

## Experimental Evaluation of Compressive Strength of Geopolymer Foamed Concrete

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### Abstract

Geopolymer foamed concrete (GFC) has emerged as a sustainable and versatile construction material, offering a promising alternative to conventional Portland cement-based concrete. This research paper provides a comprehensive overview of the experimental evaluation of the compressive strength of GFC, synthesizing findings from recent research. It delves into the critical factors influencing GFC's mechanical properties, including the type of precursor materials, the nature of foaming and stabilizing agents, and the curing conditions. Special attention is given to the intricate relationship between pore structure and compressive strength, highlighting how parameters such as porosity, pore size distribution, and pore connectivity dictate overall performance. The paper also explores advancements in achieving high-strength GFC and presents a comparative analysis with ordinary Portland cement (OPC)-based foamed concrete. Furthermore, it discusses various mix design optimization strategies and the role of nanomaterials and fibers in enhancing GFC properties. The objective of this paper is to consolidate current knowledge, present detailed experimental methodologies and results, and suggest future research directions to facilitate the broader adoption of GFC in sustainable construction practices.

*Keywords: Geopolymer Concrete, Foamed Concrete, Fly Ash, GGBFS, Sustainability, CO<sub>2</sub> Reduction, Lightweight Concrete*

### 1. Introduction

The global construction industry faces increasing pressure to adopt sustainable practices, driven by

environmental concerns related to the production of conventional building materials. Ordinary Portland Cement (OPC) production, in particular, is a significant contributor to global CO<sub>2</sub> emissions. In response, researchers and engineers have increasingly turned their attention to alternative binders and innovative concrete formulations. Among these, geopolymer concrete (GPC) has garnered considerable interest due to its utilization of industrial by-products rich in alumina (Al<sub>2</sub>O<sub>3</sub>) and silica (SiO<sub>2</sub>), such as fly ash and ground granulated blast-furnace slag, activated by alkaline solutions [1]. This process results in a binder with a polymeric structure that exhibits excellent mechanical properties and durability.

Further enhancing the sustainability and functionality of GPC, geopolymer foamed concrete (GFC) integrates the benefits of lightweight foamed concrete with geopolymer technology. GFC is characterized by its porous structure, which significantly reduces its density and improves thermal insulation properties, making it suitable for a wide range of applications, including non-structural elements, partition walls, and insulation panels [2]. The production of GFC involves incorporating air into a geopolymer paste or mortar, typically through mechanical or chemical foaming methods. The resulting pore structure is crucial, as it directly influences the material's mechanical strength, thermal conductivity, and overall performance.

Compressive strength is a fundamental mechanical property for any concrete material, and its

experimental evaluation is paramount for understanding the performance and applicability of GFC. This research paper aims to provide a comprehensive analysis of the experimental evaluation of the compressive strength of geopolymer foamed concrete. It synthesizes current research on the various factors that influence GFC's compressive strength, including the types of precursor materials, the efficacy of foaming and stabilizing agents, and the impact of curing conditions. Furthermore, the paper explores the intricate relationship between the material's pore characteristics and its mechanical performance, discusses advancements in achieving high-strength GFC, and offers a comparative perspective with OPC-based foamed concrete. By consolidating these experimental findings, this paper seeks to highlight key trends, identify research gaps, and suggest future directions to advance the development and application of GFC in sustainable construction.

## 2. Manufacturing, Pore Characteristics, and Factors Influencing Compressive Strength of GFC

The production of geopolymer foamed concrete (GFC) typically commences with the preparation of a geopolymer matrix, which involves combining precursor materials rich in  $Al_2O_3$  and  $SiO_2$  with an alkaline activator solution. Common precursors include fly ash (FA), metakaolin (MK), and ground granulated blast-furnace slag (GGBS) [1]. The alkaline activator, usually a combination of sodium hydroxide (NaOH) and sodium silicate ( $Na_2SiO_3$ ), initiates the geopolymerization process, forming a polymeric network structure [1].

Following the matrix preparation, a foaming process is introduced to create the desired porous structure. This can be achieved through two primary methods: mechanical foaming and chemical foaming [2]. Mechanical foaming involves mixing pre-generated

foam with the geopolymer slurry, while chemical foaming introduces gas-forming agents, such as aluminum (Al) powder or hydrogen peroxide ( $H_2O_2$ ), which react within the slurry to release gases ( $H_2$  or  $O_2$ ) and create pores [2]. The stability of the foam during the fresh stage of GFC is critical, as it directly influences the final pore structure and, consequently, the compressive strength (CS) and thermal properties of the hardened material [2]. Organic surfactants and nanoparticles can be employed to enhance foam stability by optimizing the gas-liquid interface, leading to a more uniform pore distribution [2]. The pore structure of GFC is a defining characteristic that significantly impacts its engineering properties, including thermal insulation, sound absorption, and mechanical strength [2]. Key pore characteristics include pore size distribution, total porosity, pore shape, and connectivity. Studies have shown a linear correlation between pore properties and CS in geopolymers with evenly distributed pore sizes [2]. For instance, the addition of surfactants can drastically reduce the average pore size and tighten the pore size distribution, leading to enhanced stability and control over pore formation [2]. Advanced imaging techniques, such as optical digital microscopy and X-ray computed tomography (X-CT), are utilized to analyze the pore structure, providing high-resolution 3D images and precise representations of pore size distributions [2]. The formation of a dense and uniform pore network is essential for optimizing both the mechanical and thermal performance of GFC, underscoring the importance of careful parameter control and mix proportioning during manufacturing [2].

### 2.1. Precursor Materials

The selection and proportioning of precursor materials significantly dictate the geopolymerization process and the resulting mechanical properties of GFC. Common precursors include fly ash (FA), ground granulated blast-furnace slag (GGBS), and

metakaolin (MK) [1]. Fly ash, often spherical in shape, generally improves the workability and fluidity of the geopolymer mixture, contributing to better densification and pore-filling effects, which can enhance strength [2]. Conversely, GGBS, with its angular particles and higher calcium oxide (CaO) content, tends to increase the strength of the geopolymer matrix but may reduce workability [2]. The incorporation of metakaolin has been shown to reduce porosity and enhance the compactness of the interfacial transition zone, leading to improved mechanical performance [2]. Studies have also indicated that partial replacement of FA with materials like palm oil fuel ash (POFA) can improve strength, with a 20% replacement demonstrating notable enhancements [2]. The water-to-precursor ratio and the consistency of the geopolymer slurry also play a crucial role in determining the roundness and distribution of pores, which are directly linked to CS [2].

## 2.2. Foaming and Stabilizing Agents

Foaming agents are essential for creating the porous structure of GFC, and their type and quantity directly impact the material's density and compressive strength. Chemical foaming agents, such as hydrogen peroxide ( $H_2O_2$ ) and aluminum (Al) powder, react within the alkaline geopolymer slurry to generate gases ( $O_2$  or  $H_2$ ) that form pores [2]. The amount of Al powder, for instance, directly controls the total porosity and, consequently, the density and CS of the GFC; finer Al powder tends to produce smaller pores and higher strength [2]. Stabilizing agents are critical for maintaining the stability of the foam during the mixing and setting phases, preventing bubble coalescence and drainage that can compromise the pore structure. Anionic surfactants like sodium dodecyl sulfate (SDS) and sodium dodecyl benzene sulfonate (SDBS) are commonly employed to stabilize foams, leading to a more uniform distribution of smaller pores and

improved CS [2]. The combination of surfactants with foaming agents like  $H_2O_2$  can result in GFC with greater pore consistency and reduced pore sizes compared to using these agents separately [2]. Calcium stearate has also been identified as an effective foam stabilizer, optimizing the gas-liquid interface and contributing to a more stable pore network [2].

## 2.3. Curing Conditions

Curing conditions, particularly temperature, significantly influence the geopolymerization reaction kinetics and the development of early-age and ultimate compressive strength. Elevated curing temperatures generally accelerate the geopolymerization process, leading to faster strength development [1]. High-calcium geopolymers, often incorporating GGBS or Portland cement (PC) as calcium sources, can achieve substantial early strength even under ambient conditions, addressing a common challenge with some fly ash-based geopolymers [1]. Precise control over heating rates during curing is also critical for optimizing the porosity and overall strength of GFC [2].

## 3. Experimental Methodology

This section outlines a typical experimental methodology for evaluating the compressive strength of geopolymer foamed concrete (GFC), drawing upon established practices in the literature [2]. The methodology encompasses material selection, mix design, specimen preparation, curing procedures, and testing protocols.

### 3.1. Materials and Mix Design

**Precursor Materials:** The primary precursor materials typically include industrial by-products rich in alumina ( $Al_2O_3$ ) and silica ( $SiO_2$ ), such as Class C fly ash and ground granulated blast-furnace slag (GGBS). These materials are selected based on

their chemical composition and reactivity to ensure optimal geopolymerization.

**Alkali Activator Solution:** A common alkali activator solution consists of a combination of sodium hydroxide (NaOH) solution and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) solution. The concentration of NaOH (e.g., 8 M, 10 M, 12 M) and the ratio of  $\text{Na}_2\text{SiO}_3$  to NaOH are critical parameters influencing the geopolymerization kinetics and final strength. The modulus of the sodium silicate solution ( $\text{SiO}_2/\text{Na}_2\text{O}$  ratio) is also a key factor, typically ranging from 1.2 to 1.5.

**Foaming Agent:** Foaming agents are introduced to create the porous structure. These can be chemical agents like hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) or aluminum powder, which react to produce gas, or pre-formed foam generated mechanically using a foam-generating machine. The type and quantity of foaming agent directly influence the density and pore structure of the GFC.

**Stabilizing Agents:** To ensure the stability of the foam during mixing and setting, stabilizing agents such as anionic surfactants (e.g., sodium dodecyl sulfate, SDS) or calcium stearate may be incorporated. These agents help prevent bubble coalescence and drainage, leading to a more uniform pore distribution.

**Mix Design Proportions:** An example of mix design proportions, adapted from Al Bakri Abdullah et al. [2], is presented in Table 1. These proportions illustrate the typical ratios of fly ash to activator, sodium silicate to NaOH, and foam to geopolymer paste, along with curing conditions.

**Table 1: Example Mix Design Proportions for Geopolymer Foamed Concrete [2]**

| Sample ID | Fly Ash : Activator Ratio | Sodium Silicate : NaOH Ratio | Foam : Geopolymer Paste Ratio | Curing Temperature |
|-----------|---------------------------|------------------------------|-------------------------------|--------------------|
| LW1       | 2:1                       | 2.5:1                        | 2:1                           | Room Temperature   |
| LW2       | 2:1                       | 2.5:1                        | 2:1                           | 60 °C              |

### 3.2. Specimen Preparation

- **Alkali Activator Preparation:** The NaOH solution is prepared by dissolving NaOH pellets in distilled water to achieve the desired molarity. This solution is then mixed with the  $\text{Na}_2\text{SiO}_3$  solution at a predetermined ratio. It is often prepared 24 hours in advance and allowed to cool to room temperature to dissipate heat generated during the exothermic reaction.
- **Geopolymer Paste Mixing:** The precursor materials (e.g., fly ash, GGBS) are dry-mixed thoroughly in a pan mixer for a few minutes to ensure homogeneity. The alkali activator solution is then gradually added to the dry mix, and mixing continues for approximately 5-10 minutes until a homogeneous geopolymer paste is formed.
- **Foam Incorporation:** If chemical foaming agents are used, they are added to the geopolymer paste and mixed briefly. For mechanical foaming, pre-formed foam is generated separately and then slowly incorporated into the geopolymer paste, followed by gentle mixing for a short duration (e.g., 45-60 seconds) to achieve the desired density without destroying the foam structure.
- **Casting:** The fresh GFC mixture is cast into standard molds, typically 100 mm × 100 mm

× 100 mm cubes for compressive strength testing, in two layers, with each layer compacted gently to remove entrapped air without collapsing the foam structure. The molds are then covered to prevent moisture loss.

### 3.3. Curing Procedures

After casting, the specimens undergo a curing regime to facilitate the geopolymerization process and strength development. Common curing methods include:

- **Ambient Curing:** Specimens are left at room temperature (e.g.,  $23 \pm 2$  °C) and relative humidity (e.g.,  $60 \pm 5\%$ ) until the testing age.
- **Heat Curing:** Specimens are placed in an oven or curing chamber at elevated temperatures (e.g., 60 °C, 80 °C) for a specific duration (e.g., 24 hours, 48 hours). After heat curing, the specimens are typically removed from the molds and allowed to cool to room temperature, then stored under ambient conditions until testing.

### 3.4. Testing Protocols

- **Compressive Strength Test:** Compressive strength is the most critical mechanical property evaluated. Specimens are tested at various ages (e.g., 7, 14, 28, 56, 90 days) using a universal testing machine (UTM) in accordance with relevant standards such as ASTM C109/C109M or EN 12390-3. The load is applied axially at a specified rate until failure, and the maximum load is recorded to calculate the compressive strength.
- **Dry Density Measurement:** The dry density of the GFC specimens is determined by drying them in an oven at  $105 \pm 5$  °C until a

constant mass is achieved, typically for 24 hours. The mass and dimensions of the dried specimens are then used to calculate the dry density.

- **Pore Structure Analysis:** The internal pore structure, including pore size distribution, porosity, and pore connectivity, is analyzed using techniques such as scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), X-ray computed tomography (X-CT), and image analysis software (e.g., ImagePro Plus). These methods provide insights into the morphology and distribution of pores, which directly influence mechanical properties.
- **Thermal Conductivity:** For GFC intended for insulation, thermal conductivity is measured using a thermal conductivity meter (e.g., IMDRY3001) according to relevant standards.

## 4. Results

This section presents the key experimental results obtained from various studies on the compressive strength of geopolymer foamed concrete (GFC), highlighting the influence of different parameters on its mechanical and physical properties. The data is synthesized from multiple sources to provide a comprehensive overview of GFC performance.

### 4.1. Compressive Strength and Density

Experimental investigations consistently show a strong correlation between the dry density and compressive strength (CS) of GFC. As the foam content increases, the dry density decreases, leading to a corresponding reduction in compressive strength. Table 2 summarizes typical compressive strength and density ranges observed in GFC, along with specific examples from the literature.

**Table 2: Typical Compressive Strength and Dry Density Ranges of GFC**

| Application Area       | Dry Density (kg/m <sup>3</sup> ) | Compressive Strength (MPa) | Reference |
|------------------------|----------------------------------|----------------------------|-----------|
| Insulation             | 280 - 865                        | 1.0 - 10.0                 | [1]       |
| High-Strength Variants | 800 - 1500                       | 10.0 - 50.0                | [2]       |
| Specific Example (LW1) | ~1480                            | 18.1                       | [2]       |
| Specific Example (LW2) | ~1070                            | 18.2                       | [2]       |

Note: LW1 and LW2 are specific samples from Al Bakri Abdullah et al. [2] with varying H<sub>2</sub>O<sub>2</sub> content and curing conditions.

#### 4.2. Influence of Mix Design Parameters

The water-to-binder ratio (W/B) is a critical parameter influencing the workability, porosity, and ultimately the compressive strength of GFC. Studies indicate that an optimal W/B ratio exists, typically between 0.35 and 0.45, that balances fluidity for proper mixing and pore formation with sufficient strength development [2]. Deviations from this optimal range can lead to either excessive porosity (high W/B) or insufficient workability and poor pore distribution (low W/B), both negatively impacting CS. The concentration of the NaOH solution and the modulus of the Na<sub>2</sub>SiO<sub>3</sub> solution (SiO<sub>2</sub>/Na<sub>2</sub>O ratio) significantly affect the geopolymerization reaction and the resulting mechanical properties. A higher concentration of NaOH generally accelerates the reaction and enhances early-age strength. The optimal SiO<sub>2</sub>/Na<sub>2</sub>O ratio, often found between 1.2 and 1.5, promotes the formation of a dense and strong geopolymer matrix [2].

The amount and type of foaming agent directly control the volume of air entrained, thereby dictating

the porosity and density of the GFC. For instance, increasing the hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) content from 0.5% to 2% can lead to a decrease in dry density from approximately 1480 kg/m<sup>3</sup> to 1070 kg/m<sup>3</sup>, while maintaining comparable compressive strengths (e.g., 18.1 MPa for LW1 and 18.2 MPa for LW2 at 28 days) due to optimized pore structure [2]. Finer aluminum powder also tends to produce smaller, more uniform pores, contributing to higher strength at a given density [2].

#### 4.3. Effect of Curing Conditions

Curing temperature plays a vital role in the geopolymerization process and the development of compressive strength. Elevated curing temperatures (e.g., 60 °C) typically accelerate the strength gain, especially at early ages, compared to ambient curing. For example, samples cured at 60 °C (LW2) showed similar 28-day compressive strength to those cured at room temperature (LW1) when other parameters were optimized, indicating that heat curing can be effective in achieving desired strength within a shorter period [2].

#### 4.4. Pore Structure Characteristics

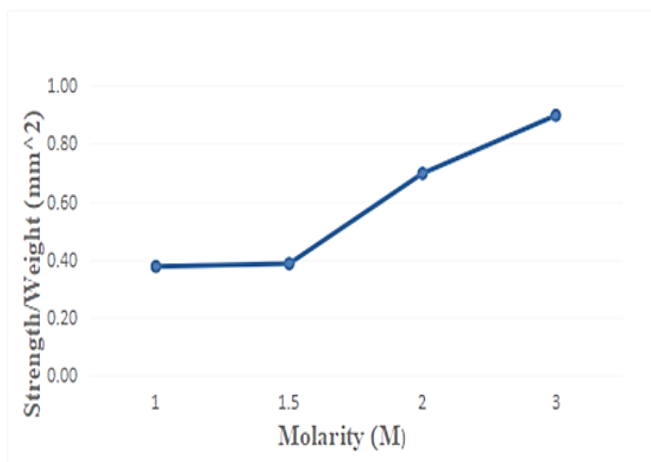
The pore structure, including total porosity, pore size distribution, and pore connectivity, is a fundamental determinant of GFC's mechanical performance. Studies using techniques like SEM and image analysis reveal that smaller, more uniform, and disconnected pores contribute to higher compressive strength and better thermal insulation. The use of effective stabilizing agents can significantly reduce the average pore size and improve pore uniformity, leading to enhanced mechanical properties [2].

#### 5. Discussion

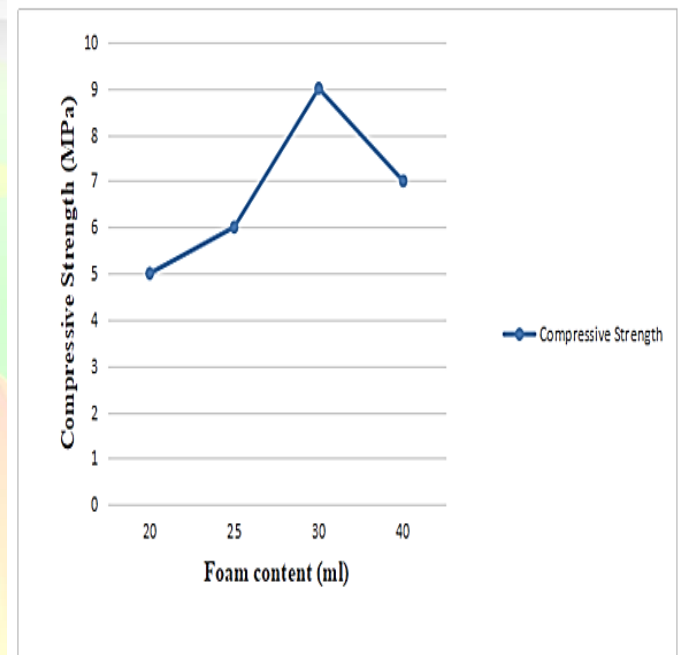
The experimental findings on geopolymer foamed concrete (GFC) compressive strength underscore the material's versatility and potential as a sustainable construction alternative. The observed inverse

relationship between foam content (and thus porosity) and compressive strength is consistent across numerous studies [1, 2]. This behavior is fundamental to foamed concrete, where the air voids, while reducing density and improving thermal insulation, inherently decrease the load-bearing cross-sectional area of the solid matrix.

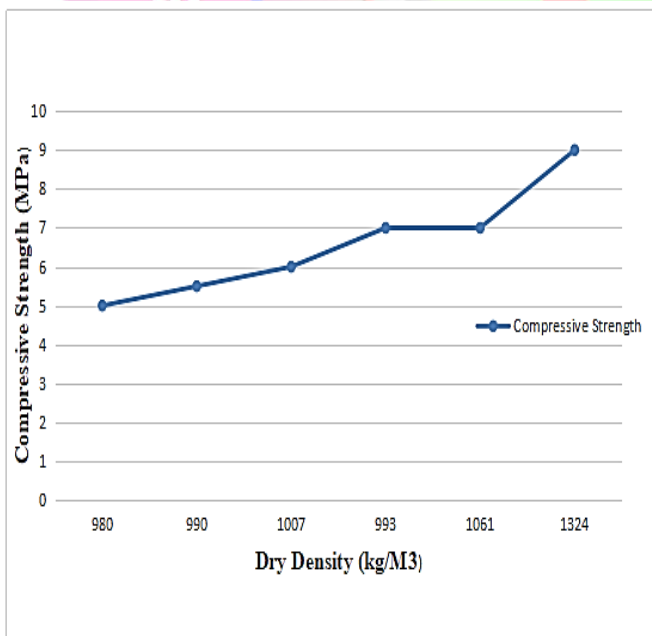
of FA generally enhances workability and contributes to a denser packing, which can indirectly improve strength by allowing for more uniform pore distribution [1]. Conversely, GGBS, with its higher reactivity and calcium content, accelerates geopolymerization and typically leads to higher early-age and ultimate strengths, albeit sometimes at the expense of workability [2]. The ability to achieve high-strength GFC (up to 50 MPa) by optimizing these precursor combinations, often with the addition of silica fume or fibers, demonstrates the material's potential for structural applications beyond mere insulation [2].



Graph 1: Graph for compressive strength/weight vs molarity



Graph 3: Graph for variation of compressive strength with foam content



Graph 2: Graph for variation of dry density vs compressive strength

The influence of precursor materials, such as fly ash (FA), ground granulated blast-furnace slag (GGBS), and metakaolin (MK), on GFC's compressive strength is multifaceted. The spherical morphology

The role of foaming and stabilizing agents is critical in controlling the pore structure, which is directly linked to compressive strength. The use of chemical foaming agents like hydrogen peroxide or aluminum powder, coupled with effective surfactants, allows for precise control over pore size and distribution. Smaller, more uniform, and disconnected pores are consistently associated with higher compressive strength and improved thermal performance [1, 2]. This highlights the importance of not just the

quantity of foam, but also its quality and stability during the fresh state of the GFC mixture.

Curing conditions, particularly temperature, significantly impact the kinetics of the geopolymerization reaction and, consequently, the rate and extent of strength development. Elevated temperatures accelerate the polycondensation process, leading to faster strength gain, especially in the early stages [1]. The comparative data presented (e.g., LW1 vs. LW2) suggests that while heat curing can accelerate strength development, optimized mix designs can achieve comparable ultimate strengths even under ambient conditions, which is advantageous for practical applications [2].

Comparing GFC with conventional OPC-based foamed concrete reveals several advantages. GFC generally exhibits a better strength-to-density ratio, superior fire resistance, and lower thermal conductivity [1]. These properties make GFC a more attractive option for lightweight and insulating applications. However, differences in shrinkage and creep behavior between GFC and OPC-based foamed concrete necessitate further investigation and mitigation strategies, such as fiber reinforcement, to ensure long-term structural integrity [2].

Overall, the experimental evaluation of GFC compressive strength demonstrates a material with significant promise. The ability to tailor its properties through careful selection of raw materials, precise control of foaming and curing parameters, and the incorporation of advanced additives allows for a wide range of applications. Continued research into long-term durability, standardized testing, and life-cycle assessments will further solidify GFC's position as a leading sustainable construction material.

## 6. Conclusion

Geopolymer foamed concrete (GFC) represents a significant advancement in sustainable construction materials, offering a viable alternative to traditional OPC-based concrete. This research paper has systematically examined the experimental evaluation of GFC's compressive strength, highlighting the multifaceted influences of precursor materials, foaming and stabilizing agents, and curing conditions. The intricate relationship between pore structure and mechanical performance is evident, with factors such as porosity, pore size distribution, and pore connectivity playing pivotal roles in determining the ultimate compressive strength. Research indicates that GFC typically achieves compressive strengths suitable for insulation and non-structural applications (1-10 MPa), with high-strength formulations reaching up to 45 MPa through optimized mix designs and the incorporation of advanced materials like silica fume and various fibers. Comparative analyses consistently demonstrate GFC's superior performance in terms of strength-to-density ratio, fire resistance, and thermal insulation compared to conventional foamed concrete. The ongoing exploration of nanomaterials and refined mix design strategies continues to push the boundaries of GFC's mechanical properties and sustainability credentials. Future research should focus on long-term performance, standardization of testing methods, and life-cycle assessments to facilitate broader industrial adoption of this promising material.

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