCG properties. SCG is a superior substitute for Portland cement, reducing the need for extensive vibration during placement. Future research should focus on enhancing SCG's strength and durability through microfiber and nanoparticle incorporation, evaluating engineering properties, considering suitable additives, proper aggregate selection, and studying its seismic performance. SCG's improved resistance to corrosion and shrinkage can revolutionize prestressed concrete. Utilizing industrial waste materials in geopolymer composites contributes to sustainable construction. In conclusion, SCG offers environmental sustainability, durability, workability, and potential cost savings, making it a promising alternative to traditional concrete in construction projects.

5. CONCLUSION

Several parameters, including molarity, binder type, fibers, superplasticizer, and curing environment, are evaluated for their impact on mechanical aspects like flexural strength, compressive strength, and split tensile strength. Based on the review:

1. FA accelerates polymerization without compromising workability. Other binders like metakaolin, GGBS, silica fume, and RHA couldn't match FA's fresh mix properties but can substitute it. GGBFS is recommended with FA for better strength, showing a potential strength enhancement of 51.45% at 50% substitution.
2. Using SF with FA improved strength by 7% at a 10% substitution, while RHA at 5% achieved a 3% improvement. Filling voids with finer particles boosts SCG strength.
3. GGBFS-modified SCG had reduced slump flow by 18%, reaching 680 mm, and a 10.44% slump reduction with increased molarity. Adding superplasticizer improved slump by 14% at 7% substitution.
4. Higher NaOH molarity increased cohesion and viscosity but reduced workability. A 12 M NaOH concentration improved strength by 25% with comparable workability.
5. Metakaolin, FA, GGBS, RHA, and silica fume are recommended for SCG, but their combined impact needs further study. SCG reduces carbon footprint in construction.
6. SCG is recommended for an eco-friendly environment, but limited recommendations pose challenges for practical implementation.

6. ACKNOWLEDGMENT

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References

1. Afroughsabet, V., L. Biolzi, and T. Ozbakkaloglu, High-performance fiber-reinforced concrete: a review. Journal of materials science, 2016. 51: p. 6517-6551.
2. Manjunatha, M., et al., Influence of PVC waste powder and silica fume on strength and microstructure properties of concrete: An experimental study. Case Studies in Construction Materials, 2021. 15: p. e00610.
3. Cleetus, A., et al., Analysis and study of the effect of GGBFS on concrete structures. Int. Res. J. Eng. Technol.(IRJET), 2018. 5(03): p. 3033-3037.
4. Özbay, E., M. Erdemir, and H.İ. Durmuş, Utilization and efficiency of ground granulated blast furnace slag on concrete properties–A review. Construction and Building Materials, 2016. 105: p. 423-434.
5. Mamatha, P., D. Narayana, and T.N. Kumar, To evaluate the mechanical & durability properties of nano sugarcane bagasse ash in cement concrete. Int J Sci Res Sci Technol, 2017. 3(8): p. 425-430.
6. Shi, C., A.F. Jiménez, and A. Palomo, New cements for the 21st century: The pursuit of an alternative to Portland cement. Cement and concrete research, 2011. 41(7): p. 750-763.
7. Singh, B., et al., Geopolymer concrete: A review of some recent developments. Construction and building materials, 2015. 85: p. 78-90.
8. Memon, F.A., et al., Effect of superplasticizer and extra water on workability and compressive strength of self-compacting geopolymer concrete. Research Journal of Applied Sciences, Engineering and Technology, 2012. 4(5): p. 407-414.
9. Zhang, Y., et al., Understanding the changes in engineering behaviors and microstructure of FA-GBFS based geopolymer paste with addition of silica fume. Journal of Building Engineering, 2023. 70: p. 106450.
10. Davidovits, J., Geopolymers: inorganic polymeric new materials. Journal of Thermal Analysis and calorimetry, 1991. 37(8): p. 1633-1656.
11. Hassan, A., M. Arif, and M. Shariq, Use of geopolymer concrete for a cleaner and sustainable environment–A review of mechanical properties and microstructure. Journal of cleaner production, 2019. 223: p. 704-728.
12. Cong, P. and Y. Cheng, Advances in geopolymer materials: A comprehensive review. Journal of Traffic and Transportation Engineering (English Edition), 2021. 8(3): p. 283-314.
13. Reddy, C.J. and S. Elavenil, Geopolymer concrete with self-compacting: A review. Int. J. Civ. Eng. Technol, 2017. 8(2): p. 163-172.
14. Thakur, M. and S. Bawa, Self-compacting geopolymer concrete: A review. Materials Today: Proceedings, 2022. 59: p. 1683-1693.
15. Praveen, P.U. and K. Srinivasan. Self-compacting geopolymer concrete-a review. in IOP Conference Series: Materials Science and Engineering. 2017. IOP Publishing.
16. Duxson, P., et al., Geopolymer technology: the current state of the art. Journal of materials science, 2007. 42: p. 2917-2933.

17. Part, W.K., M. Ramli, and C.B. Cheah, An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. Construction and Building Materials, 2015. 77: p. 370-395.
18. Abdullah, M., et al., Mechanism and chemical reaction of fly ash geopolymer cement-a review. Int. J. Pure Appl. Sci. Technol, 2011. 6(1): p. 35-44.
19. Swanepoel, J. and C. Strydom, Utilisation of fly ash in a geopolymeric material. Applied geochemistry, 2002. 17(8): p. 1143-1148.
20. Katz, A., Microscopic study of alkali-activated fly ash. Cement and Concrete Research, 1998. 28(2): p. 197-208.
21. Wang, H., H. Li, and F. Yan, Synthesis and mechanical properties of metakaolinite-based geopolymer. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2005. 268(1-3): p. 1-6.
22. Palomo, A., M. Grutzeck, and M. Blanco, Alkali-activated fly ashes: A cement for the future. Cement and concrete research, 1999. 29(8): p. 1323-1329.
23. Criado, M., A. Palomo, and A. Fernández-Jiménez, Alkali activation of fly ashes. Part 1: Effect of curing conditions on the carbonation of the reaction products. Fuel, 2005. 84(16): p. 2048-2054.
24. Hardjito, D., et al., Properties of geopolymer concrete with fly ash as source material: effect of mixture composition. Special Publication, 2004. 222: p. 109-118.
25. Van Jaarsveld, J., J. Van Deventer, and L. Lorenzen, The potential use of geopolymeric materials to immobilise toxic metals: Part I. Theory and applications. Minerals engineering, 1997. 10(7): p. 659-669.
26. Ahmed, M.F., M.F. Nuruddin, and N. Shafiq, Compressive strength and workability characteristics of low-calcium fly ash-based self-compacting geopolymer concrete. International journal of civil and environmental engineering, 2011. 5(2): p. 64-70.
27. Patel, Y.J. and N. Shah, Development of self-compacting geopolymer concrete as a sustainable construction material. Sustainable Environment Research, 2018. 28(6): p. 412-421.
28. Parashar, A., et al., Study on performance enhancement of self-compacting concrete incorporating waste foundry sand. Construction and Building Materials, 2020. 251: p. 118875.
29. Jerônimo, V.L., G.R. Meira, and L.C.P. da Silva Filho, Performance of self-compacting concretes with wastes from heavy ceramic industry against corrosion by chlorides. Construction and Building Materials, 2018. 169: p. 900-910.
30. Liu, M.Y.J., et al., Utilization of palm oil fuel ash as binder in lightweight oil palm shell geopolymer concrete. Advances in Materials Science and Engineering, 2014. 2014.
31. Zeyad, A.M., et al., Production of geopolymer concrete by utilizing volcanic pumice dust. Case Studies in Construction Materials, 2022. 16: p. e00802.
32. Al-Rawi, S. and N. Taysi, Performance of self-compacting geopolymer concrete with and without GGBFS and steel fiber. Advances in concrete construction, 2018. 6(4): p. 323.

33. Srishaila, J., et al., Experimental study on workability and strength characteristics of fly ash and GGBS based self-compacting Geo polymer concrete. Int. J. Eng. Res. Dev, 2014. 10(6): p. 68-77.
34. Memon, F.A., et al., Effect of sodium hydroxide concentration on fresh properties and compressive strength of self-compacting geopolymer concrete. J. Eng. Sci. Technol, 2013. 8(1): p. 44-56.
35. Nuruddin, M.F., et al., Effect of superplasticizer and NaOH molarity on workability, compressive strength and microstructure properties of self-compacting geopolymer concrete. International Journal of Geological and Environmental Engineering, 2011. 5(3): p. 187-194.
36. Sashidhar, C., et al., Fresh and strength properties of self compacting geopolymer concrete using manufactured sand. Int. J. ChemTech Res, 2015. 7: p. 183-190.
37. Ushaa, T., R. Anuradha, and G. Venkatasubramani, Performance of self-compacting geopolymer concrete containing different mineral admixtures. 2015.
38. Patel, Y.J. and N. Shah, Study on workability and hardened properties of self compacted geopolymer concrete cured at ambient temperature. Indian Journal of Science and Technology, 2018. 11(1): p. 1-12.
39. Budh, C. and N. Warhade, Effect of molarity on compressive strength of geopolymer mortar. International journal of civil engineering research, 2014. 5(1): p. 83-86.
40. Singhal, D., et al., Mechanical and microstructural properties of fly ash based geopolymer concrete incorporating alccofine at ambient curing. Construction and building materials, 2018. 180: p. 298-307.
41. Aliabdo, A.A., M. Abd Elmoaty, and H.A. Salem, Effect of water addition, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete performance. Construction and Building Materials, 2016. 121: p. 694-703.