Optimizing the Performance of Lightweight Aggregate Masonry Units through the Application of Various Admixtures

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ABSTRACT

The main objective of this study is to investigate how different mineral additives, namely Silica Fume (SF), Fly Ash (FA), and Ground Granulated Blast-Furnace Slag (GGBS), affect the functionality of lightweight masonry units. The amounts of additives replaced were 10%, 20%, and 30% by weight. Compressive strength, density, water absorption, shrinkage, and thermal insulation tests were performed. The test periods for all characteristics were 7, 28, and 65 days, except for thermal insulation, which was tested after 28 days. The results showed significant improvements in insulation and mechanical performance. The improved performance of these additives reflects the work that also needs to be done in the environmental and economic fields.

Keywords-lightweight concrete; thermal; strength

I. INTRODUCTION

The construction sector contributes significantly to global warming, with the cement industry alone being responsible for approximately 8% of carbon dioxide emissions [1]. Sustainable materials may contribute to minimizing environmental pollution. The use of lightweight concrete blocks can increase the efficiency of thermal insulation while reducing the structural loads of the building [2]. If their mechanical strength and durability is increased, these blocks can offer additional benefits in construction.

The properties of cementitious reinforcement materials make them a possible solution for enhancing the performance of lightweight concrete blocks. SF has excellent pozzolanic activity, which makes it an important factor in improving mechanical performance, density, and durability [3]. FA is classified into F or C based on its chemical structure, and can improve workability and strength in the long run [4]. Another type of pozzolanic additive is GGBS, which can reduce the heat generated by the hydration process of cement, and thus increase the durability of the concrete block [5]. Pozzolanic materials are obtained as by-products from industries such as silicon and ferrosilicon alloy production, coal combustion, or iron manufacturing. Therefore, their use will/may reduce the environmental impact of those industries, while improving the performance of the cement mixture [6].

This study investigates the effect of mineral additives as a substitute for cement in the manufacture of lightweight building blocks by using different replacement ratios of 10%, 20%, and 30% by weight. The performance was evaluated through compressive strength, density, water absorption, shrinkage, and thermal insulation tests. At different ages of 7, 28, and 65 days, the performance was investigated to show the behavior of lightweight concrete blocks at short and long-term ages. The compressive strength and shrinkage tests were conducted according to [7, 8], whereas density and water absorption tests were performed according to [9, 10]. At 28 days, the thermal insulation test was conducted according to [11].

II. MATERIALS AND METHODS

The materials used in this study were carefully selected to ensure that modern regulations were followed, thus enabling the production of high-quality, uniform, lightweight masonry units. Ordinary Portland Cement (Type I) was utilized as the main binder [12], which is known for its performance in masonry construction. Lightweight aggregate with a body size of up to 8 mm was selected to meet the testing and cleaning principles described in [13]. Furthermore, their premium quality was selected according to [14] to better match the properties of lightweight concrete formulations.

To maintain the performance of the mix and support water resistance, this study used potable water that meets the requirements of [15]. The additional cementitious materials, namely, Steel Fume, FA (type C), and GGBS, were selected to replace part of the cement at replacement rates of 10%, 20%, and 30% by weight, in compliance with [16] for SF, with [17] for FA, and with [18] for GGBS.

The components shown in Table I were carefully designed to achieve a balance between workability, strength, and durability. The inclusion of cementitious additives helps to achieve long-lasting construction by reducing cement consumption while still meeting the performance criteria outlined in [19] for lightweight concrete.

This study involved a series of thorough tests to assess the performance of lightweight masonry units under different conditions. The experimental part included assessments of mechanical performance (compressive strength) [7], density [9], water absorption [10], and shrinkage [8] at 7, 28, and 65 days, as well as thermal insulation [11] after 28 days. Adherence to strict measurement principles ensures that the data obtained are reliable, allowing meaningful comparisons with other studies.

TABLE I. MIX PROPORTIONS FOR LIGHTWEIGHT AGGREGATE MASONRY UNITS

Material	Quantity (kg)	Notes
Cement (OPC)	350	The proportion of cement was decreased in line with the additives, with amounts adjusted to 315 kg for a 10% replacement, 280 kg for a 20% replacement, and 245 kg for a 30% replacement.
Additive (SF, FA, GGBS)	35 (10%) 70 (20%) 105 (30%)	Incorporated as a replacement for cement based on weight.
Fine aggregate	1,000	The fine aggregate used was graded in accordance with [14].
Coarse lightweight aggregate	500	The maximum particle size was 8 mm, in compliance with [13].
Water	157.5	The mix was designed using a water-to-binder ratio of 0.45.

a. The mix proportions were calculated for 1 m³.

III. RESULTS AND DISCUSSION

A. *Mechanical and Durability Performance*

1) *Compressive Strength Development over Time*

Concrete mixtures with SF, FA, and GGBS were evaluated for compressive strength at replacement percentages ranging from 0% to 30% over 7, 28, and 65 days of curing (Figure 1) [20, 21].

As the curing time increased, the compressive strength of all mixtures increased, indicating ongoing hydration and pozzolanic process [22]. This steady increase in strength is attributed to the formation of calcium-silicate-hydrate (C-S-H) gel, which is essential for improving the structural qualities of concrete.

The incorporation of SF, FA, and GGBS had a notable effect on strength development, with each additive showing distinct patterns of behavior:

- Early-age strength was increased by the quick reaction of SF with calcium hydroxide to create C-S-H gel. However, because of the SF's high-water consumption, replacement levels beyond 20% led to decreased workability and compressive strength [23]. Its ultra-fine particles effectively filled voids, increasing matrix density.
- The pozzolanic reaction of FA was slower, leading to lower early-age strength but substantial long-term gains [24]. The highest strength (11.0 MPa) was achieved at a 30% FA replacement by 65 days. This delayed strength development stems from FA's reliance on calcium hydroxide from cement hydration to initiate its pozzolanic activity.
- GGBS demonstrated balanced performance, contributing to both early and long-term strength [25]. At a 30% replacement rate, it reached its highest compressive strength of 13.2 MPa by 65 days. Its latent hydraulic activity, activated by lime, supported immediate and sustained strength improvements.

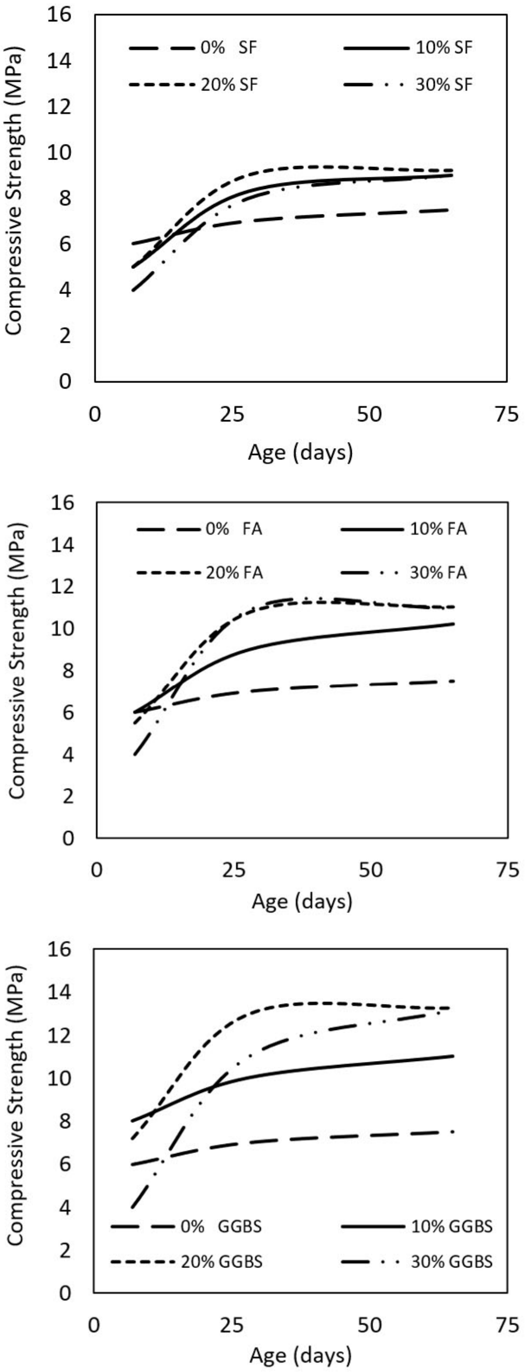

Fig. 1. Compressive strength at different ages of samples containing SF, FA, and GGBS.

At 7 days, GGBS outperformed both FA and SF at lower replacement levels, whereas SF exhibited slight reductions in strength due to dilution effects. By 28 days, GGBS showed the greatest strength gains, followed by FA and SF. At 65 days, GGBS maintained the highest strength, with FA showing notable improvements and SF plateauing at replacement levels beyond 20%. These results emphasize the importance of optimizing additive proportions to meet specific performance criteria.

2) *Water Absorption Trends over Time*

Water absorption decreased across all mixes as curing time increased (Figure 2), reflecting improvements in the microstructure due to hydration and pore refinement effects induced by the additives [10]. Reduced water absorption signifies enhanced resistance to moisture ingress, contributing to improved durability.

The base mix exhibited a decrease in water absorption from 22% at 7 days to 19% at 65 days. This reduction is attributed to the progressive densification of the cementitious matrix as hydration filled the pores over time.

Incorporating additives significantly reduced water absorption compared to the base mix, with the most pronounced improvement observed in mixes containing GGBS at a 30% replacement rate, achieving the lowest water absorption value of 14% at 65 days.

- SF demonstrated a consistent reduction in water absorption, reaching 16% at a 30% replacement rate. The ultra-fine particles of SF contributed to matrix densification by filling microvoids, although higher dosages increased water demand. The use of superplasticizers may be necessary to maintain workability at elevated SF levels.
- Water absorption decreased steadily in FA-containing mixes, with 30% FA achieving 16% at 65 days. FA's slow pozzolanic reaction supports long-term pore refinement, making it beneficial for enhancing durability in conditions involving prolonged moisture exposure
- GGBS showed the most significant reduction in water absorption, attributed to its latent hydraulic activity and effective pore refinement. This characteristic makes GGBS highly suitable for applications requiring superior water resistance.

The overall decline in water absorption with extended curing times and higher additive dosages underscores the durability benefits provided by these materials. These improvements indicate enhanced resistance to chloride penetration and other aggressive environmental agents, aligning with the requirements for long-lasting and resilient construction materials.

3) *Density Trends over Time*

Concrete density exhibited a gradual decrease across all mixes over time (Figure 3), influenced by the type and proportion of additives, as well as the duration of curing [26]. Variations in density are crucial in determining mechanical properties and are a main consideration in designing mixes for specific applications.

The density of the base mix decreased from 1150 kg/m³ at 7 days to 1124 kg/m³ at 65 days. This reduction can be attributed to minor shrinkage and the evaporation of free water during curing, reflecting typical volumetric changes associated with hydration processes. The inclusion of additives resulted in slightly lower densities due to their inherently lower specific gravities compared to cement. These reductions became more significant at higher replacement levels:

- SF led to a moderate reduction in density, stabilizing at 1100 kg/m³ by 65 days when used at a 30% replacement level. SF's fine particles enhance void filling, and its lower specific gravity contributes to a decrease in overall density. However, this effect is offset by the substantial improvements in strength provided by SF.

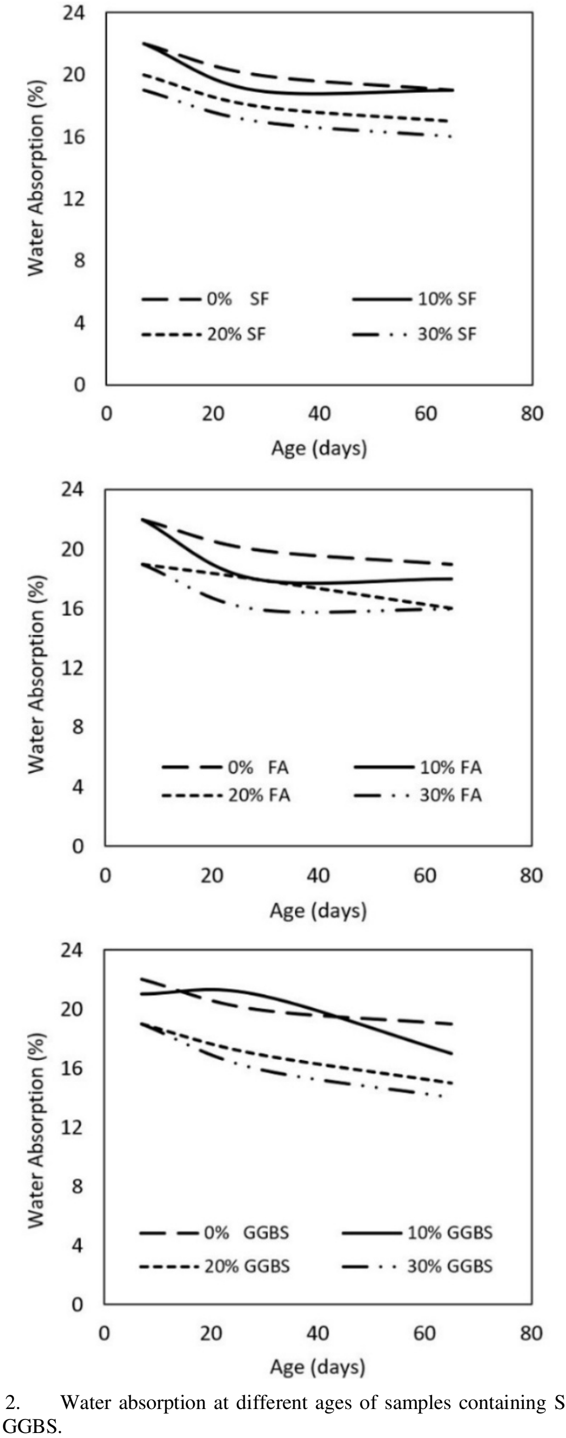

Fig. 2. Water absorption at different ages of samples containing SF, FA, and GGBS.

- FA showed greater density reductions at higher proportions, with a density of 1104 kg/m³ recorded for 30% FA at 65 days. The reduction aligns with FA's lower specific gravity, making it particularly suitable for lightweight concrete applications.
- GGBS resulted in the lowest density among the mixes, reaching 1102 kg/m³ at a 30% replacement rate by 65 days. Its latent hydraulic activity supports early and long-term densification, compensating for the reduced density by contributing to both strength and durability.

These observations stress the importance of balancing additive proportions to achieve optimal density while maintaining strength and durability. Additionally, the potential of these additives for applications requiring lightweight yet structurally robust materials is demonstrated.

4) Shrinkage Trends over Time

Shrinkage diminished with the incorporation of additives (Figure 4), with the extent of reduction varying by the type and dosage of the additive [27]. Lower shrinkage levels are crucial in minimizing cracking risks, thereby enhancing the durability and longevity of concrete structures.

Shrinkage in the base mix increased from 0.05% at 7 days to 0.1% at 65 days. This growth reflects water evaporation and hydration-related volumetric changes, highlighting the susceptibility of plain cement concrete to shrinkage-induced issues.

All additives effectively reduced shrinkage compared to the base mix, with FA delivering the most significant improvements.

- SF moderately decreased shrinkage, reaching 0.04% at 7 days and 0.08% at 65 days for a 30% replacement level. The ultra-fine particles of SF enhance packing density, even though they may increase water demand, which could necessitate adjustments in mix design.
- FA exhibited significant shrinkage reductions, particularly at higher dosages. At 30% FA, shrinkage was recorded at 0.04% at 7 days and 0.08% at 65 days. This enhancement is due to the slower reactivity of FA and its ability to refine the pore structure, which makes it particularly ideal for mass concrete applications that demand minimized shrinkage.
- Although it has shown effectiveness in reducing shrinkage, the effect of GGBS was somewhat less significant than that of FA at higher replacement levels. At 30% of granulated blast furnace slag, shrinkage was 0.04% at 7 days and 0.09% at 65 days, respectively. This is a result of the inherent hydraulic properties of granulated blast furnace slag, which minimize shrinkage while ensuring exceptional strength and durability.

These findings demonstrate the importance of selecting the appropriate additives and their precise ratios in order to maximize shrinkage control while preserving the concrete's strength and long-term durability.

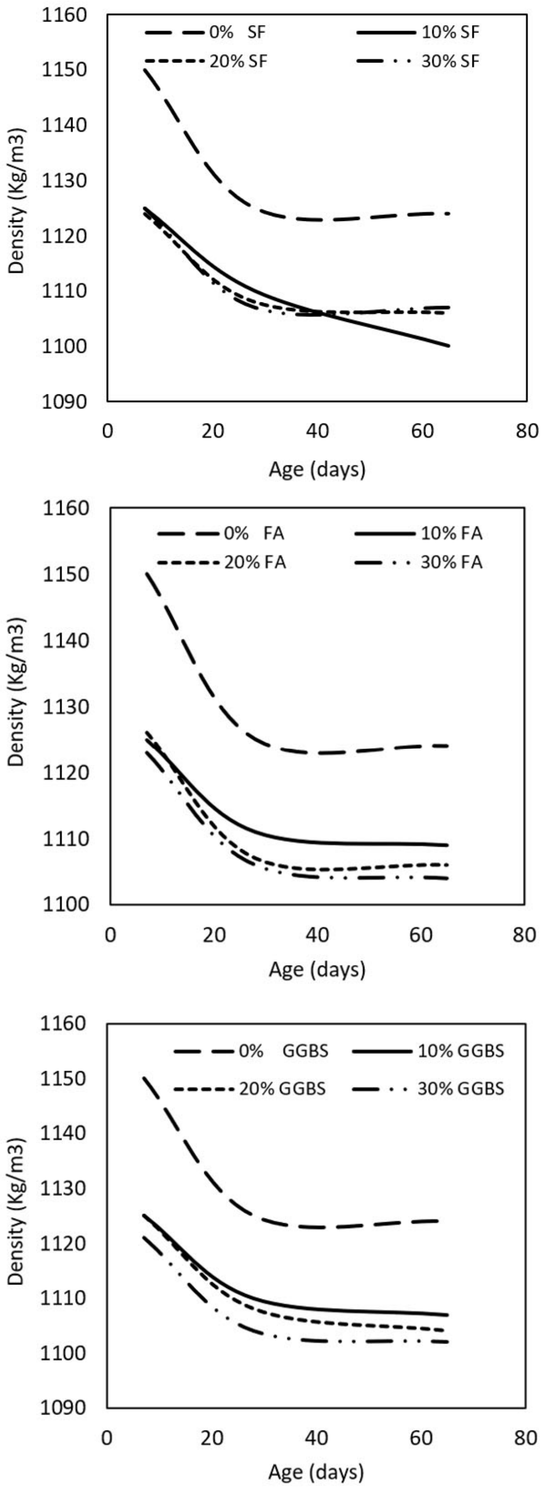

Fig. 3. Density at different ages of samples containing SF, FA, and GGBS.

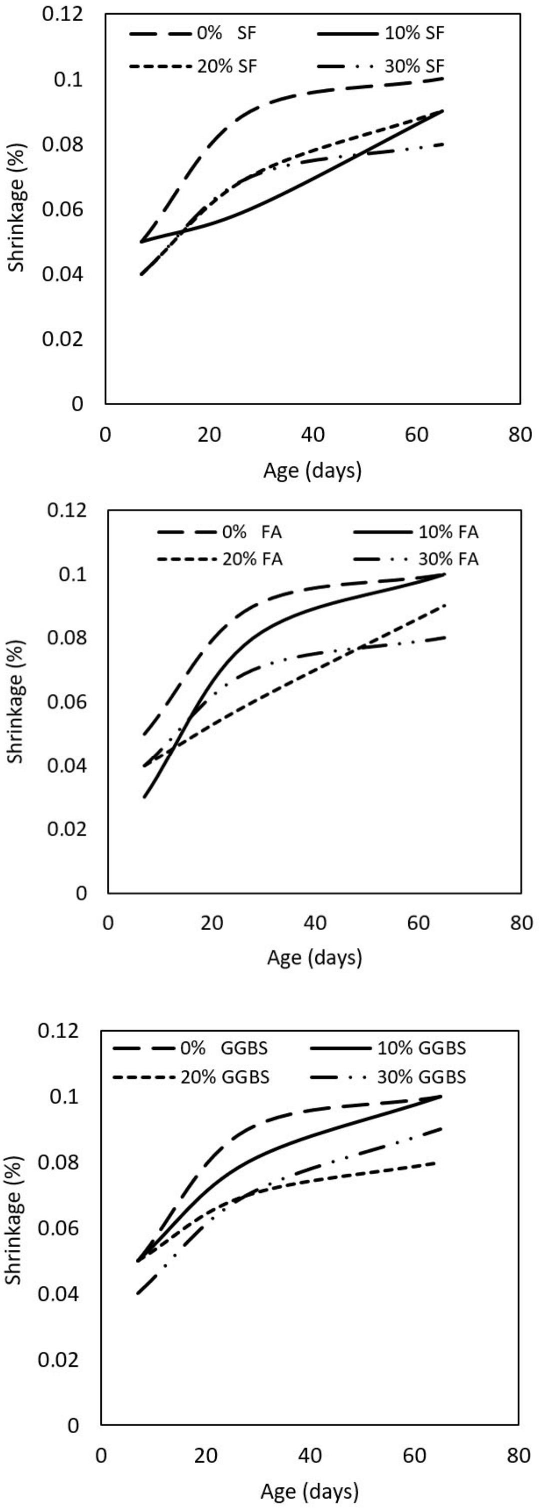

Fig. 4. Shrinkage at different ages of samples containing SF, FA, and GGBS.

5) Practical Considerations

- Strength Development: GGBS is a good choice for projects that require high strength during later curing phases, whereas FA is the finest option for enhancing long-term durability. Although SF promotes quick strength development at first, careful mix modifications are required due to its higher water consumption.
- Improvements in durability: The observed reduction in shrinkage and water absorption demonstrates how these additions can increase concrete resilience to environmental stresses. This makes modified mixtures especially well-suited for high-demand contexts, such as industrial flooring applications and maritime conditions.
- Density considerations: Although it may result in a decrease in mechanical strength, lowering the density of concrete might be beneficial for applications requiring lightweight materials. It is significant to create precisely optimized mix designs in order to achieve balance between strength and weight.
- Refined Mix Formulation: Careful water management and appropriate curing techniques are important components of a well-designed mix that will maximize the benefits of these additions. Additionally, this strategy reduces the possibility of issues like shrinkage and density drops. The utilization of these mixes in a range of construction scenarios can be enhanced by further research into their microstructural properties and long-term performance.

B. Thermal Insulation

The thermal insulation capability of concrete mixes was evaluated using the K-value (W/m·K) at 28 days for varying concentrations of FA, GGBS, and SF [28]. This part provides an overview of the findings is provided, emphasizing the effects of these additions on thermal insulation as well as their potential applications in the real world and their effects on the economy and environment.

As the benchmark for thermal insulation performance, the thermal conductivity (K-value) of the base mix was determined to be 0.68 W/m·K.

Introducing SF, FA, or GGBS reduced the K-value, improving thermal insulation. The extent of this improvement varied across additives, with SF exhibiting the most significant enhancement and FA showing moderate reductions at higher replacement levels.

- The K-value consistently decreased as the SF content increased, dropping from 0.68 W/m·K (0%) to 0.50 W/m·K (30%). SF's ultra-fine particles fill microvoids, reducing overall density and enhancing insulation. SF forms smaller, insulating air pockets that lower heat conductivity. It greatly increases insulation, but because of matrix densification, it may also enhance brittleness.
- As the FA content increased, the K-value gradually decreased from 0.68 W/m·K (0%) to 0.54 W/m·K (30%). FA encourages the formation of secondary C-S-H, improving the pore structure and enhancing insulation. It also reduces the overall density of the mix, which further improves insulation. Its lower thermal conductivity and its gradual reactivity help maintain insulation properties over time.
- The sloping of K-value for the GGBS mix ranged from 0.68 W/m·K (0%) to 0.61 W/m·K (30%). This effect is related to its higher specific gravity (density); therefore, GGBS has a smaller effect on insulation compared to SF and FA. It contributes to refining the matrix but forms fewer insulating air pockets. GGBS focuses more on enhancing compressive strength than improving thermal insulation performance.

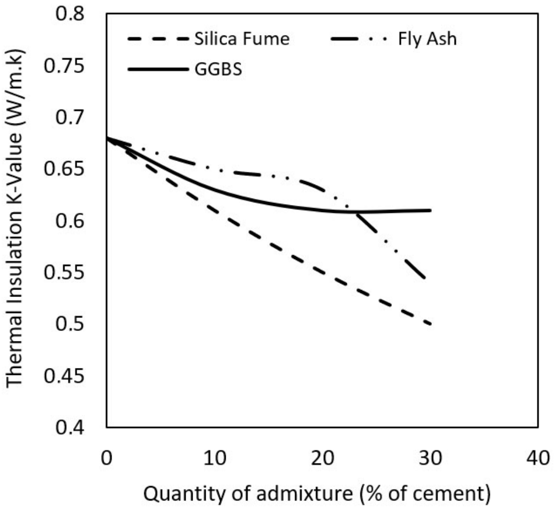

Fig. 5. Thermal insulation at 28 days for samples containing SF, FA, and GGBS.

TABLE II. DECREASE IN THERMAL CONDUCTIVITY (K-VALUE)

Additive	Proportion (%)	K-value (W/m·K)	Reduction from baseline (0.68)
SF	10	0.61	0.07
SF	20	0.55	0.13
SF	30	0.50	0.18
FA	10	0.65	0.03
FA	20	0.63	0.05
FA	30	0.54	0.14
GGBS	10	0.63	0.05
GGBS	20	0.61	0.07
GGBS	30	0.61	0.07

1) Comparative Insights

- The decrease in the K-value of SF samples demonstrates the effectiveness of its thermal insulation properties, making it a reliable solution for projects that demand improved energy efficiency.
- FA enhances thermal insulation to a moderate extent while also contributing to reduced shrinkage and improved long-term durability.

- Although GGBS provides only moderate gains in insulation, it significantly enhances strength and durability, making it well-suited for structural use.

2) Environmental Impacts

The use of SF, a byproduct of silicon and ferrosilicon alloy production [29], helps reduce industrial waste. Its contribution to improving thermal insulation can decrease energy consumption for heating and cooling in buildings, leading to lower carbon emissions. Nevertheless, the environmental benefits of SA might be tempered by its high processing costs and limited availability**.**

FA is a byproduct of coal combustion [30], while its use helps divert waste from landfills. It also enhances thermal insulation, which can help reduce energy use in buildings. However, if coal-based electricity generation continues to decline, its long-term availability may be restricted**.**

Utilizing GGBS, which is a byproduct of steel production [31], also contributes to waste reduction. Even if it offers less thermal insulation than other additives, it can result in lower maintenance costs due to its increased longevity. Its initial manufacture, however, uses more energy than fly ash**.**

3) Economic Impacts

In terms of pricing, FA is a widely available and moderately priced material that provides a cost-effective solution. GGBS mixes offer a competitive alternative in terms of price for projects that prioritize increased strength and durability [32]. The initial SF cost is often higher than that of the other mixes, but based on its insulating benefits, it/SF can reduce heating and cooling costs, resulting in energy savings.

The enhanced thermal insulation achieved because of these additives can lead to lower heating and cooling costs, which can have a major positive financial impact, particularly in regions with high temperature swings.

Using materials like FA and GGBS increases durability and decreases shrinkage, which lessens the need for maintenance and repairs over the structure's lifetime and increases cost-effectiveness.

C. Practical Implications

SF is especially effective for high-performance concrete in energy-efficient structures where robust thermal insulation is essential. GGBS is ideal for long-term infrastructure projects, like bridges and offshore structures, where thermal insulation is not a top priority. For general construction, FA can provide a well-rounded enhancement in insulation, strength, and affordability.

The inclusion of these additives can greatly boost a building's energy efficiency, aiding in meeting green building standards and advancing sustainability objectives.

Choosing the right additive and its proportion depends on the project's specific needs, requiring a thoughtful balance between insulation, strength, shrinkage, and cost factors.

The impact of improved thermal insulation using SF, FA, and GGBS on CO_2 emissions and cost savings can be evaluated based on currently available data. The following analysis shows how these insulation upgrades lead to reduced energy use, lower CO_2 emissions, and lower overall costs.

1) Assumptions for Analysis

- Baseline Energy Consumption: A building without any additives (K-value = 0.68 W/m·K) consumes 200 kWh/m² annually for heating and cooling.
- Energy Savings with K-Value Reduction: For every 0.01 W/m.K decrease in the K-value, energy consumption is reduced by 1.5%.
- CO_2 Emissions from Energy Use: The production of electricity results in approximately 0.4 kg of CO_2 per kWh
- Building Size: The analysis assumes a typical building area of 1,000 m².
- Example for SF (30% Proportion):
  - Annual Energy Savings = 54,000 kWh
  - Electricity Cost = $0.12 per kWh
  - Total Cost Savings = 54,000 × 0.12 = $6,480 per year.

TABLE III. ESTIMATED CO^2 REDUCTION AND ENERGY COST SAVINGS WHILE/WHEN USING CONCRETE WITH SF

	SF		
	10%	**20%**	**30%**
Energy savings (kWh/m²)	21	39	54
Total energy savings (kWh)	21,000	39,000	54,000
CO_2 reduction (kg)	8,400	15,600	21,600
Cost savings ($)	2,520	4,680	6,480

TABLE IV. ESTIMATED CO^2 REDUCTION AND ENERGY COST SAVINGS WHILE/WHEN USING CONCRETE WITH FA

	FA		
	10%	**20%**	**30%**
Energy savings (kWh/m²)	9	15	42
Total energy savings (kWh)	9,000	15,000	42,000
CO_2 reduction (kg)	3,600	6,000	16,800
Cost savings ($)	1,080	1,800	5,040

TABLE V. ESTIMATED CO^2 REDUCTION AND ENERGY COST SAVINGS WHILE/WHEN USING CONCRETE WITH GGBS

	GGBS		
	10%	**20%**	**30%**
Energy savings (kWh/m²)	15	21	21
Total energy savings (kWh)	15,000	21,000	21,000
CO_2 reduction (kg)	6,000	8,400	8,400
Cost savings ($)	1,800	2,520	2,520

IV. CONCLUSIONS

The construction industry is under increasing pressure to implement sustainable practices while simultaneously preserving structural performance and energy efficiency. By systematically examining the effects of mineral additives—Silica Fume (SF), Fly Ash (FA), and Ground Granulated Blast Furnace Slag (GGBS)—on the mechanical, durability, and thermal properties of lightweight aggregate masonry units, this study addresses a critical knowledge gap. It includes a comprehensive comparison of their synergistic impacts at various replacement levels (10%, 20%, and 30%), whereas previous studies have only explored individual additives. It also provides recommendations for optimizing lightweight concrete formulations.

The current study was conducted using a strict method. Initially, the mixes were designed in accordance with ASTM standards. Then, compressive strength, density, water absorption, shrinkage, and thermal insulation tests were conducted for 7, 28, and 65 days. The key findings of the research showed that GGBS achieved the highest compressive strength at a 30% replacement rate (13.2 MPa for 65 days), but SF showed the greatest reduction in thermal conductivity (K-value: 0.50 W/m K for a 30% replacement rate). Though slower to react, FA provided a balanced long-term strength (11.0 MPa) and shrinkage (0.08% at 65 days). All components reduced absorption and density, and improved durability and lightness. The 30% replacement level consistently achieved optimal performance across all metrics, highlighting the possibility of high-volume cement substitution.

The results of the study provide valuable insights regarding the trade-offs between mechanical, thermal, and environmental outcomes, highlighting the need for context-specific choices of material. Moreover, by calculating the reduction of CO_2 emissions and cost, the laboratory research is directly connected with real-world sustainability objectives.

Overall, this study provides a framework which can meet specific project requirements for lightweight concrete mixes. By validating high-volume replacement strategies, it challenges traditional limits on cement reduction and offers a way to decarbonize construction. To improve these solutions, future research should look into hybrid additive combinations and long-term field performance.

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