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REVIEW PAPER

Advancements in Geopolymer Concrete Technology: A Comprehensive Review of Fresh, Hardened and Microstructural Properties

Rawat, R.[1], **Bachheti, I.**[1] **and Pratap, B.**[2]*

[1] M. Tech. Scholar, Department of Civil Engineering, Graphic Era (Deemed to be University), Dehradun, India.
[2] Assistant Professor, Department of Civil Engineering, Graphic Era (Deemed to be University), Dehradun, India.

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ABSTRACT: This review summarizes recent developments in Geopolymer Concrete (GPC) technology, focusing on fresh, hardened, and microstructural properties. Key findings include the impact of ultrafine Ground Granulated Blast furnace Slag (GGBS) on enhancing workability and reducing setting times. GPC exhibits lower density and improved water resistance compared to traditional concrete, with compressive, flexural, and split tensile strengths increasing over time. Microstructural analyses highlight denser matrices and improve mechanical properties through effective activation processes. These advancements highlight GPC's potential as a sustainable and durable construction material, emphasizing the need for further research and development for widespread adoption in the industry. The review categorizes frequently employed precursors based on their primary chemical components and explores how different binder types impact various aspects of lightweight geopolymers. Additionally, it consolidates optimal mix designs from various studies to aid readers in choosing suitable binders and achieving desired density and compressive strength goals through the utilization of different precursors, alkaline binder solutions, and lightweight concrete.

Keywords: Compressive Strength, GGBS, Workability, Durability, Geopolymer, Microstructure.

1. Introduction

1.1. Overview

Lightweight concrete is a rigid material with a lower density than regular aggregates such as sand, clay, and gravel, resulting in less dead load while keeping acceptable strength. Its strength varies depending on the type and quantity of aggregate used, contributing to sustainable construction requirements. The emergence of lightweight aggregates, manufactured during the nineteenth and twentieth centuries, signaled a significant milestone in the advancement of lightweight concrete technology (Mousa et al., 2018; Shahrour and Allouzi, 2020). Coarse aggregates for concrete production typically consist of crushed natural rocks or stones. Different regions, depending on their geological makeup, utilize different types of natural rocks such as limestone and basalt (Shahrour and Allouzi, 2020). To tackle the aforementioned challenges, three technological approaches are proposed. These include aggregates recycled from waste concrete (Akhtar and Sarmah, 2018; Dimitriou et al., 2018; Liu et al., 2020;

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[*] Corresponding author E-mail: bheempratapbind009@gmail.com

Pawluczuk et al., 2019), repurposing coarse waste aggregates such as large-particle Bottom Ash (BA) and steel slag, and creating artificial aggregates using industrial wastes or by-products (Qian et al., 2020; Tajra et al., 2019).

Among these approaches, the artificial manufacturing method is gaining prominence as it offers a viable solution for producing both fine and coarse aggregates, meeting the demands of waste recycling and large-scale production. Presently, the primary focus lies on research into artificial coarse aggregates, spurred by the need to address shortages in fine aggregates through alternative solutions like the utilization of sea sand (Huang al., 2021, 2020a,b). Two well-established methods for manufacturing artificial lightweight aggregates are sintering and cold bonding (Qian et al., 2020; Tajra et al., 2019). Sintering predominantly depends on high temperatures, often exceeding 1000 °C, to crystallize the precursors. Conversely, the conventional cold-bonding technique typically employs cementitious pastes for bonding the raw materials together.

Geopolymer Concrete (GPC) demonstrates outstanding performance, including comparable mechanical strength, minimal shrinkage, excellent resistance to creep, and high durability even in acidic environments (Reddy et al., 2016). Numerous factors influence the properties of recycled aggregate concrete, including the quality and quantity of recycled aggregate, water-to-cement ratio, mixing techniques, additives, and supplementary materials (Guo et al., 2018; Li et al., 2016). Furthermore, recent investigations have focused on improving the properties of recycled aggregate to promote its utilization (Dimitriou et al., 2018; Li et al., 2016).

Each year, the global production of Construction and Demolition Waste (CDW) amounts to around 820 million tons (Gálvez-Martos et al., 2018; Mani and Pradhan, 2020). In the United States alone, approximately 500 million tons of CDW is yielded annually (Akhtar and Sarmah, 2018), while China produces about 200 million tons. Recycling CDW presents a highly effective solution to these challenges. Aside from the expenses associated with waste disposal and the negative impact on landscapes, reusing these materials can mitigate issues like illegal dumping, which pose both social and environmental concerns (Agwa et al., 2020). Raw materials can be natural resources such as perlite or pumice, or manufactured aggregates such as polyethylene particles, which are best acquired from trash or industrial byproducts to reduce quarry consumption (Erfanimanesh and Sharbatdar, 2020; Wang et al., 2020). Ordinary Portland Cement (OPC) is often the primary binder for lightweight concrete, although it raises environmental problems due to CO_2 emissions and habitat destruction from material extraction (Pratap et al., 2024a).

Zero-cement binders, such as geopolymer materials derived from waste aluminosilicates such as slag and Fly Ash (FA), provide a greener alternative by creating geopolymers when mixed with chemical solutions such as sodium hydroxide (Payakaniti et al., 2017). It is increasingly common to mix soils with processed rubber particles in various civil and geotechnical constructions, such as lightweight backfill (Rouhanifar et al., 2021). Incorporating fiber into soil enhances both its shear and tensile strengths, while also increasing the material's ductility. Additionally, fiber-mixed soil exhibits a higher permeability coefficient and reduced swelling potential.

Despite substantial research on geopolymers, there are few detailed studies of the mix design and attributes of LightWeight Geopolymer Concretes (LWGCs). Microstructural analysis is also used to determine the durability and thermal qualities (Nuaklong et al., 2019; Shi et al., 2020). Geopolymers are moving beyond straight cement replacements, finding specialized uses in thermal and sound insulation where lightweight variations thrive. The review classifies commonly used precursors according to main chemical components and analyses how binder type influences various aspects of lightweight geopolymers. Furthermore, it combines optimal mix designs from numerous research to assist readers in selecting appropriate binders and reaching desired density and compressive strength targets using various precursors, alkaline binder solutions, and lightweight concrete.

1.2. Economic Feasibility

Even though GPCs are made from waste materials and have many desired properties, they are generally more expensive than normal OPC concrete. GPC can often be twice as expensive as regular concrete. This cost disparity is due to the large investment in manufacturing technologies and established infrastructure acquired over time for typical OPC concrete, which results in lower overall prices (Carreño-Gallardo et al., 2018). GPC, as a relatively new technology, lacks manufacturing efficiency and infrastructure, contributing to its higher costs. However, as additional research and technologies are developed, the cost of GPC is expected to fall. Analyzing the cost breakdowns of conventional and GPC yields intriguing findings. In traditional concrete, cement typically accounts for the majority of construction expenditures.

GPC, on the other hand, has significantly lower costs for binders and aggregates because geopolymer binders are generally made from industrial waste materials (Tayeh et al., 2021). However, alkali activators are important in GPC and can significantly affect building costs. The development of cost-effective technology for producing alkali activators and binders like Sodium Silicate (SS) and Sodium Hydroxide (SH) has the potential to drastically reduce the overall cost of GPC, making it more competitive with conventional choices (Pratap et al., 2024b). In some areas, quality FAs and slag are mainly available but are being depleted due to the stop of coal-fired power plants and reduction of blast furnace operations (Hu et al., 2019). Such shortages may cause variations in GPC properties, hence limiting its large-scale production. The chemical composition of FA and slag varies widely depending on their source, causing variation in the performance of GPC. The quality and consistency of these materials are fundamental for the reliable performance characteristics of GPC.

However, high-quality FA and slag are available only in certain parts of the world and can significantly differ according to local industrial activities (Gartner and Sui, 2018). Another important hurdle against the widespread use of GPC is its production cost. Although GPC could be cheaper than Plain Cement Concrete (PCC) due to lower energy requirements as well as using industrial waste products, the prices for alkalis activators like sodium hydroxide or sodium silicate may be extraordinarily high sometimes (Nematollahi et al., 2016). In addition, since GPC production processes are not fully developed compared to those of conventional concrete, expenses incurred when obtaining materials or ensuring the quality of materials are higher, including specialized machines needed. This variation between costs becomes more obvious when large-scale building projects are considered, where the economy is always important.

1.3. GPC vs Emerging Alternatives

The most promising aspect of GPC is its potential application to significantly cut carbon emissions compared to conventional concrete, using industrial byproducts like FA, slag, and metakaolin. It enables low-carbon construction activities, associated with a shallow carbon footprint. Similarly, it is highly resistant to chemicals, fire, and attainable temperatures, making it ideal for infrastructures under adverse environments. However, GPC is one of the mix designs that requires stringent control in the mix and casting process; in most cases, it requires heat curing to reach its optimum.

This can limit its widespread adoption, particularly in regions where these conditions are difficult to maintain. Another promising alternative is alkali-activated materials, which include geopolymers as one of the groupings under its subset (Pratap et al., 2024a). Alkali-Activated Materials (AAMs) give a flexible composition of binder; thus, a greater variation of industrial byproducts can be used as precursors to this class of materials.

It is this versatility that AAM can adapt to various local resources and environmental conditions; it also provides high early strength and durability, equal to GPC. Similar to geopolymers, the use of alkali activators can induce complexities in the mixing and handling processes (Pratap and Kumar, 2024). In addition, problems in sustainability are sometimes created with the AAMs with alkali activators, which are considered special in nature, both in type and source. The other innovative approach to sustainable construction is carbon-sequestering concrete. This is a material manufactured with the specific purpose of capturing and storing carbon dioxide during the curing process, which effectively reduces the overall carbon footprint of the concrete.

Some carbon-sequestering concretes use basically just a combination of Portland cement and alternative binders, while others may ditch cement completely for such things as magnesium oxide, which naturally absorbs CO_2. The main advantage of carbon-sequestering concrete is active removal, in the contribution to driving down atmospheric CO_2 concentration for battling climate change. The technology is, however, immature, and a host of problems-like scalability, cost, and variability in performance with respect to traditional and other alternative concretes-continue to loom large (Pourjahanshahi et al., 2023).

In bio-based concretes, materials such as hemp, bamboo, or mycelium enable genuinely new avenues for building ecologically. As such, these materials are renewable, biodegradable, and can potentially have a much lower environmental impact than their counterparts of traditional cement-based products. However, in comparison, the compressive strength is lower than that of geopolymer or traditional concrete; thus, the use is limited to non-structural or low-rise buildings. The replacement materials make GPC a good combination with optimum performance and the least possible environmental impact. Its performance shows the greatest impact in sections requiring durability and bearing the tendency to survive under extreme conditions. Indeed, the main barriers to its implementation are practical challenges like the necessity of precise mix control and heat curing.

On the other hand, AAMs are versatile and could be adapted to local conditions more, even though they face some difficulties with geopolymers that are similar in nature. Concretes sequestering carbon represents a solution that holds promise for strong environmental benefits, but is still on the developmental path. Lastly, bio-based concretes are green solutions for only a handful of niche markets right now, as they have yet to be optimized for large-scale production.

Ultimately, the material selection will be based on specifications within the project regarding environmental goals, service loads, and the availability of resources from regions with different climates. GPC, with its superior sustainability and performance, depends on overcoming the associated technical challenges in its production and use.

2. Materials

2.1. Precursors

The production of Al-Si and Ca-Si materials involves distinct chemical processes, which has led to the differentiation between terminology such as "geopolymer" and "alkali-activated material". Traditionally, materials like Ground Granulated Blast furnace Slag (GGBS) and FA are grouped under the geopolymer classification, whereas precursors derived from slag are typically termed as alkali-activated materials. However, recent studies have started using the term "geopolymer" inclusively for both groups, distinguishing between calcium-based and alumina-based geopolymers. Within concrete mixtures, geopolymers act as binders, offering the possibility to partially or completely replace traditional cement. Key chemical components essential for their formation include Silicon Dioxide (SiO_2), Aluminium Oxide (Al_2O_3), Iron Oxide (Fe_2O_3), and Calcium Oxide (CaO).

These elements play pivotal roles in the molecular structure and binding properties of geopolymers. The combination of these chemical insights underscores the fact that precursor materials for geopolymer production exhibit a wide range of compositions, characterized by varying proportions of SiO_2, Al_2O_3, Fe_2O_3, and CaO. Understanding the composition of each precursor material is paramount for optimizing geopolymer formulations. This understanding enables researchers and engineers to tailor the properties of geopolymers to suit specific applications, particularly as replacements for cement in concrete. By manipulating the composition of precursor materials, researchers can fine-tune the performance characteristics of geopolymers, enhancing their durability, strength, and other desirable attributes in concrete structures. Thus, a thorough comprehension of precursor composition serves as a foundational step in the advancement and widespread adoption of geopolymers as sustainable alternatives to conventional cement-based materials.

The reaction mechanism in geopolymers occurs in three main phases: a) The breakdown of aluminosilicate into aluminate and silicate compounds; b) Condensation of the monomers (initiation of setting time); and c) Monomers polymerizing into an amorphous inorganic polymer. The alkali in cement activates GGBS particles, leading to the formation of its hydration products. The hydraulic properties of GGBS arise from chemical reactions between calcium, silica, and aluminium, which react with water to create calcium silicate and calcium aluminate hydrates. Some of these GGBS hydration products further react with Portland cement, forming additional hydrates that help block pores, resulting in a cement paste with very fine gel pores.

This process enhances the stability of the hardened cement paste by reducing the free lime content (Saranya et al., 2018). This review aims to analyze the use of lightweight aggregates in GPC, exploring their impact on durability, microstructure, and sustainability. It also investigates different methods for producing lightweight aggregates and their effects on concrete properties. However, there is a gap in understanding the mix design and attributes of lightweight GPCs, as well as a lack of systematic analysis of binder types and precursors. This review seeks to address these gaps by synthesizing existing research and providing insights for optimizing mix designs and selecting suitable materials for lightweight GPC applications.

2.1.1. Fly Ash (FA)

FA is a fine powder residue that is produced when coal is burned in power plants (Xu et al., 2021). FA and BA are residues or secondary products that are produced when coal is burned, and they need to be disposed of in an environmentally friendly way (Öz et al., 2021). The Mae Moh thermal power plant in northern Thailand produces about 3.0 million tons of lignite FA per year, which has a high silica and alumina content, making it suitable for utilization as a pozzolanic material in concrete as well as a foundational material for creating geopolymer binders (Wongsa et al., 2016).

Type F FA was characterized with a higher concentration of SiO_2, Al_2O_3, and Fe_2O_3, total 79.49% (Nuaklong et al., 2021). The FA comprising 45.23% SiO_2, 19.94% Al_2O_3, 13.15% Fe_2O_3, and 15.5% CaO, was classified as a Class C FA (Posi et al., 2013, 2015, and 2016).

2.1.2. Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a by-product of iron production in blast furnaces, processed into a fine powder form by rapid quenching with water. Because of its superior cementitious qualities and advantages for sustainability, a supplemental cementitious material is widely utilized in buildings. GGBS enhances concrete durability, reduces the heat of hydration, and mitigates environmental impact by reducing CO_2 emissions associated with cement production. Its incorporation in concrete contributes to improved strength, workability, and resistance to sulphate and chloride attacks, making it an essential component in modern construction practices. In the study by Xu et al. (2021), the primary constituents of both GGBS and cement included SiO_2, Al_2O_3, and CaO. However, in comparison to GGBS, cement possessed a higher concentration of CaO and lower levels of SiO_2 and Al_2O_3. Additionally, GGBS exhibited a predominantly amorphous phase (Tayeh et al., 2021). In the study by Hu et al. (2019), GGBS was employed as a partial substitute for FA. The proportion of particles retained on the 45-micrometer sieve was 2.0%.

2.1.3. Bottom Ash (BA)

BA is a byproduct of burning coal in power plants. It consists of heavy particles that sink to the bottom of the combustion chamber. BA contains minerals like silica, iron, and aluminium, and is often reused in construction materials such as concrete and asphalt. Its disposal requires careful management due to potential environmental impacts. Wongsa et al. (2016) used the BA upon receipt; the BA was crushed and sieved to produce fine BA and coarse BA, which were utilized in the production of LWGC. The BA proved suitable for application as both fine and coarse aggregates in high-strength concrete.

2.1.4. Recycled Concrete Aggregate (RCA) and Construction and Demolition Waste (CDW)

RCA and CDW play crucial roles in sustainable construction practices. RCA is derived from crushed concrete, offering a sustainable alternative to traditional aggregates, and reducing the need for fresh materials and landfill waste. CDW encompasses various materials generated during construction, renovation, or demolition activities, including concrete, bricks, wood, and metals. By recycling CDW and utilizing recycled coarse aggregates, construction projects can minimize ecological footprints; preserve natural resources, and principles of the circular economy. Considering that coarse and fine aggregates typically constitute 75-80% of the overall concrete volume, the integration of C and D (Construction and Demolition) wastes, particularly in the form of recycled coarse aggregates, holds significant promise (Shaikh, 2016).

Within C and D materials, approximately 75% comprises concrete, while the remainder comprises masonry, tile, asphalt, and other components. The study by Rahman and Khattak (2021) intended to introduce the idea of Roller-Compacted GPC (RCGPC) in an effort to improve the mechanical properties of entirely recycled coarse aggregates. The Loss on Ignition (LOI) in CDW exceeds that of Natural Aggregates (NAs) because of the presence of Portland cement and gypsum within the recycled aggregates (Arenas et al., 2017).

2.1.5. Pumice Aggregate (PA)

PA is a lightweight, porous volcanic rock used as an aggregate in construction materials such as concrete, plaster, and stucco. It is formed from volcanic eruptions and possesses excellent insulation properties, making it suitable for lightweight concrete applications. PA reduces the overall weight of the concrete while maintaining strength, aiding in easier handling and transportation. Its porous nature also enhances drainage and reduces water absorption in construction projects. Volcanic pumice, characterized by its natural lightweight attributes and sponge-like structure, is found in granular form, which results from the rapid cooling of molten lava (Wongsa et al., 2018).

PA can be utilized as a lightweight aggregate in structural concrete, prepared by refining natural materials such as pumice, scoria, or tuff. However, in the case of LWGCs made with PA, the compressive strength was notably reduced, rendering it suitable for the production of concrete blocks.

2.1.6. Clay Brick Aggregate (CBA)

CBA is a sustainable alternative to traditional coarse aggregates in concrete production. It involves crushing and recycling waste clay bricks to create aggregates for use in construction. CBA offers several benefits, including reduced environmental impact by diverting waste from landfills; lower production costs compared to NAs, and improved thermal insulation properties in concrete structures. In an experiment by Wongsa et al. (2018), crushed clay brick and pumice, LWGCs demonstrated superior heat insulation and fire resistance properties in comparison to GPCs containing NAs.

2.2. Light Weight Aggregate (LWA)

Lightweight aggregates are materials used in construction that are lighter in weight compared to traditional aggregates like gravel or crushed stone. These aggregates are typically derived from natural materials such as expanded clay, perlite, shale, or slate, or from synthetic materials like foamed blast furnace slag or expanded perlite. The primary advantage of lightweight aggregates is their reduced density, which makes them particularly useful in applications where weight is a concern, such as in the construction of high-rise buildings, bridges, and precast concrete elements.

Lightweight aggregates offer benefits such as improved workability, reduced dead load on structures, and enhanced energy efficiency. Additionally, their low thermal conductivity can provide insulation properties, making them suitable for applications where thermal performance is important. However, they may have lower strength compared to traditional aggregates, so careful consideration is needed in their selection and use in construction projects. Overall, lightweight aggregates play an important role in modern construction, offering versatility and sustainability in various applications.

2.2.1. Natural Aggregate (NA)

Natural lightweight aggregates, like expanded clay, shale, slate, and pumice, offer construction materials with low density. These substances undergo processes such as heating or expansion to achieve their lightweight properties. Widely used in construction, they reduce structural dead loads, provide thermal insulation, and ease handling during construction.

Applications include lightweight concrete, fill materials, and insulation. The study by Wongsa et al. (2018) utilized various materials, including crushed CBA, PA, and crushed limestone aggregate. The coarse aggregates used in this work by Tayeh et al. (2021) are local dolomite, leca, and pumice. Öz et al. (2021) used quartz aggregates of various diameters, serving as NA used in the production of concrete. Wongsa et al. (2016) used NAs, like sand and crushed limestone. The natural coarse aggregate utilized by Hu et al. (2019) was crushed basalt aggregate sourced from a local site. It possessed an irregular morphology characterized by sharp edges.

2.2.2. Artificial Aggregate

Engineered materials called artificial lightweight aggregates are used in construction to lighten concrete without sacrificing structural integrity. LWAs are generally composed of FA, shale, or expanded clay and have good strength, low density, and thermal insulation qualities.

Engineered materials called artificial lightweight aggregates are used in construction to lighten concrete without sacrificing structural integrity. LWAs are generally composed of FA, shale, or expanded clay and have good strength, low density, and thermal insulation qualities. In the experiment by Posi et al. (2013) and Posi et al. (2016), recycled lightweight blocks were processed into different aggregate sizes: fine aggregate, medium aggregate, and coarse aggregate. These aggregates were categorized based on particle sizes ranging from 0.001 to 1.18 mm for fine aggregate, 1.18 to 4.75 mm for medium aggregate, and 4.75 to 12.5 mm for coarse aggregate. Recycled packaging foam used in the study by Posi et al. (2015) was sourced from discarded packaging foam of household electrical appliances. Initially, the foam pieces, ranging from 3.0 to 4.0 cm, were manually broken down and further ground using a food blender. Subsequently, the crushed foam underwent sieving to achieve particle sizes ranging from 2.36 to 4.75 mm. Öz et al. (2021) also used cold-bonded Light Weight Fine Aggregates (LWFA) as an artificial aggregate, employed together with quartz. Arenas et al. (2017) and Shaikh (2016) used CDW as an artificial aggregate.

2.3. Alkali Mixture for Activation and Binding

Alkali activators, such as SH, SS, potassium hydroxide (KOH), and calcium hydroxide ($Ca(OH)_2$), initiate chemical reactions with alumina, silica, and other compounds in geopolymer solutions. Sodium and potassium ions, in various forms like silicate, carbonate, and sulphate, are crucial in these reactions. These compounds release hydroxyl ions (OH-), aiding the disintegration of aluminate and silicate compounds in geopolymer precursors like FA. Typically, a single type of hydroxide, mostly SH for convenience, is present in the activation solution. SH and SS were utilized as alkaline activators for producing geopolymer binder by all the researchers, and their proportions are given in Table 1. Table 2 presents the chemical composition of different materials.

3. Mix Design

Optimal mix designs for various GPC with lightweight aggregates are outlined in this review paper. The emphasis is on formulations with superior compressive strength and reduced densities. Components such as binder type and content, alkali activators, lightweight aggregates, curing conditions, and densities are highlighted. This information provides valuable insights for researchers and practitioners seeking to optimize mix designs for lightweight geopolymer applications.

3.1. Mixing

GPC production starts with mixing the alkaline activating solution and binding precursor, initiating chemical reactions to form gels and polymers. Aggregates are then added, and the mixture is poured into moulds, covered to prevent moisture loss. Subsequently, samples are cured in ovens, controlled rooms, or both successively. Geopolymer pastes were made using one-part technology, dry-mixing precursors and alkaline activators for 5 min.

Water was added for a duration of three minutes due to quick setting. Mixture cast into 100 mm × 100 mm × 100 mm moulds, covered, and demoulded after 24 hrs at 25 °C. Eight specimens per mix proportion were prepared for future casting (Xu et al., 2021). FA and superplasticizer mixed for 5 min, then aggregates for 2 min. Silica fume (SS) added and mixed for 1 min. Fresh mixtures compacted in moulds on a vibrating table for 10 sec.

Table 1. Proportions of alkaline solutions adopted by various researchers

Study	SS/SH ratio
Wongsa et al. (2018)	0.5, 1.0, 1.5
Wongsa et al. (2016)	-
Shaikh (2016)	2.5
Öz et al. (2021)	2.5
Rahman and Khattak (2021)	1
Posi et al. (2015)	1
Posi et al. (2013)	1
Nuaklong et al. (2021)	0.60
Hu et al. (2019)	2.0
Arenas et al. (2017)	0.29
Posi et al. (2016)	0.33, 0.67, 1.0, 1.5, 3

Cylindrical samples with 10 cm diameter and 20 cm height cast for compressive and splitting tensile strength tests (Wongsa et al., 2018). The study examines four mix series: GPC0 (control) with 100% NCA, and 3 others with 15%, 30%, and 50% RCA replacing Natural Coarse aggregates (NCA). Alkali activator to FA ratio is constant. Conventional mixing includes dry-mixing aggregates, adding class F FA, pouring alkali solutions gradually until uniformity is achieved visually (Shaikh, 2016). For lightweight oil well cement, cement, FA, and GGBS are mixed dry for 1 min, followed by 2 min of fine and coarse aggregate mixing. Water and superplasticizer are gradually added over 2 min. In LWGC, solid components and aggregates are dry-mixed for 3 min, while liquid materials, including sodium silicate, sodium hydroxide, and superplasticizer, are premixed and added for 3 more minutes (Tayeh et al., 2021). LWGC and Conventional Geopolymer Concrete (CGC) were mixed at 25 °C. FA and superplasticizer were mixed for 5 min, then aggregates for 2 min. SS was added for 1 min. After 8 min, fresh concrete was tested for slump, cast, and compacted.

Samples: Cylindrical (100 × 200 mm) for strength tests, plates (150 × 150 × 60 mm) for abrasion resistance, cubes (100 × 100 × 100 mm) for conductivity and Ultrasonic Pulse Velocity (UPV) tests (Wongsa et al., 2016). Figure 1 shows the cast cylinders of GPC concrete with CDW (Arenas et al., 2017).

Table 2. Chemical composition of lightweight geopolymer concrete

References	**Contents**	Fe_2O_3	Al_2O_3	K_2O	MgO	CaO	SiO_2	TiO_2	P_2O_5	SO_3	BaO	**LOI**	Na_2O
Xu et al. (2021)	FA	9.19	26.9	1.28	3.49	9.14	43.4	0.91	0	1.65	0	2.9	3.16
Xu et al. (2021)	GGBS	0.27	16	0.43	8.69	39.9	31.1	0.72	0	2.44	0	2.71	0
Wongsa et al. (2018)	FA	11.5	20.8	2.4	2.2	14.5	39.4	0.5	0.2	4.2	0	1.5	1.4
Wongsa et al. (2018)	CBA	5.1	15.2	1.5	1.2	0.6	67.9	0.8	0	0	0	0	0.8
Wongsa et al. (2018)	PA	4	16.7	3.4	0.9	2.4	60.4	0.5	0.2	0	0	0	4
Shaikh, (2016)	FA	12.48	25.56	0.7	1.45	4.3	51.11	1.32	0.885	0.24	0	0.57	0.77
Tayeh et al. (2021)	FA	3.95	28.78	1.33	1.18	2.46	55.57	0.21	0	0.37	0	0.97	0.72
Tayeh et al. (2021)	GGBS	0.95	15.56	0.41	5.78	41.23	31.79	0.88	0	2.86	0	0.51	0.39
Rahman and Khattak (2021)	FA	12.17	14.82	1.59	0.79	13.87	36.4	0	0	0.57	0	0	0
Rahman and Khattak, (2021)	RCA	12.96	2.52	0.9	0.4	59.68	17.78	0	0	0.76	0	0	0
Öz et al. (2021)	FA	7.02	22.2	2.34	1.7	1.47	61.3	0.9	0	0.06	0	2.6	0.27
Nuaklong et al. (2021)	HCFA	11.9	19.9	2.4	1.9	14.2	36.2	0	0	3.6	0	0.4	0
Nuaklong et al. (2021)	LCFA	2.9	25.8	1.8	0.5	4.2	60.6	0	0	0.4	0	2.3	0
Wongsa et al. (2016)	FA	11.5	20.8	2.4	2.2	14.5	39.4	0.5	0.2	4.2	0.1	1.5	0
Wongsa et al. (2016)	BA	18	12.1	2.5	2.4	25.3	31.8	0.5	0.3	3.7	0.2	3.2	0
Arenas et al. (2017)	FA	5.86	21.5	1.67	1.84	3.94	63.9	0	<0.01	<0.01	0	3.32	0.68
Arenas et al. (2017)	CDW	3.54	9.57	1.87	2.45	17.9	57.8	0	0.11	0.42	0	9.19	0.61
Posi et al. (2016)	FA	13.15	19.95	2.15	2.02	15.5	45.23	0	0	0.3	0	0.88	0.52

3.2. Curing Procedure

Beam specimens measuring 100 mm × 100 mm × 400 mm were prepared using the mould. Using a vibratory hammer and a top plate, the mixture was crushed inside the mold. Following compaction, the specimen was taken out of the mold, sealed appropriately, and then put in an oven to cure at a high temperature (Rahman and Khattak, 2021). For a full day, the GPCs were cured at 100 °C in the oven. Once the samples had cured, they were removed from the molds and stored at room temperature until they were old enough to be tested (Öz et al., 2021). Figure 2 shows the cast specimens of concrete cured at elevated temperatures (Rahman and Khattak, 2021).

After casting, GPC is steam-cured for 24 hours at 60 °C. Specimens are cured under standard circumstances following demoulding and before testing. Durability properties are examined on day 28, although mechanical properties are studied at days 7 and 28. Concrete cylinders measuring 200 mm in height and 100 mm in diameter have compressive strength and elastic modulus, and indirect tensile strength is measured by those with a 150 mm diameter and 300 mm height (Shaikh, 2016). For compaction, the freshly mixed material was put into moulds and set on a vibration table. After that, specimens were shielded from evaporation throughout the curing process with a thin layer of plastic film (Hu et al., 2019). A little increase in compressive strength was observed when the temperature was raised from 25 to 90 °C. This increase was ascribed to improved geopolymerization and the creation of more byproducts (Posi et al., 2016).

Fig. 1. Geopolymer concrete specimens
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(a) **(b)** **(c)** **(d)**

Fig. 2. GPC specimens after exposure at: a) 25 ºC; b) 400 ºC; c) 600 ºC; and d) 800 ºC
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4. Results

4.1. Fresh Properties

4.1.1. Workability

Workability is a key property of concrete, indicating its ease of handling and placement. It is influenced by various factors and ensures that concrete can be effectively mixed, placed, and compacted without issues such as segregation or bleeding. Achieving the right workability is essential for constructing durable and high-quality concrete structures. PA particles water content improved workability, raising the concrete slump. LWGCs with CA had a lower slump than CGCs with NA, due to rounder river sand particles compared to fine CA, despite similar shapes in crushed limestone and coarse CA particles (Wongsa et al., 2018). Figure 3 exhibits the variation in slump value for different SS/SH ratios as well as for various aggregates (NA, CA, and PA). GPCs had better workability than the control mix. The workability enhanced from 1.1% to 7.63% as compared to the control. Aggregate properties and binder components affect flowability. The rise in workability as compared to the control mix is shown in Figure 4 (Öz et al., 2021). SS has a high viscosity and restricts mixture flow, higher SS/SH ratios reduced slump values (Wongsa et al., 2016). Slump values significantly decreased as the amount of GGBS in the binder was increased, particularly at higher GGBS concentrations. The high calcium ion content dissolved from GGBS caused a quick reaction with the alkali activator, which precipitated as calcium silicate hydrate, which was the cause of this loss in workability.

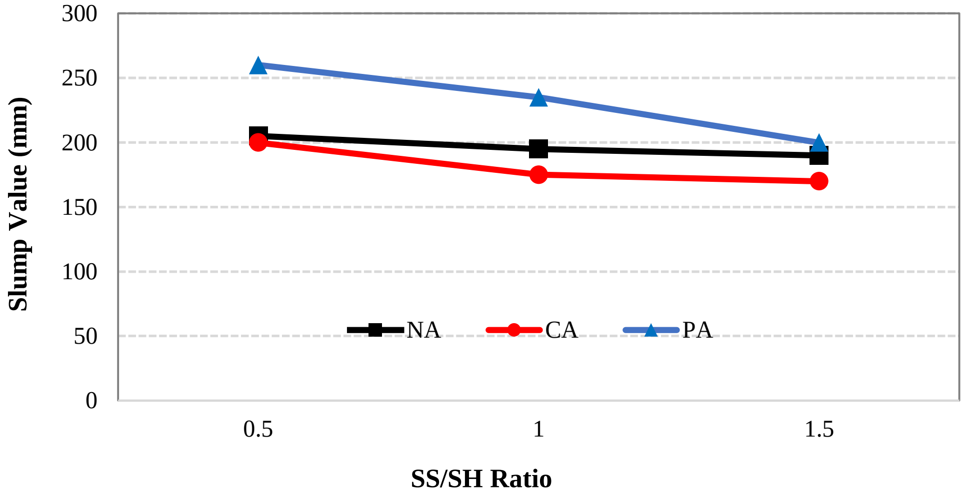

Fig. 3. Effect of aggregate type and SS/SH ratios on slump value

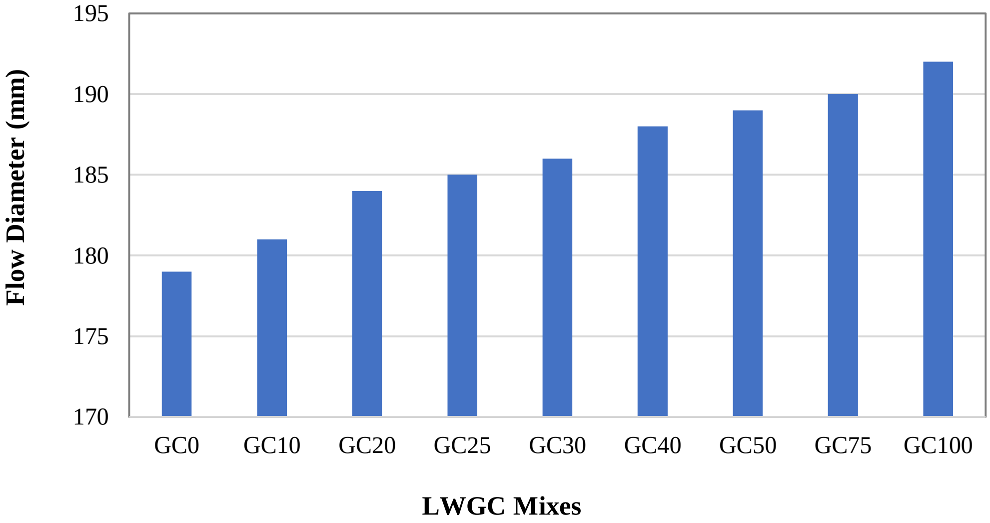

Fig. 4. Flow diameter of various LWGC mixes

The high calcium ion content dissolved from GGBS caused a quick reaction with the alkali activator, which precipitated as calcium silicate hydrate, which was the cause of this loss in workability. The mixes with higher slag content showed lower workability as compared to ordinary concrete (control mix). The trend in workability can be seen in Figure 5 (Hu et al., 2019).

4.1.2. Setting Time

Setting time is the amount of time needed for a cementitious substance, such as mortar or concrete, to solidify and harden from a malleable, working state. It is a crucial characteristic influencing workability and building schedules. Temperature, admixtures, cement type, and water-to-cement ratio all affect setting times. Achieving the intended building results requires careful observation and management of the setting time. The crushing time may lengthen as the GPC setting time does, and vice versa. When GGBS is added (Group B) or the alkaline content is increased (Group A), the strength of the geopolymer mix increases (Xu et al., 2021).

High-Calcium Fly Ash (HCFA) geopolymer sets quickly at low NaOH concentrations due to calcium leaching and precipitation, reducing workability and resulting in low density. Higher NaOH concentrations (10 and 15 M) extend setting times, slightly improving workability and increasing concrete densities (Posi et al., 2016). The GGBS content primarily influenced the setting time of geopolymer composites.

Mixtures without GGBS took a significantly longer time to set. However, the incorporation of GGBS in the binder considerably reduced both the initial and final setting times of the geopolymer composites. Additionally, as the GGBS content increased, the setting time (both initial and final) consistently decreased, as we can see in Figure 6 (Hu et al., 2019).

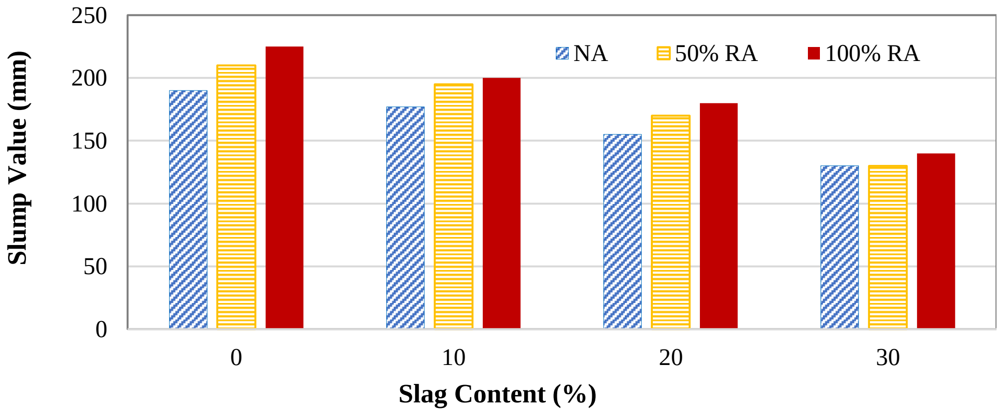

Fig. 5. The trend in workability at various slag contents

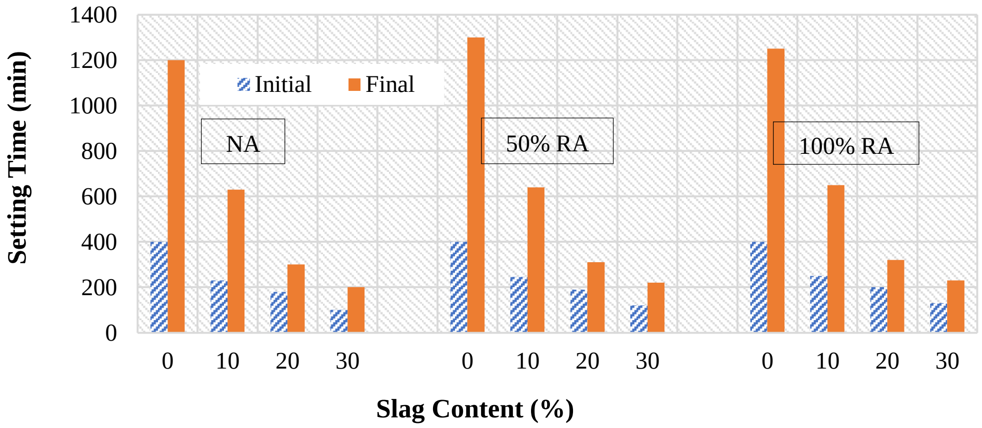

Fig. 6. Setting time vs slag content

4.1.3. Density

The loss of density was experienced in LWGCs with PA as compared to those that had either CA or NA. At temperatures of 400 °C, 600 °C, and 800 °C, for instance, the PA-1.0 samples lost their density by 24%, 29%, and 31%, respectively. CA-1.0 samples also had lower reductions than PA-1.0 samples too but to smaller degrees: 14%, 17%, and 18%. The corresponding losses for NA-1.0 were 5%, 6%, and 7%. The reason behind this greater loss in PA is due to higher water absorption, which leads to more mass loss resulting in lower compressive strength at high temperatures (Wongsa et al., 2018). The as-cast surfaces of concrete blocks with OPC content (0%, 5%, 10%, and 15%) reveal that 0% OPC leads to low density due to the presence of many voids. The addition of 5% and 10% OPC reduces voids and increases density, with 10% OPC achieving the highest density and strength. Although, at 15% OPC, the mixtures became too dry, resulting in rough surfaces that are less dense and strong. This is shown in Figure 7 (Posi et al., 2016). The density values fell between 2165 kg/m^3 and 2432 kg/m^3, depending on GGBS content as well as the recycled aggregate replacement ratio. Density was increased when FA was substituted with GGBS, but decreased by 4-8% when using recycled aggregates due to its lower density (Hu et al., 2019).

4.1.4. Segregation and Bleeding

Segregation and bleeding are common issues in concrete mixes. Segregation occurs when coarse aggregates settle and separate from the mortar, leading to uneven distribution of materials. Bleeding involves the migration of water to the surface due to the settling of heavier materials, leaving a layer of water on the surface. Both issues can compromise the strength and durability of concrete, leading to uneven surfaces and reduced quality.

Table 3. Density of various samples

Sample ID	Density (kg/m^3)
NA-1.0-25	2339
NA-1.0-400	2212
NA-1.0-600	2162
NA-1.0-800	2099
CA-1.0-25	1961
CA-1.0-400	1700
CA-1.0-600	1652
CA-1.0-800	1638
PA-1.0-25	1357
PA-1.0-400	1079
PA-1.0-600	1023
PA-1.0-800	1016

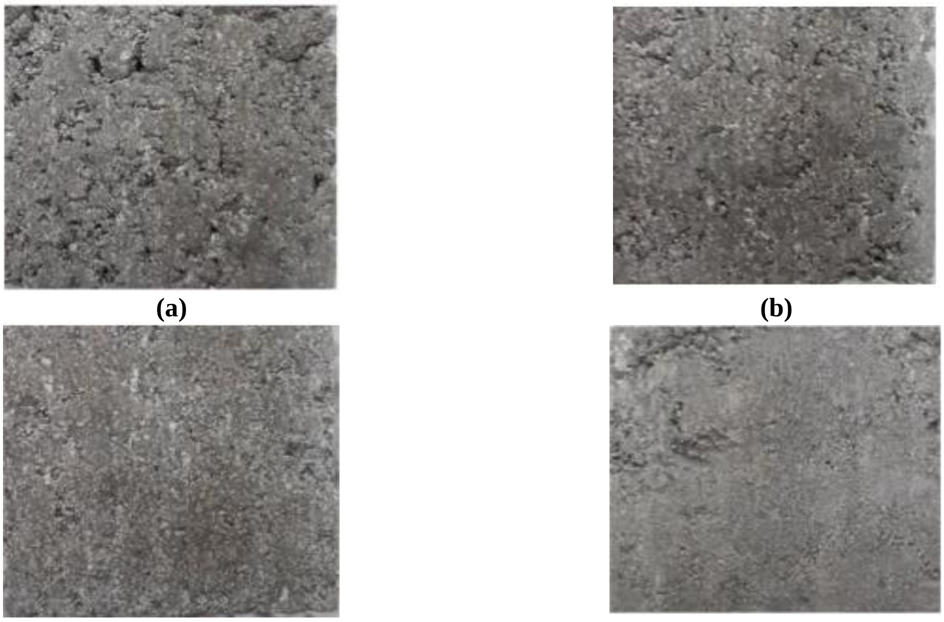
(a) **(b)** **(c)** **(d)**

Fig. 7. Cast surface of concrete for varying proportions of OPC content: a) 0% OPC; b) 5% OPC; c) 10% OPC; and d) 15% OPC

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Proper mix design and handling techniques are essential to minimize segregation and bleeding and ensure uniform and durable concrete structures. No segregation or bleeding was observed in any of the mixes by any researchers.

4.2. Durability

4.2.1. Water Absorption

Water absorption refers to the process by which substances take in water molecules. In various contexts, water absorption plays critical roles, from biological organisms to industrial materials. In plants, water absorption occurs through the roots, facilitating nutrient uptake and supporting growth. In materials science, understanding water absorption is crucial for assessing properties like durability and permeability in construction materials or determining the efficacy of absorbent products like diapers.

The phenomenon of water absorption underscores the fundamental role water plays across different domains of science and everyday life. Water absorption in GPC rises with higher RCA contents, showing about 20% more absorption at a 50% RCA content. This aligns with sorptivity and is attributed to the greater absorption of water by RCA due to adhered old mortars, which are typically more porous than NCA (Shaikh, 2016). The water absorption rates of GPCs ranged from 7.5% to 11.2% at day 1, 5.6% to 9.4% at day 7, and 4.4% to 8.6% at day 28.

Correspondingly, the apparent porosity values varied from 11.6% to 16.4%, 5.5% to 13.5%, and 5.3% to 6.6% for the same test ages, respectively (Öz et al., 2021). Water absorption in LWGC slightly rose with higher aggregate/ash ratios. For instance, at 28 days, for 0F mixes with ratios of 2.0, 2.2, 2.4, and 2.6, absorption rates were 30.13%, 30.70%, 31.40%, and 32.15%, respectively. Porosity followed a similar trend, increasing with higher aggregate/ash ratios (Posi et al., 2013).

4.2.2. Chemical Resistance

The research conducted by Shaikh (2016) demonstrated that the partial replacement of grade coarse aggregates by RCA leads to considerable increases in chloride penetration in GPC as observed from the GPC15, GPC30 and GPC50 series; 67%, 90% and 129%, respectively, from the initial control.

Such low resistance may have been induced by water absorption and high porosity associated with it due to the permeable mortar attached to its surface and the brick materials in it. GPC has been acknowledged to perform better than conventional PCC when subjected to harsh environments like industrial waste disposal sites, acid soils, and ocean waters (Posi et al., 2015). The use of geopolymer binders that are low in calcium minimizes the formation of expansive substances like ettringite or gypsum in sulphate attacks, which are commonly seen in cement. Besides, this can also be explained by good chemical resistance resulting from dense microstructures that hinder the entry of harmful ions.

4.2.3. Freeze-Thaw Resistance

Freeze-thaw durability is an important issue for concrete structures located in cold climates. This is so because GPC generally exhibits good freeze-thaw resistance as it has low water absorption and finer pore texture (Huang, Wu et al., 2021). However, the most reliable freeze-thaw resistance properties depend on the mix design, including the type and amount of activators employed. Some researchers have observed that GPC activated by sodium silicate has better freeze-thaw resistance than GPC activated by sodium hydroxide due to the production of a more cohesive and less porous matrix.

4.2.4. Chloride Ion Penetration

The resistance of GPC to chloride ion penetration is crucial in estimating its durability, especially in marine areas. Numerous studies indicate that GPC often presents a lesser degree of chloride penetration compared to normal concrete because it has a much tighter microstructure and lower volumes of empty spaces (Öz et al., 2021). Nevertheless, employing the RCA as GPC components may lead to reduced resistance against chloride ions due to increased porosity and water usage within the RCA. Consequently, this calls for aggregate type selection and mix design, which will ultimately improve GPC against attack by Cl ions.

4.2.5. Long-Term Durability

While there are not many long-term durability studies about GPC, the studies that exist indicate that GPC can keep its mechanical properties and resistance to environmental degradation for a long time. FA-based GPC, for instance, has shown little loss in strength and maintained its structural integrity after an extended time of exposure to severe conditions such as high temperatures and harsh chemicals (Nuaklong et al., 2018).

4.3. Mechanical Properties

4.3.1. Compressive Strength

The fundamental mechanical characteristic of concrete is its compressive strength, which denotes its capacity to withstand pressure or axial stresses. Usually, it is assessed by compressing cylindrical or cubic specimens until they break. In order to evaluate the structural soundness and load-bearing ability of concrete in a variety of applications, such as infrastructure, buildings, and bridges, compressive strength is essential. It is common to need a well-designed mix, high-quality materials, sufficient curing, and appropriate building techniques to achieve high compressive strength. Among the various factors studied by Posi et al. (2013), the highest compressive strength of 15.4 MPa was achieved. NaOH solution concentration of 10 M, higher curing temperatures up to 60 °C, and lower aggregate/ash ratios for improved strength.

Tayeh et al. (2021) found the following compressive strength observations as specified in Table 4 on varying the various aggregate percentages in the concrete mix. Rahman and Khattak (2021) observed that increasing NaOH molarity from 6 M to 10 M in the GPC mixture with 100% RCA at 60 °C significantly boosted both Unconfined Compressive Strength (UCS) and modulus of elasticity (E) Mixtures with 8 M and 10 M NaOH saw UCS increases of 61% and 100%, respectively, compared to 6 M.

This is due to increased OH production, vital for aluminosilicate gel formation and strength. The compression test and failed specimens are shown in Figure 8. Nuaklong et al. (2021) found that the use of Carbon Fiber (CF) resulted in increased compressive strength, likely due to enhanced matrix structure via micro-aggregate effect, leading to a more compacted microstructure.

Table 4. Compressive strength of various concrete mixes on varying aggregate sizes

Concrete mix	Aggregate type	Compressive strength (28 Days) (MPa)
LWGC (FA)	100% Dolomite	58.1
LWGC (GBFS)	100% Dolomite	56.8
LWGC (FA)	50% Dolomite + 50% Leca	48.7
LWGC (GBFS)	50% Dolomite + 50% Leca	47.5

(a) **(b)**

Fig. 8. a) Compression test; and b) Failed GPC specimens
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Beyond 1% CF content, there is a notable rise in the compressive strength of geopolymer mortar. Mixtures with 0.2% and 0.3% CFs exhibited 11-21% and 10-19% higher compressive strengths, respectively. A graph of the compressive strength before and after exposure to temperatures of 400 °C, 600 °C, and 800 °C observed by Wongsa et al. (2018) is provided in Figure 9.

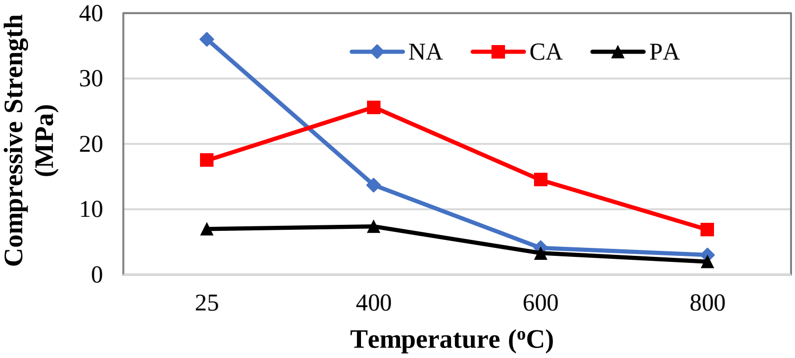

Fig. 9. Effect of temperature on the compressive strength

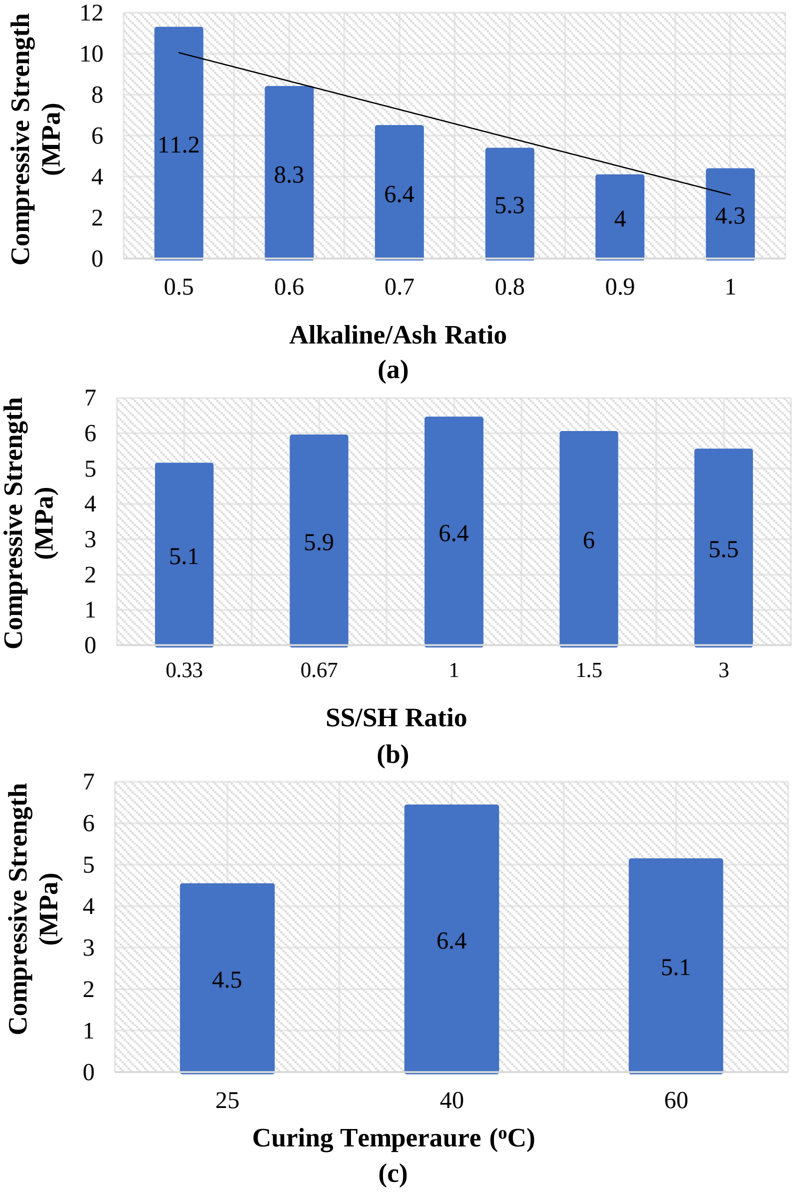

Fig. 10. a) Effect of alkaline to ash ratio on the compressive strength; b) SS/SH ratio effect on the compressive strength; and c) Effect of different curing temperatures on the compressive strength

Posi et al. (2015) observed different trends in changing the concentration of alkali/ash ratio and SS/SH ratio, and also the change in curing temperatures. The trends are shown in Figures 10a, 10b, and 10c.

4.3.2. Flexural Strength (FS)

FS, also known as modulus of rupture, is a key mechanical property of materials, especially in engineering and construction. It measures a material's ability to withstand bending without breaking. For instance, in structural engineering, it's crucial for designing beams, columns, and other elements subject to bending loads. Materials like concrete, wood, and steel exhibit FS, which is determined through standardized tests. Understanding FS aids in optimizing designs, ensuring safety margins, and selecting appropriate materials for various applications. It is a fundamental parameter in ensuring the structural integrity and longevity of built environments. The use of light-density aggregates (Leca and pumice) in 100% proportion led to a decrease in density and FS compared to other mixtures. Lightweight concrete (C-100-L and C-100-P) achieved lower FS compared to conventional mixtures. GPC with light-density aggregates also exhibited lower density and FS. The best FS for LWGC mixes (FG-50D50 L and FG-50D50 P) was achieved when combined with 50% FA and 50% ground blast furnace slag, with results of 7.18 MPa and 7.24 MPa, respectively, at the test age of 28 days (Tayeh et al., 2021). The trend of FS of different mixes is shown in Figure 11. The study by Rahman and Khattak (2021) found that the FS of RCGPC increased notably with the addition of alkali activators. Specifically, the inclusion of Na_2SiO_3 resulted in a substantial 40% enhancement in FS due to the improvement of the adhesion bond between RCA and the geopolymer matrix.

Moreover, higher NaOH molarity further bolstered the FS, showing a significant 32% increase. RCGPC mixtures demonstrated superior FS compared to RCA conventional concrete mixtures, exhibiting up to a remarkable 71% improvement. Figure 12 shows the test for flexure along with the failed specimen.

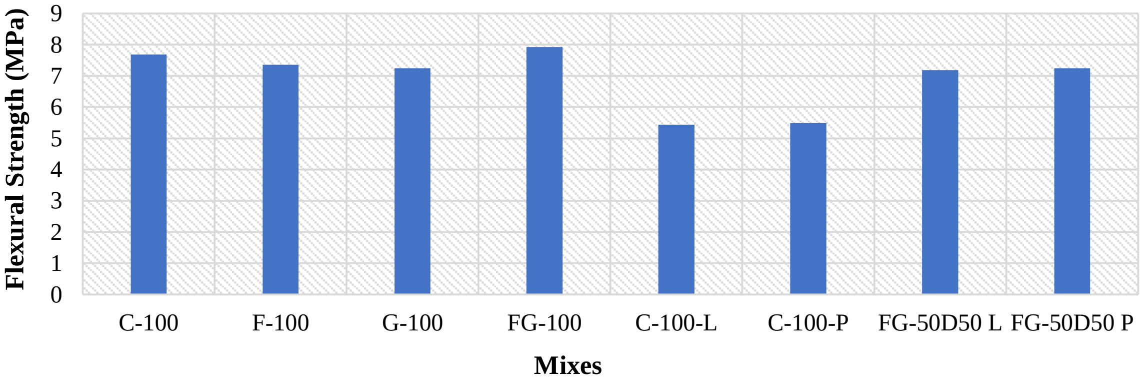

Fig. 11. Variation in flexural strength

(a) **(b)**

Fig. 12. a) Flexure strength test; and b) Failed specimen
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The FS test results of GPCs in the experiment by Öz et al. (2021) indicated that increasing the LWFA in the mixtures led to higher FS. The optimal replacement level was found to be 25%, with minimal impact on FS observed at 30% and 40% replacement levels.

However, higher replacement levels resulted in significant strength loss, with reductions of 16%, 23%, and 28% at 50%, 75%, and 100% replacements, respectively, after 28 days. FSs of geopolymer mortar increased notably with fiber addition, particularly at a CF content of 0.2%. This effect was more significant in mixtures made from RCA.

The maximum increase observed was 54% for the 100R-0.2CF composite compared to the unreinforced sample (100R mixture) (Nuaklong et al., 2021). The variation in FS is shown in Figure 13. Mixtures with GGBS show significant strength improvements: up to 43% increase without recycled aggregate, up to 92% increase with 100% recycled aggregate. They also suffer less reduction in FS compared to those with FA alone, especially at higher recycled aggregate contents. Specifically, reductions in FS were less than 13% and 26% for mixtures with FA and GGBS at 50% and 100% recycled aggregate content, respectively, compared to 24% and 37% reductions for mixtures with FA alone (Hu et al., 2019).

4.3.3. Split Tensile Strength

Splitting tensile strength measures a material's resistance to tensile stress applied perpendicular to its surface. It is crucial for assessing brittle materials like concrete or rock, often used in construction. This indirect testing method involves applying force diametrically to a cylindrical specimen until failure occurs, providing insights into a material's durability and performance. Replacement of NA with RCA decreased splitting tensile strength. The inclusion of 100% RCA reduced tensile strength from 2.6 MPa to 1.9 MPa. The addition of CF enhanced tensile strength, with a maximum increase of 38% observed in a 50% RCA + 0.2% CF mixture. However, at 0.3% CF, the tensile strength slightly decreased compared to 0.2% CF, possibly due to improper fiber dispersion (Nuaklong et al., 2021). At 28 days, both cement concrete and geopolymer samples showed decreased tensile strength with lightweight aggregate use. Dolomite aggregate produced the highest strength. Lightweight concrete, C-100-L (leca) and C-100-P (pumice) had lower tensile strengths: 3.82 MPa and 3.74 MPa, respectively (Tayeh et al., 2021). The splitting tensile strength of various mixes is shown in Figure 14. In this investigation by Wongsa et al. (2016), LWGCs showed an average splitting tensile to compressive strength ratio of 9.6%, higher than CGCs' 6.6%. In contrast to high-calcium fly ash GPC, LWGCs with heat curing and comparable SH concentration had a higher ratio (9.6% vs. 6.9%). The range of stated values for conventional concretes (8-14%) was not exceeded by the splitting tensile to compressive strengths ratios for LWGCs (7.5-14%) and has been given in Table 6 (Wongsa et al., 2016).

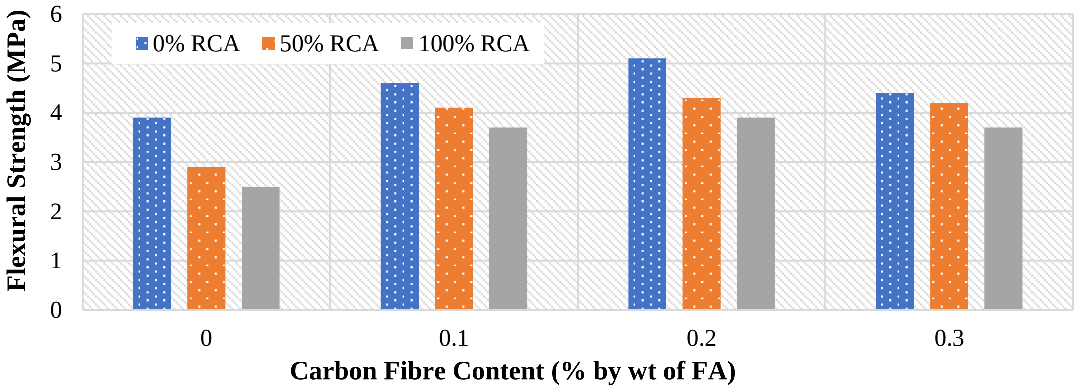


Fig. 13. Variation in flexural strength due to a change in fiber content

Table 5. Tensile strength variation of different RCA

Mixture	Tensile strength (MPa)
100% RCA (0R)	2.6 > 1.9
50% RCA + 0.3% CF	-
50% RCA + 0.2% CF	38% increase
50% RCA + 0.1% CF	8% increase
50% RCA + 0% CF	No change

4.4. Microstructural Characterization

4.4.1. Scanning Electron Microscopy (SEM)

Observing the surface appearance and structure of materials at high magnification is possible with the use of SEM, a potent imaging technique. SEM uses a concentrated electron beam to scan the surface of the sample, producing signals that can provide incredibly sharp, detailed images. SEM is used to identify the microstructure, which shows the composition of two types of concrete: GPC and regular concrete, which contains Portland cement with a weight ratio of 450 kg/m^3. As shown in Figure 15a, partially dissolved cement grains exhibited several surface cracks, likely caused by the heat generated during cement hydration.

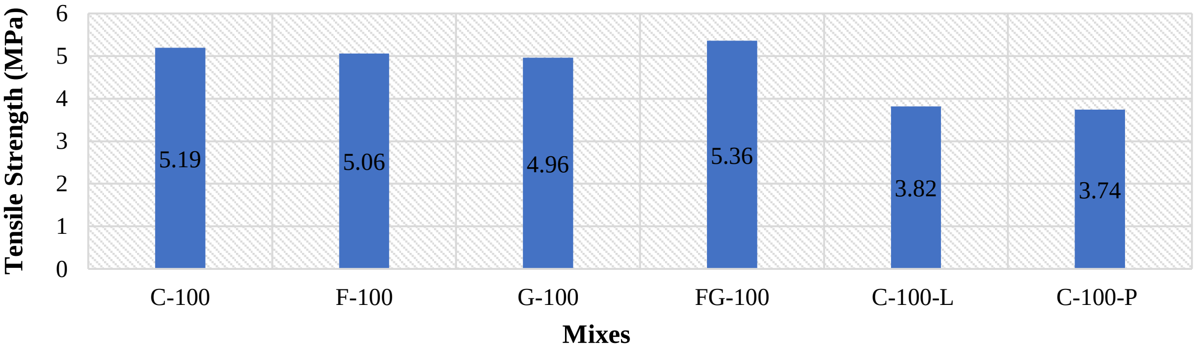
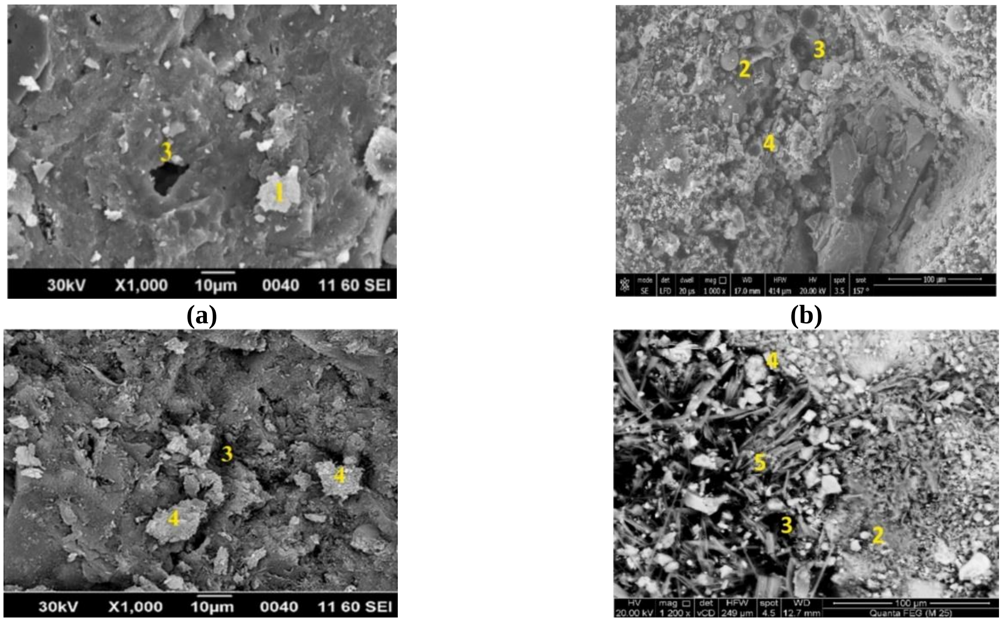


Fig. 14. Splitting tensile strength of various geopolymer mixes

Table 6. Ratio of splitting tensile to compressive strength (%)

Type of concrete	Ratio of splitting tensile to compressive strength (%)
LWGCs (lightweight geopolymer concrete)	7.5 - 14
CGCs (conventional geopolymer concrete)	6.6
High-calcium fly ash geopolymer concrete	6.9



(a) (b)

(c) (d)

Fig. 15. SEM images for conventional and geopolymer mix: a) Cement concrete; b) FA geopolymer mix; c) GGBS geopolymer mix; and d) FA and GGBS geopolymer mix
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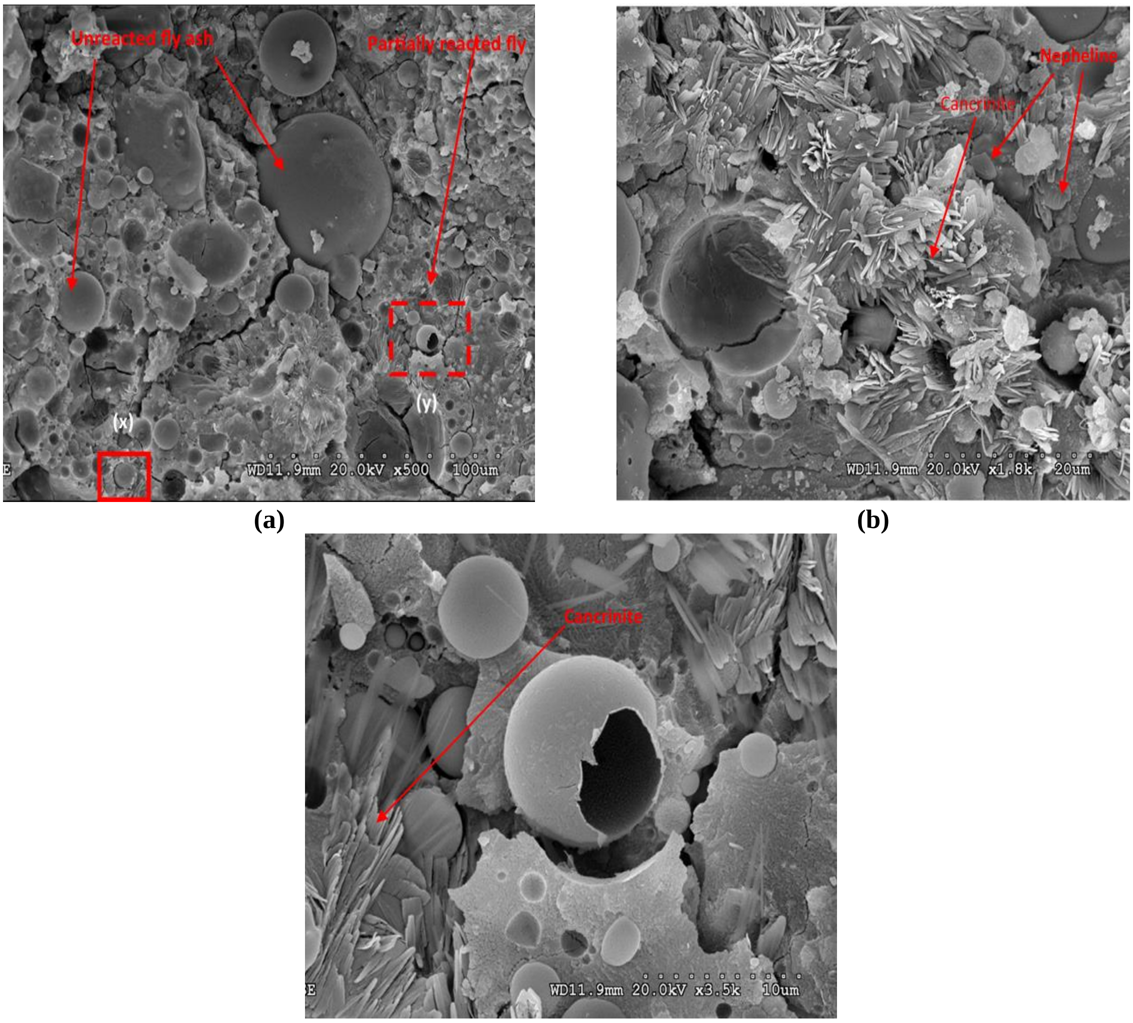
This suggests that, similar to traditional cement concrete, not all cement grains form Calcium Silicate Hydrate (C-S-H) gel. In contrast, the microstructure of the geopolymer, depicted in Figures 10b and 10c, reveals a typical SEM micrograph of a mix containing FA. The image shows geopolymer gel with partially or completely unreacted FA particles, along with the formation of pores and a heterogeneous matrix, which were not present in the original FA. This matrix formation resulted from the geopolymerization reaction that occurred after mixing the FA with the alkaline activator liquid (Tayeh et al., 2021).

The SEM images are shown in Figure 15. SEM micrographs of the RCA-RCGPC mixture were examined, revealing the use of an 8 M NaOH solution as the activator (Figure 16). Within these micrographs, it was evident that some FA particles remained partially or wholly unreacted within the mixture. This presence of unreacted FA particles elucidates the comparatively lower strength of the mixture when compared to mixtures utilizing Na_2SiO_3 as an activator (Rahman and Khattak, 2021). SEM analysis revealed distinctive morphological alterations in the GPCs. These changes are attributed to the predominant presence of Al and Si, derived from FA during alkali activation, which are the main constituents contributing to GPC gel formation. Additionally, the GPCs are composed mainly of Na_2O, Al_2O_3, and SiO_2, along with traces of Fe_2O_3 (Öz et al., 2021). Images are shown in Figure 17.



(a) (b)

(c)

Fig. 16. a) SEM of RCA-RCGPC with 8 M NaOH cured at 600 ºC; b) Zoomed image of ‘‘x”; and c) Zoomed image of ‘‘y”

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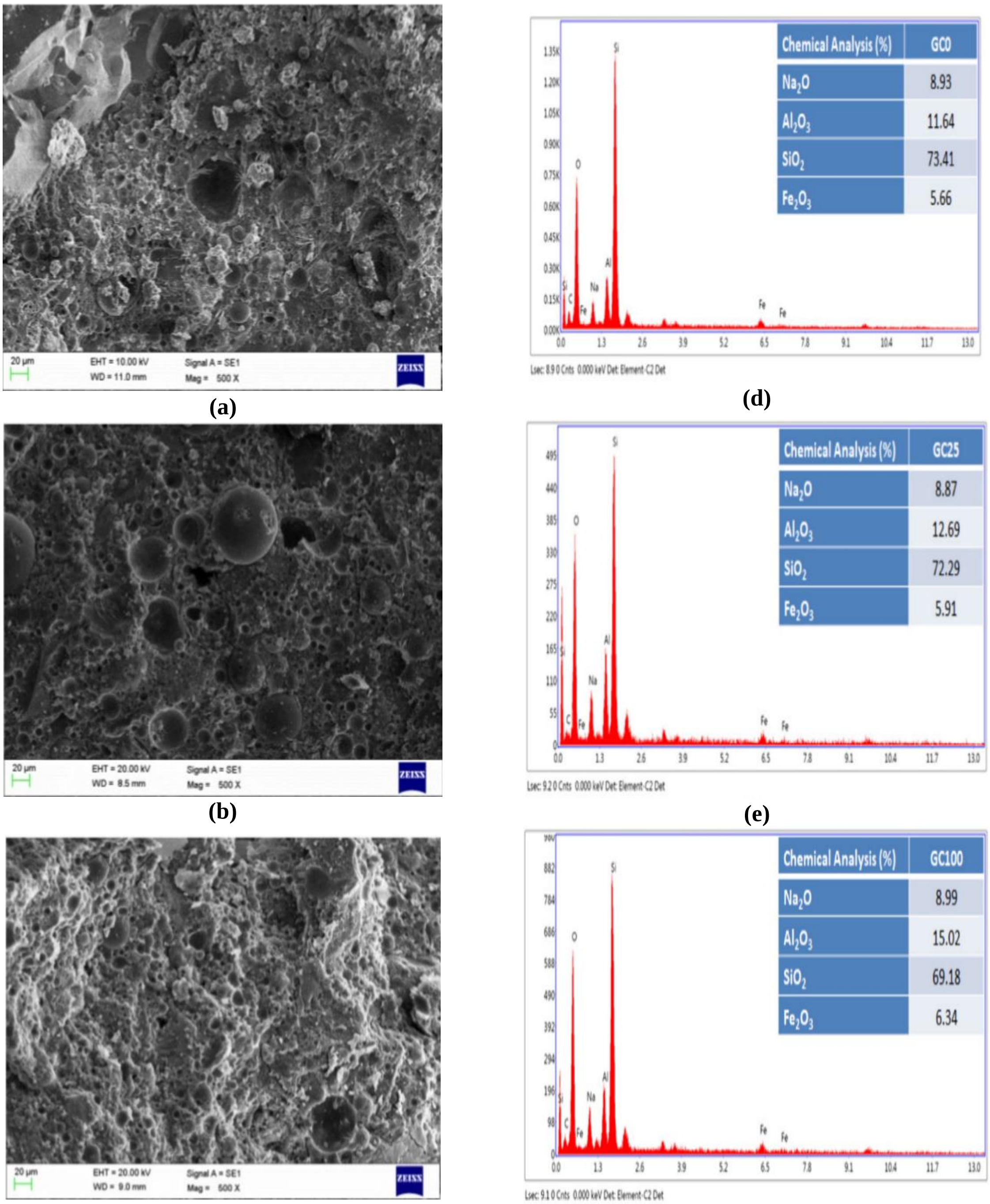
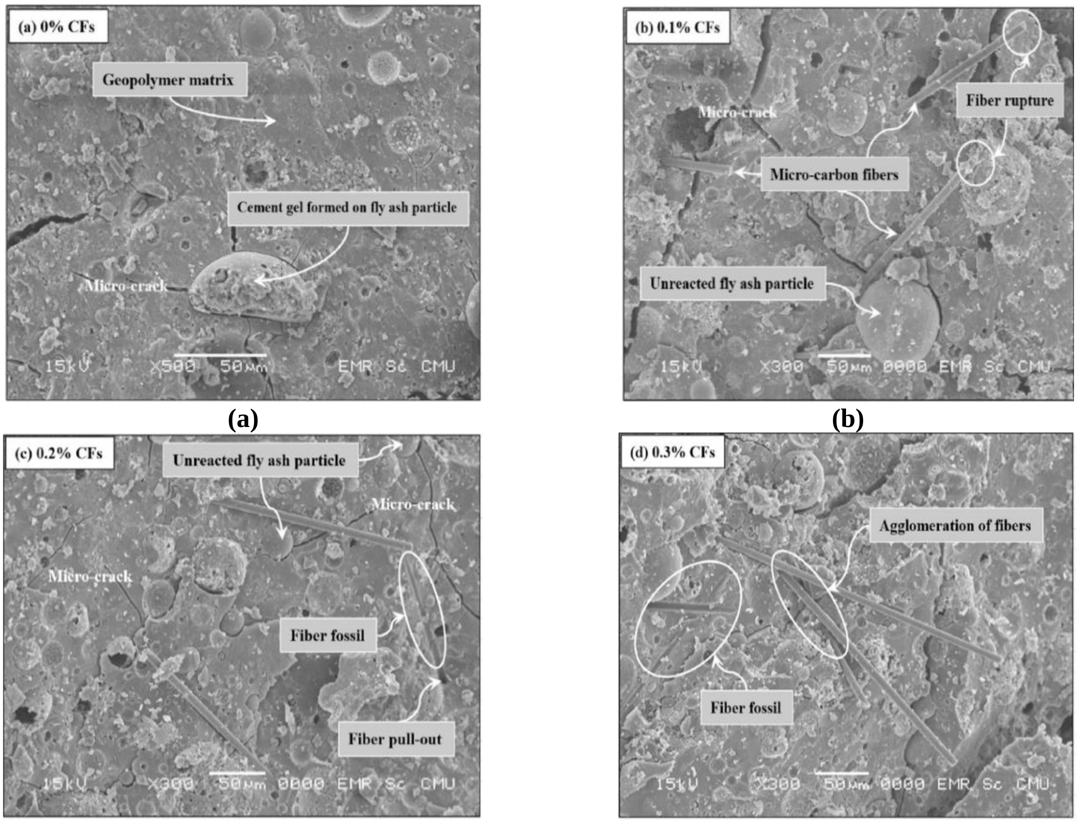


(a) (d) (b) (e) (c) (f)

Fig. 17. SEM images of: a) GC0; b) GC25; c) GC100, EDX results of: d) GC0; e) GC25; and f) GC100 “Permission and rights have been taken from the publisher and its license number-5776380472157”

SEM images in Figure 18 show unreacted FA particles hindering crack propagation in geopolymer pastes, though cracks may still occur due to increased stress. CF acts as micro-aggregates with minimal effect on crack resistance despite strong bonding, fiber fracture, and pullout dissipating energy. As depicted in Figures 18a to 18d, both fiber fracture and fiber pullout behaviours were observed. Fiber frocking is a clear sign of strong attachment between CF, carbon composite, and geopolymers. Therefore, it is likely that energy losses happened through the frictional movement of the fibers. A porous "fiber fossil" layer indicates pullout under shear stress. Excessive carbon fibers hinder the alkaline solution-FA reaction, potentially reducing SiO_2 and Al_2O_3 leaching in 0.3% CF-containing pastes (Nuaklong et al., 2021).



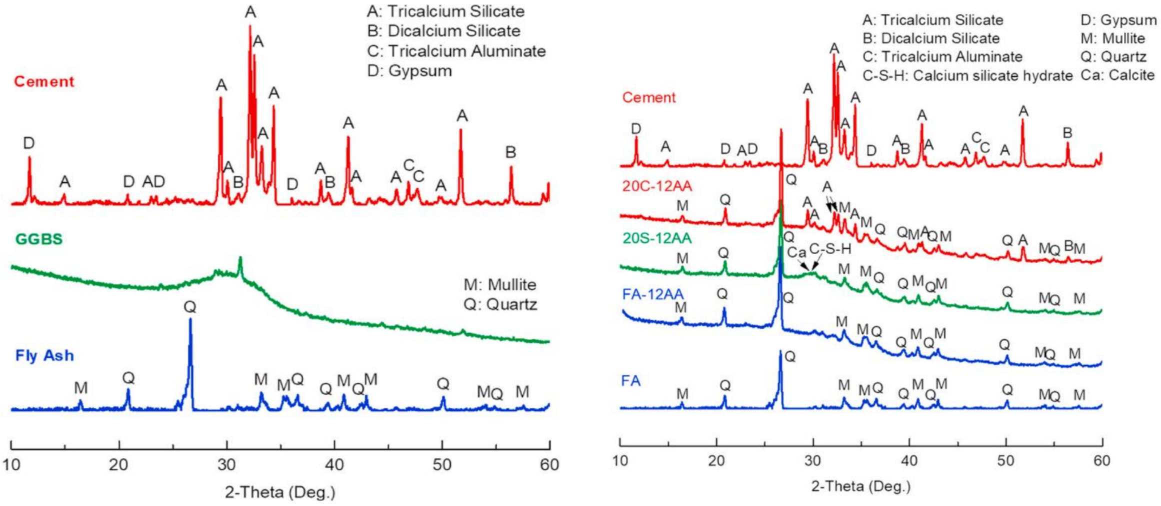
(a) (b)

(c) (d)

Fig. 18. SEM image of geopolymer paste sample having: a) 0% CFs; b) 0.1% CFs; c) 0.2% CFs; and d) 0.3% CFs, "Permission and rights have been taken from the publisher and its license number-5776390408245"

4.4.2. X-Ray Diffraction (XRD)

A non-destructive analytical method for determining a material's crystallographic structure is XRD. An X-ray is utilized to bombard a material in an XRD test, and the diffraction pattern is analyzed. When X-rays interact with the sample's crystal lattice, constructive interference occurs at specific angles dictated by the lattice spacing, which leads to the development of this pattern. The preservation of quartz and mullite, which were previously present in FA and were not impacted by alkali activation, demonstrated the amorphous character of FA geopolymer products in Figure 19 (Xu et al., 2021).

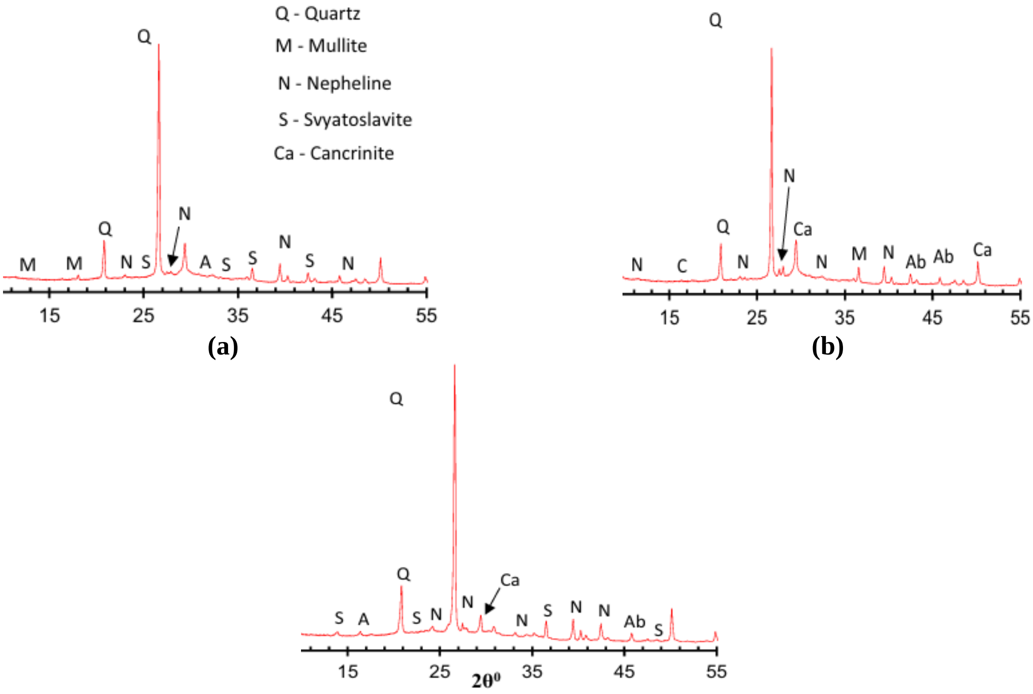


(a) (b)

Fig. 19. a) XRD patterns of FA, GGBS, cement; and b) Geopolymer Light Aggregates (GLAs), "Permission and rights have been taken from the publisher and its license number-5776901001535"

The XRD graphs showed unreacted quartz and mullite compounds, which were in line with the results of the XRD micrographs shown in Figures 20 and 21. All of the mixture's Mullites reacted with 10 M NaOH to produce nepheline, svyatoslavite, and cancrinite, demonstrating a strong geopolymeric reaction. The aluminosilicate compounds were found to have lower peaks when NaOH was used as the only alkali activator (Rahman and Khattak, 2021).

In a study by Öz et al. (2021), peaks for albite ($NaAlSi_3O_8$-A), nepheline ($AlNaSiO_4$-N), and hematite (Fe_2O_3-H) may be seen in the XRD patterns of GC0, GC25, and GC100, together with crystalline quartz (SiO_2-Q) and mullite ($Al_2O_3.2SiO_2$-M). These peaks show that Q, M, and H are present in the FA. Furthermore, the peaks for A and N show how FA reacts to activators in Figure 22. The A and N peaks indicate that FA reacted with the activators. As shown in Figure 22, the addition of lightweight fly ash to GPC reduced the intensity of the Q peak. This is evident from the pronounced Q peaks at 21° 2θ and 26.8° 2θ.



(a) (b)

(c)

Fig. 20. XRD of GPC mixes cured at 60 ºC: a) 6 M NaOH with 1:1 Na_2SiO_3; b) 8 M NaOH with 1:1 Na_2SiO_3; and c) 10 M NaOH with 1:1 Na_2SiO_3
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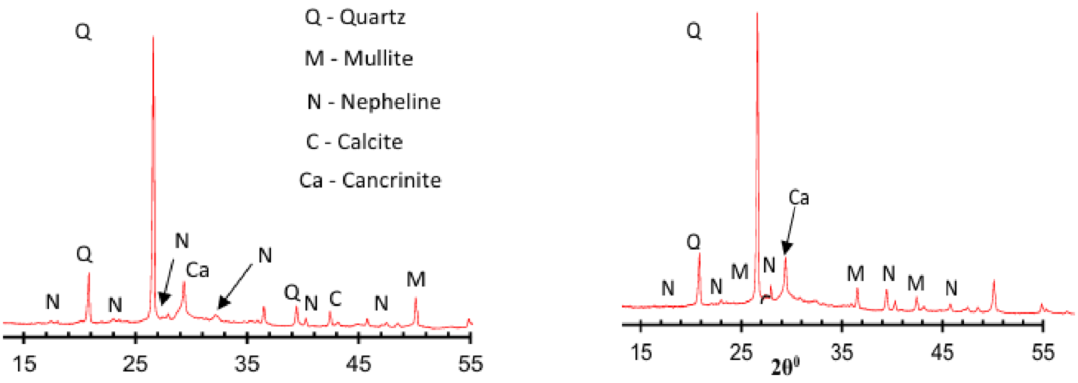

(a) (b)

Fig. 21. XRD of: a) 8 M NaOH cured at 60 ºC; and b) 8 M NaOH with 1:1 Na_2SiO_3/NaOH ratio cured at 25 ºC
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The decreasing intensity of the Q peak with increasing LWFA can be attributed to the reduced presence of quartz sand, which has a high SiO_2 content. Despite the reduction in the Q peak, the increase in strength can be explained by the fact that FA-based LWFA plays a chemical role in the matrix, similar to that of FA.

4.4.3. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is an approach to determine a sample's molecular composition by measuring the amount of infrared light it absorbs. When infrared light interacts with a sample, certain wavelengths are absorbed, corresponding to specific vibrational modes of the chemical bonds within the molecules. By measuring which wavelengths are absorbed, FTIR can provide information about the functional groups present in the sample, helping to identify its chemical structure and composition. The spectra showed peaks at 3700-3400 cm^{-1} and 1700-1600 cm^{-1}, indicating O-H stretching and H-O-H bending from water (H_2O) molecules formed during geopolymerization. O-C-O stretching at around 1400 cm^{-1} was observed, indicating sodium carbonate (Na_2CO_3) formation from reaction with CO_2. Significant Si-O-T stretching occurred at 1200-950 cm^{-1}, with increased intensity indicating higher geopolymerization. The mixes containing carbon fibers showed a more pronounced Si-O-Si or Si-O-Al stretching peak compared to the control mixture. Although CFs are chemically inert, they likely act as a dispersion agent, helping to de-agglomerate the FA particles. This enhanced dispersion leads to more leaching of SiO_2 and Al_2O_3 from the source materials, thereby increasing the degree of geopolymerization. Mixtures with 0.1% CFs showed less intensity increase in the 1200-950 cm^{-1} band compared to higher CF contents (Nuaklong et al., 2021) as shown in Figure 23.

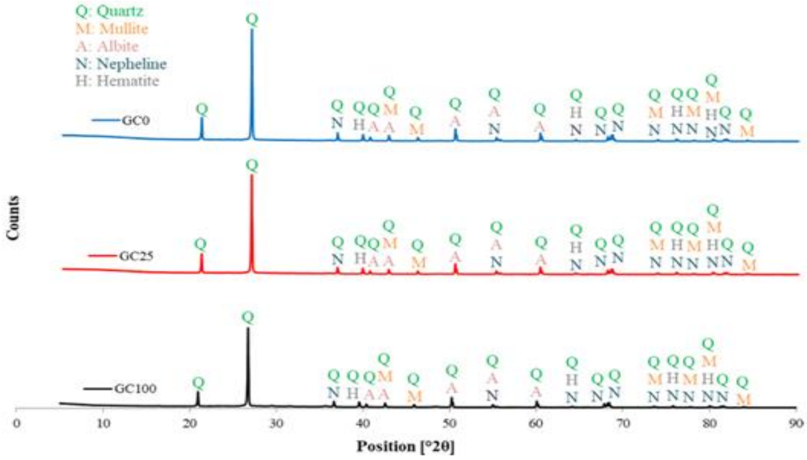

Fig. 22. XRD patterns of GC0, GC25, and GC100
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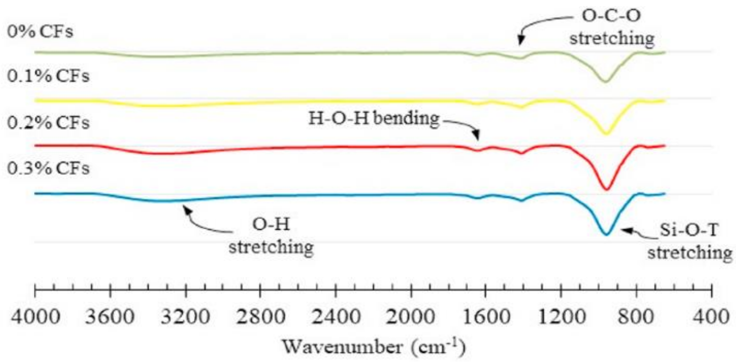

Fig. 23. FTIR spectra of geopolymer paste with different micro-carbon fiber contents
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5. Conclusions

The study elucidates the evolution of lightweight aggregates and their vital role in sustainable concrete construction. It outlines diverse methods for lightweight aggregate production, such as recycling waste materials and creating artificial aggregates, addressing sustainability needs.

Additionally, it emphasizes the environmental advantages of geopolymer binders in lightweight concrete, potentially reducing the ecological footprint of OPC. Furthermore, it underscores the necessity for ongoing research on mix design and attributes of LWGCs to enhance performance and encourage their extensive use in construction.

- Particle characteristics, aggregate types, and binder components significantly influence concrete workability. Fine aggregates like lightweight fine aggregates and smooth spherical aggregates enhance flowability and workability. Factors such as SS/SH ratio and GGBS content in the binder impact slump values.
- Alkaline content, binder composition, and curing conditions affect setting time. Higher NaOH concentrations generally extend setting times, enhancing workability but potentially impacting density and strength.
- Proper mix design and handling techniques can effectively minimize segregation and bleeding, ensuring uniform concrete quality and durability.
- Water absorption rates are influenced by aggregate types, GGBS content, and curing conditions. Denser structures with lower water absorption are achieved with higher alkalinity and GGBS additions.
- FS is influenced by aggregate types, binder components, and curing conditions. Lightweight aggregates and specific binder combinations can optimize FS.
- Replacement of NA with RCA and the addition of carbon fibers can affect split tensile strength positively, with optimal combinations enhancing performance.
- SEM Analysis: SEM reveals morphological changes and compositions, highlighting the impact of alkali activation and aggregate types on microstructure.
- XRD Analysis: XRD patterns demonstrate crystallographic changes and phase compositions, emphasizing the role of alkali activators and curing conditions.
- FTIR Analysis: FTIR spectra provide insights into molecular compositions, indicating water content, gel formation, and chemical reactions during geopolymerization. Overall, GPC technology offers promising advancements in achieving desired fresh and hardened properties, with further research focusing on optimizing mix designs, enhancing durability, and ensuring sustainable construction practices.

6. Availability of Data and Materials

Data will be made available on request from the corresponding author.

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8. Declarations

The survey research directed has received ethical clearance from the ethics committee of the graphic era (deemed to be university), dehradun, uttarakhand-248002, India. All respondents provided consent to participate in the research. Also the authors confirm they have had no involvement with artificial intelligence (AI) tools in the writing of this article.

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