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Exploring the Synergy of Fly Ash and GGBS in Geopolymer Concrete: A Review

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ABSTRACT: Geopolymer concrete stands out as a sustainable alternative to Ordinary Portland Cement (OPC) concrete, making use of industrial by-products like fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as binders. This review examines in further detail the ingredients, mix design strategies, and the mechanical and durability characteristics of Flyash-GGBS geopolymer concrete. The process of geopolymerisation, which is activated by alkaline agents such as sodium hydroxide and sodium silicate, converts aluminosilicate-rich materials into durable binders with remarkable mechanical properties. Fly ash improves workability and supports environmental sustainability, while GGBS boosts compressive, flexural, and tensile strengths. Despite its benefits in cutting down carbon emissions and enhancing durability, there are still challenges in fine-tuning mix designs and curing conditions for consistent results. This paper also emphasizes the synergistic relationship between fly ash and GGBS, exploring advancements in activators and admixtures that enhance the performance of geopolymer concrete, positioning it as a viable solution to reduce the environmental footprint of traditional cement-based materials.

Keywords: Geopolymer concrete, Fly ash, GGBS, Alkaline activators, and Sustainability

I. INTRODUCTION

As the construction industry seeks sustainable alternatives, geopolymer concrete (GPC) has gained attention as an environmentally friendly substitute for traditional cement-based concrete. Among the various aluminosilicate materials, FAand GGBS stand out due to their widespread availability and reduced environmental impact. Unlike conventional Portland cement concrete, which consists of cement, water, sand, and crushed stone aggregate, geopolymer concrete utilises these industrial byproducts as binders, offering a greener solution for construction. However, because of its adaptability and potential to provide creative flexibility, ordinary concrete is regarded as a significant construction material worldwide(Glavind, 2009). As infrastructure has grown and cement manufacturing has increased, issues with resource productivity, sustainability, climate change, and building durability have emerged and must now be addressed (Mehta, 2004).As to the United States Geological Survey (USGS) and the European Cement Association Cembureau (2021), China accounted for 57.2% of the world's cement output, trailed by India (7.0%), the United States (2.1%), the European Union (6.1%), and the rest of the world (27.6%). According to Hasanbeigi et al. (2010), the manufacture of cement releases roughly 0.9 tonnes of CO2 per tonne of cement, making it the second-largest source of CO2 emissions worldwide and contributing between 5 and 8% of total CO2 emissions (Mikulčić et al. 2016). As a result, there is pressure on the cement sector to lower its carbon footprint, and several approaches are being investigated. These include the use of substitute materials that can minimise emissions and partially replace OPC, such as fly ash, blast furnace slag, and silica fumes (Imbabi et al., 2012). Moreover, technological advancements such as the use of hydration control additives have shown promise in enhancing the strength of OPC, allowing for a reduction in the amount of cement required and thereby decreasing CO_2 emissions by at least 30%(Dengler et al., 2023). Despite these efforts, the widespread application of alternatives like aluminate cement and geopolymers is limited due to cost and raw material availability, ensuring that OPC remains a dominant material in construction (Dengler et al., 2023).

Geopolymer Concrete is produced by mixing geopolymer binder with fine and coarse aggregates in the presence of alkaline solution

(Shehab et al., 2016).Geopolymer binders, introduced by Davidovits, present a capablesubstitute to ordinary Portland cement (OPC) owing to their potential to utilise industrial by-products like fly ash, ground granulated blast furnace slag, and silica fume, thereby addressing environmental concerns associated with OPC production (Singh, 2018).The geopolymerization developmentencompasses the alkaline activation of aluminosilicate-rich materials, which are dissolved in an alkaline solution, typically sodium or potassium-based, to form a polymeric gel that hardens into a solid binder(Usha et al., 2014).

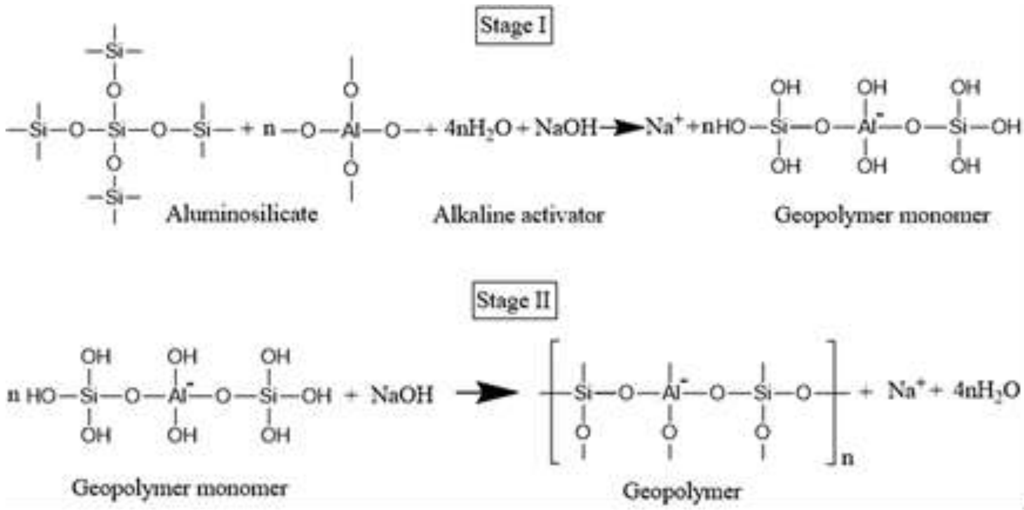

Figure 1. Geopolymer Reaction Mechanism (Cao et al., 2018)

Geopolymerisation typicallyhappens in four phases, which are dissolution, gelation, solidification, polycondensation, and crystallization (Ghosh and Ghosh, 2018).In contrast to Portland cement, all four stages can happen separately or all at once to create a solid substance with better strength and durability qualities (Van et al., 2012). The mechanical characteristics of the final geopolymer concrete are determined by several variables that affect this process, including the kind of raw materials used, the concentration and kind of alkaline activators, and the curing condition (Nath and Sarker, 2013Geopolymers are appropriate for both structural and non-structural applications due to their high early strength and tolerance to harsh conditions (Singh, 2018). However, challenges remain in optimising the chemical composition and curing conditions to achieve consistent performance across different applications (Ndagia and Jaafar, 2019).

II. CONSTITUENTS OF GEOPOLYMER CONCRETE

The constituents of GPCinclude a binder material like fly ash and ggbs,base activators like Sodium hydroxide and Sodium silicate, aggregates, and necessary admixtures (Chowdhury et al., 2021). The key constituents of geopolymer concrete include FA, GGBS, metakaolin, and silica fume, which serve as the primary binders due to their high silica and alumina content (Asmara, 2023).

2.1 Binders

Pozzolanic materials with high silica and alumina percentages by mass are ideal as raw ingredients for the binder. Being readily available, found in abundance, and with better chemical properties, fly ash and GGBS are the preferred choices for use.

2.1.1 Fly ash

A byproduct of burning coal in thermal power plants is fly ash,which primarily contains fine, spherical particles that include silica, alumina, and iron oxides, with less than 10% calcium oxide (Dabi and Patwa, 2018). Coal ash, which makes up 75–85% of the total, is created when mineral impurities in coal fuse while burning and is obtained from exhaust gases using bag filters or electrostatic precipitators (Siddique and Khan, 2011). The global production of fly ash is significant, with countries like India producing about 112 million tonnes annually due to the high ash content in its coal (Dwivedi and Jain, 2014). Historically considered a problematic waste due to its environmental hazards, including heavy metal leaching and air pollution, fly ash is now increasingly recognized for its potential applications (Kamara et al., 2023). It is extensively utilised in the building sector, especially in the manufacturing of concrete, where it enhances strength and durability, and in the production of fly ash bricks, which are economical and efficient for building construction (Kundu, 2022).Table 1 displays the chemical makeup of fly ash used by different authors.

Table 1. Fly ash's chemical composition (percentage by mass).

Author	SiO_2	Fe_2O_3	Al_2O_3	CaO	K_2O	Na_2O	SO_3	MgO	LOI
Partha et al., 2013	53.71	11.17	27.20	1.90	0.54	0.36	0.30	N. A	0.68
Nath & Sarker, 2014	50	13.5	28.25	1.79	0.46	0.32	0.38	0.89	0.64
Mehta & Kumar, 2016	61.73	6	26.30	1.7	N. A	0.18	0.017	0.65	N. A
El-Hassan & Ismail, 2017	48	12.5	23.1	3.3	0.0	0.0	N. A	1.5	1.1
Rao and Rao, 2018	60.11	4.25	26.53	4.00	N. A	0.22	0.35	1.25	3.25
Bellum et al. (2020)	58.23	4.56	25.08	2.87	0.87	0.41	1.16	1.21	1.59
Sunarsih et al., 2023	41	26.94	15	8.64	2.43	N. A	0.50	0.74	N. A

2.1.2 GGBS

GGBS is a byproduct of the iron manufacturing process, specifically from blast furnaces where iron ore, coke, and limestone are melted at high temperatures, resulting in molten iron and slag. The slag, primarily composed of silicates and alumina, is quickly cooled using pressuredjets of water to form grainy particles, which are then crushedto a fine powder known as GGBS(Siddique & Khan, 2011). As a Supplementary Cementitious Material (SCM), GGBS is well known for improving concrete's qualities while lessening the environmental effect of Portland cement manufacture (Ogirigbo et al., 2018). The incorporation of GGBS in concrete not only improves mechanical properties but also improves durability by reducing pore connectivity, which mitigates risks such as Sulphateattack and chloride penetration, although it may slightly reduce resistance to carbonation(Divsholi et al., 2014). Table 2 provides the chemical properties of GGBS used by various researchers.

Table 2. GGBS's chemical composition (percentage by mass).

Author	SiO_2	Fe_2O_3	Al_2O_3	CaO	K_2O	Na_2O	SO_3	MgO	LOI
Partha et al., 2013	29.96	0.52	12.25	45.45	0.38	0.31	3.62	N.A	2.39
Nath & Sarker, 2014	32.46	0.61	14.3	43.1	0.33	0.24	4.58	3.94	0.09
Mehta & Kumar, 2016	43.4	N. A	12.5	40.3	0.6	0.9	N. A	1.5	2.1
El-Hassan&Ismail, 2017	34.7	0.8	14.4	42	0	0	N. A	6.9	1.1

Rao and RAO, 2018	34.06	0.8	20.00	32.6	N. A	N. A	0.90	7.89	3.72
Bellum et al., 2020	32.25	1.10	12.14	44.7	N. A	0.87	0.84	4.23	1.98
Sunarsih et al., 2023	23.50	0.95	8.20	62.10	0.10	N. A	0.94	0.30	N. A

2.2 Alkaline Activators

Alkaline activators play a vitalpart in the production of GPC, catalysing the polymerization of aluminosilicate sources, which are used as a sustainable substituteforconventional Portland cement. Commonly used basic activators include Sodium hydroxide (NaOH) and Sodium silicate (Na_2 SiO_3), which are recognized for their efficiency in increasing the mechanical properties of GPC, although they contribute to carbon emissions during their production (Adeleke et al., 2023). Various combinations and concentrations of these activators to optimise the performance of geopolymer concrete. For instance, increasing the molarity of NaOH from 10 M to 16 M has been shown to improve compressive strength by 3.75–10.2% after 28 days(Rihan et al., 2024). Additionally, the use of alternative activators such as wood ash lye has been investigated, demonstrating that it can effectively replace NaOH, offering a more environmentally friendly option(Isa & Awang, 2025). The proportion of sodium silicate to sodium hydroxide is also critical, with studies indicating that specific ratios can significantly impact the compressive strength and workability of the concrete(Blasiak et al., 2023; Rathod & Sanni, 2023). Moreover, innovative approaches such as using magnetized water in the preparation of alkaline activators have shown promising results, enhancing both the mechanical properties and durability of geopolymer concrete(Khattab et al., 2023). The utilisation of silica fume-derived sodium silicate in combination with NaOH has also been explored, highlighting the potential for utilising high-silica content by-products in geopolymer activators(Adeleke et al., 2023). The progress and refinement of alkaline activators play a crucial role in enhancing both the sustainability and functionality of geopolymer concrete, presenting a practical substitute for conventional cement-based materials.

2.3 Aggregates (Coarse and Fine)

Aggregates make up nearly 70% of the total volume of concrete, with the typical mass distribution between coarse and fine aggregates being approximately 65% and 35%, respectively (Chowdhury et al., 2021). The economic and environmental advantages of using local aggregates are well-documented, as they reduce transportation costs and environmental impact (Nwofor and Eme, 2016). For geopolymer concrete, the selection and testing of aggregates are vital to ensure the anticipated mechanical properties and durability.

2.4 Admixtures

The use of FA and GGBS in geopolymer concrete is known to reduce workability, necessitating the practice of superplasticizers to enhance the handling and application of the concrete mix (Xie et al., 2019). Among the superplasticizers (SPs) utilised in GPC are polycarboxylates, polycarboxylate ether (PCE), naphthalene, lignosulfonates, melamine, sulfonated melamine formaldehyde (SMF), and sulfonated naphthalene formaldehyde (SNF), and of these SPs, SNF and PCE are the most commonly utilised in India. (Anudeep et al., 2024). SNF superplasticizers are generally compatible and effective in refining the workability of GPC;the practice of polycarboxylate superplasticizers requires cautiousattentionto the specific mix design and environmental conditions to ensure optimal performance (Saifuddin et al., 2014; Nematollahi & Sanjayan, 2014).

2.5 Mix Design

The development of mix design codes for GPC using FA and GGBS is an area of active research, though standardized codes are not yet universally established. The formulation of GPC utilising FA and GGBS requires a detailed strategy that fine-tunes multiple factors to attain the target mechanical properties and promote sustainability. The mix design process typically involves selecting the appropriate activator to binder ratio, aggregate to binder ratio, and the concentration of the alkaline activator, which significantly affect the workability and strength of the concrete (Sangi et al., 2023).

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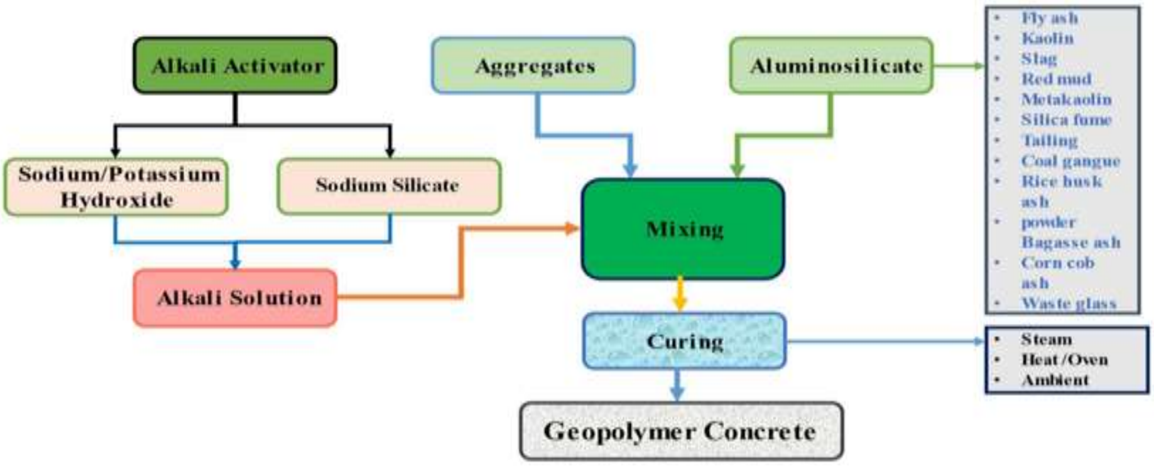

Figure 2. Production Process of GPC (Cao et al., 2022)

Various studies have employed optimisation techniques such as the Taguchi method to refine the mix design, considering factors like binder content, alkaline-to-binder ratio, and the use of superplasticizers to improve workability and strength (Ali et al., 2024; Karthikand Mohan, 2021). The mix design can also be tailored to specific strength requirements, with some methodologies allowing for adjustments based on desired compressive strength and alkaline activator content (Reddy et al., 2018). Additionally, the practice of recycled aggregates in GPC has been explored, demonstrating that fly ash and GGBS can synergistically improve the performance of recycled aggregate geopolymer concrete (Gopalakrishna and Dinakar, 2023).

III. FRESH CONCRETEPROPERTIES OF FA-GGBS GEOPOLYMER CONCRETE

FA and GGBS-basedGPC exhibits distinct fresh concrete properties that are influenced by the mix proportions, activator concentrations, and curing environments. The fresh characteristics of this type of concrete are typically assessed using tests such as slump flow, T50cm, V-funnel, and L-box, which help determine its workability and self-compacting abilities (Vigneshkumar et al., 2024). The inclusion of superplasticizers is often necessary to maintain fluidity, with studies indicating that a 2% superplasticizer quantity can effectively alter the workability of self-compacting geopolymer concrete (SCGC)(Vigneshkumar et al., 2024). The concentration of NaOH used as an activator also plays a crucial role; increased concentrations tend to enhance the mechanical properties but may affect the fresh properties by reducing workability(Pandey et al., 2024). The addition of GGBS to FA-based GPC can accelerate setting times and improve strength, although it may reduce workability unless compensated by additional water or superplasticizers (Amini & Ekaputri, 2022). The curing method significantly impacts the fresh properties, with steam curing enhancing strength but potentially affecting the initial workability (Pandey et al., 2024). Moreover, the use of alternative aggregates, such as geopolymer fine aggregate, can maintain similar fresh properties to those of conventional concrete, ensuring that the GPC remains a viable alternative (Thankam et al., 2021).

IV. MECHANICAL PROPERTIES OF FLY ASH- GGBS GEOPOLYMER CONCRETE

4.1 Compressive Strength

Geopolymer concrete has mechanical properties comparable to those of conventional concrete (Jalal et al., 2024).The compressive strength of fly ash-GGBS GPC is inclined to several factors, together with the proportions of FA ash and GGBS, the molarity of the alkaline solution, and the curing conditions (Castillo et al., 2021). Fly ash-GGBS geopolymer concrete is characterised by high early strength relative to conventional concrete containing Ordinary Portland Cement (Chen et al.,2015).The relationship between fly ash and ground granulated blast furnace slag (GGBS) in geopolymer concrete is synergistic, as both materials contribute to the mechanical and durability properties of the concrete. Fly ashand GGBSare used as partial or full replacements for cement in GPC, which pointedly reduces CO_2discharges compared to OPC concrete(Patil and Deshamukh, 2022).

Table 3. Compressive Strength Analysis of Various FA-GGBS Studies

Authors	Study Focus	Key Findings	Level of Replacement
Parthiban et al., 2013	Impact of slag substitution on mechanical characteristics of FA-based GPC.	Increasing slag content led to enhanced mechanical properties.	FA was substituted by GGBS at 20% replacement levels, ranging from 20% to 100%.
Rashad, 2013	Properties of base-activated FAGPCcombined with slag.	Mechanical strengths and drying shrinkages increased as the slag percentage rose, whereas workability dropped.	Slag was added to FA at levels of 0, 5, 10, and 15% by weight.
Deb et al., 2014	Effect of slag and FA blends on GPC strength & permeation properties.	Strength increased with higher slag content; slag and fly ash improved strength and durability.	GGBFS was used at 10% and 20 % of the total binder.
Thakkar et al., 2014	GPC with FA& GGBS under open-air curing.	GGBS addition improved the compressive strength & workability compared to pure FA-based GPC.	The FA/slag proportions varied from 90/10, 70/30and 50/50.
Nath & Sarker, 2014	Effects of GGBS on workability, setting, and early strength properties of FAGPC.	GGBS improved early strength development. Workability &setting time decreased by higher GGBS levels.	FA was replaced up to 30% by GGBS at 10% levels.
Rajini & Rao, 2014	Mechanical properties of geopolymer concrete with varying fly ash and GGBS replacement levels.	Geopolymer concrete performed well with FA and GGBS, showing good compressive and tensile strength at ambient curing.	GGBS was replaced up to 100% by FA in intervals of 25%
Zende & Mamatha, 2015	Mechanical properties of GPC using FA& GGBS with sodium hydroxide&sodium silicate.	Increased slag content (up to 75%) improved strength and reduced drying shrinkage, especially at higher molarity solutions.	GGBS replaced FA in proportions of 25%, 50%, and 75%
Srinivas & Rao (2016)	Optimization of mix design for low calcium FA and slag-based GPC.	Optimized mix design led to equivalentstrength of M30 & M50 grades.	Two different formulations (70% FA + 30% GGBS) and (50% FA + 50% GGBS).
Gopalakrishnan & Chinnaraju, 2016	Durability of FA& GGBS-based GPC exposed to acid and chloride environments.	40% GGBS substitutionbyFA showed the best performance in terms of durability and strength.	GGBS replaced FA up to 50 % in replacement levels of 10%.
Abhilash et al., 2016	Mechanical properties of GPC with shifting levels of FA & GGBS.	Mechanical characteristics improved with an increasein GGBS.	GGBS replaced FA up to 50 % in replacement levels of 25%.
Wardhono et al., 2017	Effect of slag addition on strength development of FA-based GPC.	30% slag addition improved Strength, workability, & setting time; results comparable with conventional concrete.	FA was replaced with 90%, 70%, and 30% Slag.
Takekar & Patil, 2017	Mechanical properties of FA& GGBS-based GPC.	GGBS replacement showed higher early strength than FA GPC. Compressive strength was highest at 50% GGBS replacement.	GGBS was used to substitute fly ash at several proportions (0%, 25%, 50%, 75%, and 100%).
Arun et al.,	Effect of FA & GGBS	Compressive strength improved	FA was replaced with

2018	with varying molarities on workability and mechanical properties.	with raising GGBS content, with optimal performance at 70% GGBS replacement.	GGBS by 0%, 30%, 50%, and 70% by mass.
Ghosh & Ghosh, 2018	Impact of fluctuating slag proportion on the engineering properties of GPC.	30% slag incorporation showed anincreasein compressive strength and reduced porosity.	GGBS varied as 90,85,70,50, and 40% of FA.
Bellum et al., 2020	Mechanical and durability properties of FA and GGBS-based GPC.	60% GGBS and 40% FA mix proved to be the optimal mix.	FA was replaced up to 60% by GGBS at 10% levels.
Ahamed et al., 2023	Sustainable GPC with FA& GGBS, and recycled aggregates.	Higher GGBS content resulted in enhanced strength.	FA was replaced up to 100% by GGBS at 10% levels.

Rashad (2013) observed that the mechanical properties of FA-slag GPC enhance as the slag content increases. Similarly, Bellum et al. (2020) and Ahamed et al. (2023) found that raising the GGBS content in FA-GGBS GPC leads to higher concrete strength. Ahamed et al. (2023) specifically stated that the highest strength was achieved when fly ash was completely replaced by GGBS.

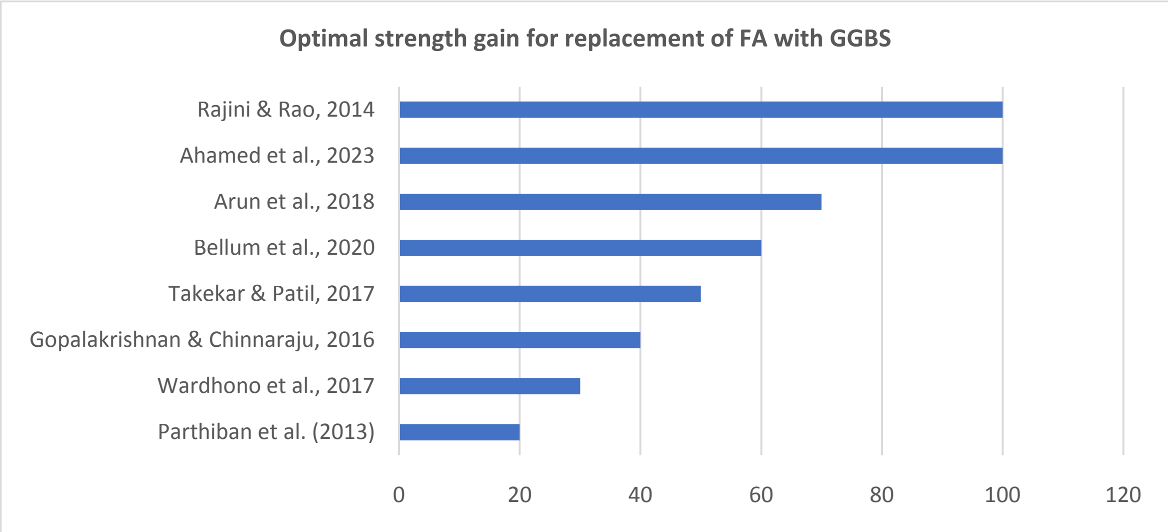

Figure 4. Optimal replacement of FA by GGBS

The previous conclusion contrasts with other studies, which suggest that optimal compressive strength is achieved when GGBS constitutes the majority of the binder. Shah (2017) and Arun et al. (2018) found that a 70/30 FA/slag ratio yields the highest strength, while Srinivas and Rao (2016) identified an 85/15 ratio as optimal. Pilehvar et al. (2018) observed that adding 40% GGBS to FA-based geopolymer upsurges compressive strength, highlighting the lack of a standardized mix design code.

4.2 Flexural Strength

The addition of GGBS or slag to FA-based GPC has been shown to significantly improve its flexural strength, as indicated by several studies. Parthiban et al. (2013) reported that the addition of higher slag content in FA-slag GPC leads to a corresponding enhancement in flexural strength. This trend was further supported by the findings of Deb et al. (2014), who observed a similar improvement in flexural strength as the slag proportion in the mix was increased. Deb et al. (2014) demonstrated that higher GGBS content in FA-based GPC resulted in increased flexural strength, with a rise from 3.20 MPa to 4.92 MPa when GGBS proportion was increased from 10% to 20%. Zende & Mamatha (2015) further corroborated this finding, observing a notable enhancement in flexural strength as the quantity of

GGBS increased. In their study, a mix of 50% fly ash and 50% GGBS achieved a flexural strength of 4.01 MPa at 28 days. Patil and Deshamukh (2017) found that a mix of 60% fly ash and 40% GGBS resulted in a significant improvement in flexural strength, reaching 13.08 N/mm² at 28 days, surpassing conventional concrete. Similarly, Bellum et al. (2020) concluded that the highest flexural strength of 8.61 MPa for a mix containing 60% GGBS further supporting the beneficial effect of GGBS on concrete performance. More recently, Nagalingam et al. (2020) reinforced these findings, showing that higher GGBS content leads to improved flexural strength in fly ash-GGBS geopolymer concrete. Collectively, these studies suggest that raising the GGBS proportion in FA-based geopolymer concrete enhances its flexural strength, contributing to greater structural robustness and durability.

4.3 Split Tensile Strength

The synergistic effect of binders, specifically FA and GGBS, plays a significant role in enhancing the split tensile strength of GPC. Studies have shown that the optimal combination of these binders results in improved tensile properties due to the unique chemical interactions between the alumino-silicate components of FA & the hydraulic properties of GGBS. A study by Patil and Deshamukh (2017) observed that the split tensile strength for GPC mixes, with 70% FA and 30% GGBS, was significantly higher than traditional concrete, with values increasing from 1.11 N/mm² at 7 days to 3.55 N/mm² at 28 days. Similarly, Rajini and Rao (2014) observed a notable increase in split tensile strength with the addition of GGBS, where the mix with 25% FA and 75% GGBS attained a tensile strength of 4.94 MPa at 28 days. The synergistic effect is further exemplified by the findings of Nagalingam et al. (2020), where the split tensile strength of mixes containing both binders showed progressive enhancement with increasing GGBS content, reaching 4.30 MPa at 28 days for the 50% FA and 50% GGBS mix. This indicates that the combination of FA and GGBS optimises the binding mechanism, contributing to superior mechanical properties. Furthermore, the elevated tensile strength observed in these systems, as reported by Aanal Shah (2017) and Rathod and Hombal (2017), reflects the role of binder interactions in improving the microstructural integrity of the geopolymer matrix, thereby enhancing its resistance to tensile stresses. Thus, the synergistic effect of FA and GGBS in GPC leads to a marked improvement in split tensile strength, highlighting the effectiveness of these binders in optimising concrete performance.

V. DURABILITY PROPERTIES OF FLY ASH- GGBS GEOPOLYMER CONCRETE

5.1 Water Absorption

The water absorption characteristics of geopolymer concrete are greatly impacted by the FA to GGBS ratio. Studies have revealed that increasing the proportion of GGBS in the mix reduces water absorption due to the formation of a denser microstructure (Jayajothi et al., 2014). Flyash-GGBS mixes with higher GGBS content (e.g., 60% GGBS and 40% FA) exhibited inferior water absorption rates compared to mixes with lower GGBS content (Bellum et al., 2020a). The type and amountof alkaline activators, such as Sodium hydroxide (NaOH) &Sodium silicate (Na_2SiO_3), also play a vitalpart in determining water absorption. Higher alkaline activator-to-binder ratios can lead to improved durability and reduced water absorption, as they enhance the formation of a compact gel structure (Sunarsih et al., 2024). Ambient curing has demonstrated production of GPC with good better and durability, including low water absorption rates (Pruthviraj & Anadinni, 2022). However, heat-curing can further enhance the microstructural properties, leading to even lower water absorption (Reddy & Reddy, 2023). The addition of supplementary materials, such as nano-silica or eggshell powder, can further reduce water absorption by improving the microstructure and reducing porosity (Deb et al., 2016). Under elevated temperatures, flyash-GGBS geopolymer concrete has demonstrated good thermal stability and low water absorption. This makes it suitable for applications where concrete is exposed to high temperatures (Yilmazoglu et al., 2022).

5.2 Sorptivity

Pruthviraj and Anadinni (2022) investigated the mechanical properties and sorptivity coefficient of geo-polymer concrete with a 50:50 GGBS & FA binder ratio, comparing M20 and M40 grades of GPC with normal concrete (NC). The results demonstrated that GPC exhibited 1.28 times lower water absorption than normal concrete, suggesting improved quality and durability. Yilmazoglu et al. (2024) discovered thatthe sorptivity of FA and GGBS GPC decreased significantly with increasing GGBS content, with reductions of up to 6.5 times. Chary and

Munilakshmi (2023) evaluated the sorptivity of a fly ash-GGBS geopolymer concrete mix (40% FA, 30% GGBS, 30% eggshell powder) and found that it exhibited superior durability properties, showing lower sorptivity than conventional concrete. Additionally, Nagajothi et al. (2022) studied the sorptivity of G30 grade GPCmade from fly ash and GGBS, and their results revealed that its absorption rate was similar to that of traditional concrete.

5.3 Acid Resistance

Flyash-GGBS geopolymer concrete exhibits significant acid resistance, making it acapablesubstitutefortraditionalOPC concrete in acidic environments. The incorporation of GGBS into FA-based GPC enhances its durability against acid attacks, as evidenced by loss in weight & compressive strength degradation when exposed to acidic solutions such as Hydrochloric acid (HCl) and Sulfuric acid (H_2SO_4)(Singh et al., 2023). Research has indicated that GPC with a higher proportion of GGBS plus additional admixtures of minerals like silica fume and metakaolin demonstrates superior performance compared to those with 100% flyash, particularly in terms of maintaining structural integrity and minimizing mass loss under acid exposure(Yierlapalli et al., 2023). The formation of calcium silicate hydrate (CSH), calcium aluminosilicate hydrate (CASH), and sodium aluminosilicate hydrate (NASH) gels contributes to the densification and compactness of the geopolymer matrix, further increasing its ability to withstand chemical attacks (Singh et al., 2023). Experimental investigations have consistently demonstrated that FA-GGBS GPCoutclassestraditional concrete regarding acid resistance, with lower mass and compressive strength losses observed over extended exposure periods(Nagajothi et al., 2022; Chowdaiah et al., 2018). This enhanced performance is attributed to the inherent properties of geopolymers, which are less porous and more chemically stable than traditional cementitious materials, making them suitable for use in hostile environments where acid exposure is a concern(Chary & Munilakshmi, 2022).

5.4 Sulphate Resistance

The proportion of FA to GGBS has a major impact on the geopolymer's resistance to sulphates, as evident from studies that a higher GGBS content in the binder enhances sulphate resistance due to the formation of more stable hydration products such as calcium-aluminum-silicate-hydrate (C-A-S-H) and sodium-aluminum-silicate-hydrate (N-A-S-H) gels (Xie et al., 2019a). A mix with a GGBS:FA ratio of 3:1 exhibited better resistance tosulphateattack compared to mixes with lower GGBS content (Mohamed et al., 2022). The type and concentration of the alkaline activator, typically a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), play a crucial role in thesulphateresistance of geopolymer concrete. Higher concentrations of NaOH can improve the formation of a dense microstructure, thereby enhancing resistance tosulphateions (Nagajothi et al., 2022). Additionally, curing conditions, such as temperature and humidity, significantly affect the hydration process and the resulting microstructure of the geopolymer paste(Wallah et al., 2005). The type ofsulphatesolution (e.g., Sodium sulphate, Magnesium sulphate) and the duration of exposure also influence thesulphateresistance of geopolymer concrete. Magnesiumsulphatesolutions are generally more aggressive than Sodiumsulphatesolutions due to the additional damage caused by Magnesium ions, which can react with the hydration products and form expansive compounds like gypsum ($CaSO_4 \cdot 2H_2O$) and brucite (Mg (OH)2) (Cho et al., 2018; Park et al., 2017).Sulphate ions can enter the GPC's pore structure and react with the hydration products to produce expansive compounds. Concrete may expand and crack because of magnesium ions reacting with calcium from the hydration products to generate gypsum and brucite when exposed to magnesium sulphate(Park et al., 2017; Cho et al., 2018). The microstructure of geopolymer concrete plays a critical role in itssulphateresistance. A denser microstructure with lower porosity reduces the ingress ofsulphateions, thereby improving resistance. However, exposure tosulphatesolutions can lead to the formation of cracks and the deterioration of the microstructure over time (Ismail et al., 2013; Long et al., 2017). Geopolymer concrete usually exhibits bettersulphateresistance compared to OPC concrete. This is credited to the absence of calcium hydroxide in the geopolymer matrix, which is a key reactant insulphateattack in OPC concrete (Saavedra et al., 2016; Bhutta et al., 2014). After 180 days of exposure to Magnesium sulfate, geopolymer concrete showed only a 33% reduction in compressive strength, compared to a 48% reduction for OPC concrete (Saavedra et al., 2016). The superiorsulphateand acid resistance of FA-GGBS geopolymer concrete makes it an ideal material for construction in aggressive environments, such as marine environments, sewage treatment plants, and areas with high sulphate-rich soils (Xie et al., 2019a; Bhutta et al., 2014).

5.5 Chloride Resistance

The incorporation of GGBS into FA-based GPCnotably enhances its resistance to chloride ingress. Studies have shown that GGBS modifies the microstructure of the geopolymer matrix, leading to a denser and more impermeable structure. This reduction in porosity limits the penetration of chloride ions, thereby improving durability (Prusty & Pradhan, 2023). The addition of GGBS increases the formation of calcium-bearing gels, such as C-S-H (calcium-silicate-hydrate) and N-A-S-H (sodium-aluminum-silicate-hydrate) gels, which contribute to a more compact microstructure. This is evident from XRD and EDS analyses, which highlight higher atomic Ca/Si ratios in GGBS-containing mixes (Prusty & Pradhan, 2023). GGBS-based geopolymer concrete exhibits higher chloride binding capacity compared to fly ash-only mixes.

This is credited to the presence of calcium ions, which respond to chloride ions to form insoluble calcium chloroaluminate compounds, thereby reducing free chloride ions in the pore solution (Gopalakrishnan & Chinnaraju, 2016).

GPC exhibits lower chloride diffusion coefficients compared to OPC, even when considering its higher porosity. This is due to the unique pore structure and gel chemistry of geopolymers (Ismail et al., 2012).The mix design of Flyash-GGBS geopolymer concrete plays a critical role in its chloride resistance. An increase in the water-to-binder ratio from 0.32 to 0.38 enhances chloride erosion resistance. However, further increases in this ratio compromise the material's mechanical properties (Feng et al., 2024). Higher slag content generally improves chloride resistance, but excessive slag replacement can lead to reduced strength and increased porosity. Optimal slag content is typically around 40% replacement of fly ash (Prusty & Pradhan, 2023; Feng et al., 2024). The type and dosage of alkaline activators significantly influence the microstructure and chloride resistance of GPC. Sodium silicate-based activators are particularly effective in promoting the formation of dense gels (Nagajothi et al., 2022).

VI. CONCLUSION

Fly ash-GGBS geopolymer concrete is paving the way for more sustainable construction practices by making use of industrial by-products as binders. The collaboration between fly ash and GGBS not only enhances mechanical properties but also significantly lowers the carbon footprint when compared to traditional OPC concrete. Recent advancements in mix design strategies, like optimizing binder ratios and alkaline activator concentrations, have further boosted the strength and durability of geopolymer concrete. However, there are still challenges to tackle, including curing conditions, cost-effectiveness, and the need for standardized mix designs. Future research should aim to refine these factors and investigate innovative activators to broaden the use of geopolymer concrete in various structural applications. By addressing these challenges, fly ash-GGBS geopolymer concrete has the potential to become a revolutionary material for sustainable infrastructure development.

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