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Experimental Study on Strength and Performance of Foamed Concrete with Glass Powder and Zeolite

Mahmoud Al-Khazaleh ¹[®], P. Krishna Kumar ²^{*}[®], Deya Qtiashat ¹[®], Ali Alqatawna ¹[®]

¹ Department of Civil Engineering, Munib and Angela Masri Faculty of Engineering, Aqaba University of Technology, Aqaba, 11947, Jordan. ² Department of Civil Engineering, SRM Madurai College for Engineering and Technology, Sivaganga, Tamil Nadu, 630612, India.

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Abstract

Cement manufacturing accounts for approximately 7% of anthropogenic CO_2 emissions. To mitigate environmental impact and achieve "net zero" by 2050, developing cementitious materials that minimize cement consumption is crucial. This research aims to reduce cement usage in Foamed Concrete (FC). The study investigates the mechanical, durability, and thermal properties of FC using two distinct Supplementary Cementitious Admixtures (SCA): Glass Powder (GP) and natural zeolite. Cement was replaced with SCA at varying percentages (0%, 5%, 10%, 15%, 20%, and 25% by weight) in FC. The FC density was adjusted by incorporating foam at 15% and 30% of the total volume of concrete. The study evaluated the flowability of each mix in its fresh state. The mechanical properties were assessed by measuring compressive strength and ultrasonic pulse velocity. The performance of FC was further analyzed in terms of thermal conductivity, sorptivity, and water absorption. The test results revealed that FC with GP combinations exhibited high flowability and an improved strength-to-density ratio. Additionally, water absorption, sorptivity, and thermal conductivity were significantly reduced compared to conventional FC. An extensive cost-benefit analysis highlighted the feasibility of utilizing common waste materials to produce high-grade FC and assessed the impacts of cementitious admixtures as viable alternatives to cement.

Keywords: Foamed Concrete; Glass Powder; Natural Zeolite; Sorptivity; Plastic Density; Thermal Conductivity.

1. Introduction

In recent years, excessive cement usage has contributed significantly to carbon dioxide emissions and the depletion of natural resources. The cement production process emits NO_x , SO_x , and other particulates into the atmosphere, exacerbating global warming and climate change. Moreover, noise and vibrations from mechanical activities and quarry blasting adversely affect workers' health. Fuel stockpiles for cement manufacturing equipment also pollute groundwater. Consequently, the growing cement industry is regarded as a major environmental polluter. A 2021 survey reported that 4,300 million metric tonnes of cement are produced globally, with India contributing 330 million tonnes. Cement production accounts for approximately 7% of anthropogenic CO_2 emissions, and India ranks among the top seven greenhouse gas emitters [1]. To mitigate environmental impacts and achieve "net zero" emissions by 2050, developing SCA with minimal environmental effects is essential. The construction sector increasingly emphasizes stronger and lighter building practices to reduce structural weight and associated costs. Future construction materials must also be durable, cost-effective, and eco-friendly [2]. Cellular concrete, also known as aerated concrete, is widely used for manufacturing lightweight precast components in high-rise buildings [3, 4].

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^{*} Corresponding author: krishnakumar@srmmcet.edu.in

The incorporation of cement substitutions in aerated concrete can significantly enhance the sustainability of highrise construction. Aerated concrete is expected to meet performance criteria such as strength, durability, and affordability. FC, a type of aerated concrete, is produced by introducing foam into the cement matrix, creating at least 10% air voids within the structure. The air-dry density of FC can be adjusted by varying the foam content in the mix [2, 5]. The quality of FC and its suitability as a construction material largely depend on moisture mobility within the concrete. Water absorption in FC is influenced by the total pore volume, while sorptivity is determined by pore volume, fineness, discontinuity, and tortuosity [6]. The use of fly ash as a mineral admixture in FC increases the water-to-solid ratio required for a stable and workable mix. Less workable mixes exhibit higher sorption due to increased paste volume, which restricts foam addition, creates voids, and enlarges concrete pores. Consequently, capillary pores are increased [7]. Fine fly ash particles react with $Ca(OH)_2$ released during cement hydration to form cementitious compounds. However, insufficient Ca(OH)₂ production due to reduced cement content may leave some fly ash particles unreacted, thereby slowing FC hydration [8]. The hydration rate of FC is directly proportional to its cement content, which influences temperature rise. Replacing cement with inert materials or adding inert components to the mix can reduce the heat of hydration [9]. For instance, substituting up to 20% of cement with fly ash reduces hydration heat and improves the strength-to-density ratio of FC [5]. However, this approach has not adequately addressed the durability characteristics of FC. The high strength-to-density ratio is attributed to the lower specific gravity of fly ash compared to sand [7]. Existing studies suggest that fine inert components in FC enhance strength through pozzolanic reactions and filler effects without significantly altering or slightly reducing density. However, fine components decrease mix consistency due to their high surface area, which increases water demand. Superplasticizers are therefore essential to improve the fresh state properties of FC with fine admixtures [10].

Fine fly ash particles refine large pores, enhancing hydration product precipitation sites. Consequently, replacing cement and sand with fly ash has improved FC's lightweight properties, compressive strength, and drying shrinkage performance [11]. Incorporating mineral admixtures into FC can reduce Portland cement content from 600 kg/m³ to 300 kg/m³, lowering peak hydration temperatures by 24% and delaying maximum hydration by five hours [5]. Drying shrinkage in aerated concrete is influenced by curing conditions and filler ingredients. For example, autoclave curing of fly ash-based aerated concrete significantly reduces shrinkage [12]. Nanoparticles with high surface area-to-volume ratios can modify the microstructure of cementitious composites in both fresh and hardened FC. For example, Nano-Silica (NS) at 2% of cement weight enhances FC's shear resistance and thixotropic behavior. However, unequal dispersion of NS in concrete can lead to flocculation, which absorbs excess free water and destabilizes the mix. Proper dispersion of micro-admixtures is therefore critical [13]. Stable foam is achieved through Van der Waals interactions between micro-betaine molecules and NS particles, while electrostatic interactions between betaine and nanoparticles influence pore-wall crystallization. Improper dispersion of NS can result in uneven foam distribution, reducing material strength [14, 15]. Silica fume (SF), another widely used admixture, reduces water absorption and significantly enhances FC's density, thermal conductivity, and compressive strength by refining pore structures and densifying the microstructure [16-19]. Previous research demonstrates that micro- and nano-admixtures improve FC performance.

However, optimizing dosage is crucial to balancing mechanical properties and durability. Mineral admixtures such as fly ash, SF, nano-alumina, and NS enhance mechanical properties but may adversely affect parameters like oven-dry density, water-to-solid ratio, or performance characteristics such as water absorption, sorptivity, and thermal conductivity. Superplasticizer optimization is also necessary to mitigate adverse effects, such as foam drainage and delayed hydration. Globally, zeolite has been used as a concrete ingredient for over three decades. Zeolite improves workability, reduces bleeding, and minimizes permeability and self-shrinkage cracking in high-performance concrete [20]. Similarly, GP derived from industrial waste has been studied for its effects on the fresh-state properties and mechanical strength of FC [21]. However, comprehensive research on improving FC's thermal conductivity, sorptivity, and water absorption using zeolite and GP is limited. This research article aims to experimentally evaluate the advantages of using waste-derived mineral admixtures, such as zeolite and GP, as cement substitutes in FC. Comparative analyses of conventional FC, zeolite-modified FC, and GP-modified FC are conducted. The thermal conductivity, sorptivity, and water absorption studies were conducted, and a cost-benefit analysis is performed to assess the feasibility of implementing these admixtures in practical applications. The study methodology is depicted in Figure 1 of implementing these admixtures in practical applications.

2. Materials and Mix Proportions

Ordinary Portland Cement (OPC) 53-grade, manufactured by Ramco Cements, India, and conforming to IS: 12269: 2013 standards, was utilized throughout this study. Potable water with a pH of no less than 6, free from organic materials, salts, or turbidity, was employed for the preparation of FC. The pre-foaming method was adopted for FC production. Rheocell 30, a protein-based foaming agent, was used to generate foam with a density of 40–65 kg/m³. The foam density and slump stability were examined over time to ensure the consistency of the foaming agent, following ASTM C796 standards. Based on the findings, the foaming agent was diluted with water at a ratio of 1:30 to produce stable foam [22]. Foam generation was achieved through the wet mixing process using a foam generator. The desired FC density

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was obtained by mixing the aqueous foam with the cement matrix for two minutes. Pulverized sand, passing through a 300-micron sieve, was used in the preparation of the cement matrix. Crushed soda-lime glass, collected from local waste disposal sites, was sieved using a 600-micron sieve to remove coarser particles. Clinoptilolite zeolite was sourced from a urea manufacturing facility in Tuticorin, India. The zeolite was calcined in a furnace at 750°C with a heating rate of 15° C/min and subsequently cooled to room temperature. The physical and chemical properties of all ingredients used in FC are presented in Table 1. The particle size distribution curve of the materials used in this study is shown in Figure 2.



Figure 1. Methodology of the study

Table 1. Chemical and physical properties of cement and admixtures

Oxide Compounds	Cement	Zeolite	Glass Powder				
SiO ₂ (%)	21.4	63.88	75.70				
Na ₂ O (%)	0.85	6.8	12.15				
CaO (%)	63.5	2.38	6.57				
Al ₂ O ₃ (%)	6.2	11.56	1.24				
MgO (%)	2.2	1.04	1.62				
SO ₃ (%)	2.7	0.5	-				
K ₂ O (%)	0.85	0.91	1.94				
Fe ₂ O ₃ (%)	0.56	0.21	0.78				
Loss on ignition (%)	1.738	11.81	-				
Physical Properties							
Specific Surface (m ² /kg)	312	118.2	175				
Specific Gravity	3.02	2.3	2.39				
Density (g/cm ³)	1.35	1.03	1.07				

The mix proportions were determined through a trial-and-error approach. A constant water-to-binder ratio of 0.4 was maintained across all mixes. Glass powder (GP) and zeolite were used as partial cement replacements in FC at various dosages, as outlined in Table 2. Two target densities were achieved by incorporating foam at 15% and 30% of the total concrete volume. The mixing process was conducted using a laboratory-grade planetary mortar mixer. Initially, the calculated amounts of cement and supplementary admixtures were dry-mixed for 2 minutes. Water was then added gradually to achieve a consistent base mortar. The required volume of foam was subsequently introduced into the cement mortar, as shown in Figure 3. The cement slurry and foam were mixed continuously for 2 ± 1 minutes at a constant rotation speed to ensure uniform foam dispersion. The resulting mix was assessed for plastic density before being poured into molds. After 24 hours of casting, the specimens were demolded and sealed in cellophane-taped polyethylene bags, as illustrated in Figure 4. For each mix, the following specimens were cast for experimental analysis: 10 cubes ($100 \times 100 \times 100 \text{ mm}$), 5 cylinders (100 mm diameter $\times 200 \text{ mm}$ height), and 2 prisms ($40 \times 40 \times 160 \text{ mm}$).



Figure 2. Particle size distribution of the materials used

Series	Mix Id	Foam Volume	Cement (kg/m ³)	Admixture (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)
Conventional FC	СМ	15%, 30%	665	-	1330	266
	G5		631.75	33.25	1330	266
	G10		598.5	66.5	1330	266
GP	G15	15%, 30%	565.25	99.75	1330	266
	G20		532	133	1330	266
	G25		498.75	166.25	1330	266
	Z5		631.75	33.25	1330	266
Zeolite	Z10		598.5	66.5	1330	266
	Z15	15%, 30%	565.25	99.75	1330	266
	Z20		532	133	1330	266
	Z25		498.75	166.25	1330	266

Table 2. Mix proportion details



Figure 3. Foamed concrete preparation (Before and after foam addition)



Figure 4. Casting and curing of Foamed Concrete

3. Tests

The flow test was conducted in accordance with ASTM C1437, Standard Test Method for Flow of Hydraulic Cement Mortar. The spread diameter of the mortar was measured and calculated using Equation 1.

$$Spread = Average spread diameter - flow mould inner base diameter$$
 (1)

The plastic density (wet density) of FC was determined following the weight-to-volume ratio method outlined in ASTM C567. The oven-dry density of FC was also calculated in accordance with ASTM C567. Compressive strength tests were conducted using a 40-ton Compression Testing Machine (CTM) as per ASTM C109. FC cube specimens (100 mm \times 100 mm) were membrane-cured for 28, 56, and 90 days, and the specimens were subjected to a loading rate of 0.5 kN/min. The quality of FC was evaluated using the Ultrasonic Pulse Velocity (UPV) test in accordance with ASTM C597-02. The test was performed through direct contact on prismatic samples (160 mm \times 40 mm). One end of the prism was exposed to a 5 Hz ultrasonic pulse wave, while the receiving end captured the wave signal. Higher pulse velocities indicated greater material homogeneity. The pulse velocity was calculated using Equation 2.

Pulse Velocity =
$$\frac{L}{T}$$
 (2)

where; L is Width of the FC specimen (mm), and T is Time taken by the pulse wave to propagate (min).

The water absorption of FC was determined in accordance with ASTM C642 (2006) using 100 mm cube specimens. FC cubes cured for 28 days were oven-dried for 3 days to eliminate residual moisture and then allowed to ventilate at room temperature for 24 hours. The dry weight of the cubes was recorded as Wd. Subsequently, the cubes were immersed in water for 24 hours. After removal from the water bath, the saturated weight of the cubes was recorded as s. The water absorption of FC was calculated using Equation 3.

Water Absorption (%) =
$$\frac{(Ws - Wd)}{Wd} \times 100$$
 (4)

where, Ws, mass of specimen after 24 hr. immersion period (kg), Wd is mass of specimen before immersion period (kg).

The capillary water rise on FC samples was measured as per ASTM C 1585-04, Sliced FC cylinders of 100 mm diameter and 50 mm thick were dried in an oven at $100 \pm 5^{\circ}$ C before being put in a water bath with a water level of 3– 5 mm above the bottom surface as shown in Figure 5. A non-absorbent sealing compound prevented water from entering the cylinder from the outside. Water absorption in 30 minutes was calculated by weighing the sample. The capillary absorption coefficient was calculated using the Equation 4.

$$S = \frac{l}{t^{1/2}} \tag{5}$$

where , *I* is dW/Ay (mm), *S* is sorptivity in mm.sec^(-1/2), *t* is Elapsed time period of experiment (sec), y is density of water (kg/m³), and *dW* is Change in weight of specimen (kg).



Figure 5. Sorptivity test setup

The test apparatus was created as per IS 9489:1980 as shown in Figure 6. Two steel plates were placed to the top and bottom of 100mm cube. The plate above the cube is cold and the plate under direct heat is hot plate. The plate temperature differential was measured with an infrared thermometer. TEG sensors transfer heat energy into electricity. To measure voltage (*V*) and current (*I*), the TEG was connected to a multimeter. Plate to FC cube contact was ensured by providing 2.5 kPa load to the top plate. During testing, the lab temperature was 37°C. If the temperature drops below 35°C, hot air heats the cube sides. Allow the hot plate to heat evenly. When the hot plate hits 500 °C (*T*1), an infrared thermometer is used to record the cool plate temperature (*T*2). Similarly, the temperature change is ($\Delta T = T1 - T2$). The Fourier heat flow equation 5 below calculates specimen thermal conductivity.

$$k = \frac{W}{A} \left(1 \times \frac{d}{\Delta T} \right) \tag{6}$$

where *A* is Contact area of FC cube with the plate (mm²), *d* is Specimen height (mm), *W* is Power generated (Watt) = current (*I*) x voltage (*V*), and ($\Delta T = T1 - T2$) is Temperature difference between hot and cold plates (°C).



Figure 6. Thermal conductivity test setup

4. Results and Discussions

4.1. Spread

The workability of the FC mix was evaluated using a flow test. Figure 7 illustrates the workability results of FC mixes incorporating GP and zeolite as cement replacements at varying foam volumes. At 15% foam volume, the spread diameters were measured as 153 mm, 156 mm, 163.5 mm, 173.5 mm, and 181.5 mm for 0%, 5%, 10%, 15%, 20%, and 25% GP substitutions, respectively. The maximum spread diameter of 181.5 mm was observed at 25% GP substitution, representing a 25.4% increase compared to conventional FC. Similarly, at 30% foam volume, the spread diameters for 5%, 10%, 15%, 20%, and 25% GP substitutions were 1.8%, 8.9%, 16.9%, 26.4%, and 38.6% higher, respectively, than conventional FC. The improved spread can be attributed to the smooth shape of GP, which reduces mortar friction, thereby increasing flowability. Conversely, the use of zeolite as a cement replacement significantly reduced the spread diameters. At 30% foam volume and 25% zeolite substitution, the spread was the lowest, showing reductions of 4.71%, 8.49%, 15.09%, 20.75%, and 22.64% compared to conventional FC for 5%, 10%, 15%, 20%, and 25% zeolite substitutions, respectively. Previous studies have indicated that calcined natural zeolite affects concrete workability due to its high specific surface area, particle agglomeration, zeolitic micropores, and clay impurities [23]. The increased water demand in the FC mix due to these characteristics enhances inter-particle friction and viscosity, thereby reducing the spread diameter. The angular shape and low specific gravity of zeolite also contribute to this reduction. The results demonstrate that the spread diameters varied based on the concentration and surface adsorption properties of the admixtures. Additionally, the mixes with 15% foam volume exhibited higher spread diameters than those with 30% foam volume. The increased foam volume reduced the spread due to the introduction of air into the cement matrix, which enhanced cohesiveness and reduced the overall weight of the FC mix, thereby decreasing workability at higher foam volumes.



Figure 7. Spread of FC with respect to Admixture concentration

4.2. Densities

The density of FC is influenced by the water-to-binder ratio and air void sustainability. Additionally, the size, shape, and distribution of air voids play a crucial role in determining FC density [24]. The relationship between foam volume, admixture proportions, and the air-dry and wet densities of FC mixes is presented in Table 3. With increasing GP substitution, both the plastic (wet) and oven-dry densities of FC showed a slight decrease. The air-dry density of all FC mixes containing GP ranged from 1204 kg/m³ to 1475.5 kg/m³. At 25% GP substitution, the air-dry density decreased by 2–3% compared to plain FC for both foam volumes. This observation aligns with findings by Khan et al. attributed the reduction in density to the lower density of GP relative to cement. Consequently, FC made with GP exhibited lower densities than conventional FC. The difference between wet and dry densities for FC with 15% foam volume was approximately 50±10 kg/m³. However, for FC with 30% foam volume, this difference was significantly larger. Substitution of cement with zeolite further reduced the wet and dry densities of FC. The highest air-dry density, 1473 kg/m³, was observed at 5% zeolite substitution with 15% foam volume, while the lowest, 1187 kg/m³, occurred at 25% zeolite substitution with 30% foam volume. Compared to conventional FC, the oven-dry density decreased by 4% at 30% foam volume with 25% zeolite substitution. The reduction in density with higher zeolite content can be attributed to the material's lower specific gravity and its porous structure [25]. Zeolite high alumina content enhances its water retention capacity within its pores, thereby reducing the free water available in the mix. This phenomenon increases foam fragmentation and leads to insufficient water content in the mixture. Consequently, macro voids are introduced during mixing and casting, further affecting the FC density.

	Plastic Density (kg/m ³)				Air Dry Density (kg/m ³)			
Mix Id	GP		Zeolite		GP		Zeolite	
	FV 15%	FV 30%	FV 15%	FV 30%	FV 15%	FV 30%	FV 15%	FV 30%
0	1523	1275	1523	1275	1475.5	1232	1475.5	1232
5	1512	1268	1521.5	1272	1468.5	1224	1473.5	1214
10	1506.5	1263	1518	1268	1463.5	1219	1469.5	1209
15	1502	1254	1516	1261	1458.5	1212	1466.5	1201
20	1498.5	1252	1511.5	1254	1454.5	1209	1462.5	1193
25	1489.5	1248	1507	1249	1446	1204	1457	1187

Table 3. Plastic density and air dry density of FC with various admixture concentrations

4.3. Hard State Characteristics

4.3.1. Compressive Strength

The average compressive strength values observed with the progressive addition of GP (glass powder) as a substitute for cement at various percentages and foam volumes are presented in Figure 8. The highest compressive strength of 15.56 MPa was achieved after 90 days of curing when 10% GP was substituted at a foam volume of 15%. Beyond this substitution level, a modest decline in strength was observed. At a foam volume of 30%, the highest compressive strength after 90 days was 10.91 MPa when 20% GP was substituted. Further increases in GP replacement resulted in reduced strength values.

Even at lower densities, FC with GP replacement demonstrates superior compressive strength. The enhanced compressive strength in FC to the combined influence of the pozzolanic action and filler effect of GP. Throughout the process of hydration, the pore solution of cement becomes rich in Ca2⁺, SiO4²⁻, and OH⁻ ions. The pore solution has the ability to dissolve the amorphous silica in GP, leading to the creation of a Si-rich layer on the surface of GP. Upon exposure to Ca_2^+ ions, this layer undergoes a transformation into a CSH gel. The CSH gel enhances the compressive strength of FC. Nevertheless, the level of hydration was contingent upon the amount of cement present. Exceeding the appropriate level of GP content reduces the amount of accessible Ca_2^+ ion and lowers the pH in the pore solution, resulting in a drop in the hydration of FC. Similarly, the increase in foam volume diminishes the interaction between the silicon-rich layer on the surface of GP and the calcium ions, leading to a decline in the creation of C-S-H gel. Therefore, the highest foam volume was achieved when 10% and 20% of the GP was substituted at the respective foam volumes. Few studies found similar results when substituting GP in conventional concrete [25, 26]. The substitution of GP in the FC resulted in a decrease in early age strength (7 days strength) due to the delayed Pozzolanic reaction [27]. The water absorption property of GP was observed to be less than cement [28], consequently the foam breakage will be very minimum during mixing as a result of it density of the concrete was maintained or very low density drop was detected with GP addition. Hence, it is evident from the test results that the strength of FC with GP concentration depends on foam volume. Further, the compressive strength reduction happened after the optimal GP dose, indicating lack of hydration.

The 90-day compressive strength of the conventional FC was decreased when cement was substituted with zeolite. A 25% replacement of cement with zeolite resulted in strength reductions of 50% and 61.2% after 90 days for 15% and 30% foam volumes respectively. An augmentation in the degree of decrease was seen with the introduction of zeolite. The honeycomb structure and high specific surface area of zeolite allowed it to absorb excess water, causing the zeolite particles to become denser. This led to an inadequate distribution of air gaps and a decrease in the pozzolanic activity

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of binders. Moreover, the augmentation of zeolite concentration hinders the process of cement hydration and diminishes the initial strength at early stages. The attainment of strength in later age was relatively greater. The pozzolanic interactions between SiO_2 and Al_2O_3 in zeolite and CH result in the formation of C-S-H gels and C-A-H gels. These reactions have a significant role in enhancing the later age compressive strength of concrete [26]. Karakurt et al. provided a rationale for the decrease in density and compressive strength of autoclaved aerated concrete when calcinated natural zeolite is added [27]. Zeolite has strong affinity to water, which decreases the water available in the mix; this leads to the density reduction as a result of macro holes formation in the mix. The correlation between the density and 28-day compressive strength of GP and zeolite in FC is illustrated in Figure 9.



Figure 8. FC Compressive Strength with respect to Admixture Concentration at various Foam Volume



Figure 9. FC Compressive Strength with respect to dry density

4.3.2. UPV

Figure 10 illustrates the variation in ultrasonic pulse velocity (UPV) values with respect to different FC admixtures. The inclusion of GP (glass powder) resulted in enhanced UPV values, indicating improved interlocking of mineral admixtures with the cement matrix in FC. This interlocking effect contributed to an increase in UPV. As the GP concentration in FC increased, the mechanical strength and stiffness of the FC also improved. Conversely, the test findings revealed that zeolite replacement led to a decrease in UPV values. For FC mixes containing zeolite, the UPV increased with density, and a reduction in density resulted in lower UPV values. Similar observations have been reported in previous studies on FC subjected to UPV testing [29]. The improvement in UPV values with GP inclusion, despite the reduction in density, can be attributed to factors such as solid pore wall boundaries, paste complexity, and homogeneous void distribution. However, at 25% GP replacement for both foam volumes, a reduction in UPV was observed. This trend is consistent with the findings from compressive strength tests, where the UPV values were lower compared to those of conventional FC.



Figure 10. UPV with respect to Admixture substitution

Figure 11 showed that there is a high dependency between the UPV values and the density of the FC mixes when zeolite substitution takes place. The density drop is proportional to the drop in UPV values. Whereas on substituting cement with GP even at lower density of the FC the UPV values were higher, this ensures the integrity of the cement matrix.



Figure 11. UPV variation with respect to density of FC

4.3.3. Water Absorption

Figure 12 depicts the water absorption characteristics of FC combinations with GP and zeolite replacements across varying foam volumes. Substituting GP resulted in reduced water absorption. The lowest water absorption values were 5.09% and 8.6% for 15% and 30% foam volumes, respectively, when 25% GP was substituted. These values represented reductions of 26.33% and 14.68%, respectively, compared to conventional FC at the corresponding foam volumes. The decrease in water absorption with GP substitution can be attributed to a reduction in permeable pores, as evidenced by the lower dry densities associated with GP inclusion. This demonstrates that GP contributes to a denser microstructure in FC, effectively lowering its permeability. In contrast, FC with 25% zeolite substitution absorbed 7.57% and 10.71% of water at 15% and 30% foam volumes, respectively. Zeolite replacement was found to increase water absorption uniformly across foam volumes. Valipour et al. similarly observed that natural zeolite enhances water absorption compared to cement [30]. This increase is attributed to the higher porosity and water retention capability of zeolite. The increased water absorption reflects the filling of FC voids with water, a phenomenon influenced by the quantity and distribution of interlinked and isolated air spaces. The observed variations in water absorption values in FC are therefore closely tied to the internal pore structure and connectivity.



Figure 12. Water absorption with respect to admixture concentration

4.3.4. Sorptivity

The durability of FC is significantly influenced by its sorptivity characteristics, particularly as exterior wall panels are often exposed to high humidity and rainy climates. The study of FC sorptivity evaluates its performance in such applications. Figure 13 illustrates the reduction in sorptivity values with an increase in GP concentration in FC. At a 25% GP replacement level, the sorptivity values were 0.36 mm/min and 0.25 mm/min for foam volumes of 15% and 30%, respectively. These values represent reductions of 39.49% and 47.91%, respectively, compared to conventional FC. This reduction can be attributed to the distinct boundaries of air bubbles, which hinder water absorption in FC with GP. Additionally, the presence of entrapped pores decreases the volume of paste, leading to a reduction in the number of capillary openings. The increase in foam volume further contributes to the reduction in sorptivity. The lower sorptivity and water absorption values highlight the superior water repellence of FC with GP replacement, demonstrating exceptional resistance to moisture. In contrast, the sorptivity values increased as the zeolite substitution level rose. When 25% zeolite was substituted, the sorptivity increased by 11.67% and 10.41% for foam volumes of 15% and 30%, respectively. The percentage increase was more pronounced at lower foam volumes compared to higher ones. Similar findings have been reported, indicating enhancements in sorptivity properties of concrete containing natural zeolite [30, 31]. The increased sorptivity in FC with zeolite replacement is attributed to the microstructure of zeolite and its higher dosage levels. Once the microvoids within the zeolite are saturated with water, the FC surface becomes less capable of absorbing additional water, leading to a reduction in capillary absorption over time.



Figure 13. Sorptivity variations with admixture concentration

4.3.5. Thermal Conductivity

Figure 14 illustrates the relationship between the proportion of GP and zeolite substitutions in FC and its thermal conductivity. Increasing the GP replacement in FC at a fixed foam volume resulted in a reduction in thermal conductivity. The lowest thermal conductivity was observed in mixes with 25% GP replacement. Specifically, at foam volumes of 15% and 30%, the thermal conductivity was reduced by 17.9% and 21.25%, respectively, compared to conventional FC. This reduction is attributed to alterations in the microstructural properties and a decrease in density. Figure 15 highlights the correlation between thermal conductivity and dry density in FC with GP [32]. The graph clearly indicates that the thermal conductivity of FC with GP replacement is strongly influenced by its dry density. Microstructural changes that contribute to density reduction also impact the thermal conductivity of FC. For FC with 25% zeolite replacement, the thermal conductivity values were measured at 0.365 W/mK and 0.18 W/mK for foam volumes of 15% and 30%, respectively. These values represent reductions of 37.6% and 52% compared to plain FC. The rate of thermal conductivity reduction increased proportionally with foam volume. This pronounced reduction is attributed to the high specific heat capacity of zeolite and the low density of FC containing zeolite, which collectively reduce thermal conductivity more effectively [33].



Figure 14. Thermal conductivity variations with admixture concentration



Figure 15. FC Thermal conductivity variations with respect to dry density

5. Cost / Benefit Analysis

A cost analysis was conducted to evaluate the economic benefits of incorporating GP and zeolite as supplementary cementitious admixtures (SCA) in the production of FC. Table 4 presents the manufacturing cost for one cubic meter of FC at a foam volume of 15%. The analysis revealed that substituting cement with SCAs significantly reduces production costs and lowers cement consumption. From an environmental perspective, this approach offers a sustainable solution to address the challenges associated with CO2 emissions resulting from cement production. By using waste-derived SCAs as a partial replacement for cement, the environmental impact of FC manufacturing can be mitigated in a costeffective manner.

1 able 4. Cost analysis								
Mix	Materials Used	Price / Unit (INR)	Quantity (/m ³)	Cost (INR)				
FC	Cement	380/50 kg bag	665 kg	5054				
	Water	215/ kilo litre	200 kg	43				
	Foaming Agent	2500/20L	10 L	1250				
	Sand	55/ kg	1330 kg	73150				
	Energy consumption	7.75 / kWh	1 kWh	7.75				
	Total Cost							
GP 20 FC	Cement	380/50 kg bag	532 kg	4043.2				
	Water	215/ kilo litre	200 kg	43				
	Foaming Agent	2500/20L	10 L	1250				
	Sand	55/kg	1330 kg	73150				
	Energy consumption (crushing and grinding)	7.75 / kWh	3.15 kWh/kg	24.41				
	Total Cost							
Z 25 FC	Cement	380/50 kg bag	498.75 kg	3790.5				
	Water	215/ kilo litre	200 kg	43				
	Foaming Agent	2500/20L	10 L	1250				
	Sand	55/kg	1330 kg	73150				
	Energy consumption (calcination)	7.7 / kWh	1 kWh	7.7				
Total Cost								

6. Conclusions

The strength and performance of FC with two distinct admixtures, Glass Powder (GP) and Zeolite, were compared with conventional Foamed Concrete (FC). Cement in FC was replaced with GP and Zeolite at varying concentrations, and the foam volume was adjusted to 15% and 30% of the total volume. To assess the fresh state characteristics, tests on spreadability and plastic densities were performed. Strength and performance were evaluated using compressive strength, ultrasonic pulse velocity (UPV), water absorption, sorptivity, and thermal conductivity tests. Based on the findings, the following conclusions were drawn:

- Workability: The workability of FC improved significantly with GP substitution. Higher GP concentrations increased the spreadability, making FC suitable for practical void-filling applications. This was accompanied by a notable reduction in density. Conversely, zeolite substitution reduced the spreadability of FC, limiting its applicability in obstructed shuttering zones.
- Strength-to-Density Ratio: A superior strength-to-density ratio was achieved with 10% GP substitution at 15% foam volume and with 20% GP substitution at 30% foam volume. In contrast, FC containing zeolite exhibited a reduction in strength.
- Durability and Thermal Properties: The incorporation of GP significantly enhanced FC's thermal conductivity, water absorption, and sorptivity properties. Zeolite substitution reduced thermal conductivity but did not positively influence other parameters. Substituting up to 25% of the cement with GP proved to reduce cement consumption while producing high-quality FC suitable for future construction practices.
- Cost Efficiency: The cost analysis revealed that the use of admixtures reduced the production cost of 1 m³ of FC by 1.2% to 1.5%. Substantial cost savings are expected in large-scale concreting applications.
- Sustainability and Recommendations: This study advocates the use of GP as a cement substitute in FC to promote sustainable construction practices. To optimize FC performance, GP substitution is recommended at up to 25%. Specifically, 10% GP for 15% foam volume and 20% GP for 30% foam volume showed positive effects on strength parameters. Further research is encouraged to explore the microstructural behavior and expansion/shrinkage characteristics of FC with GP admixtures.

7. Declarations

7.1. Author Contributions

Conceptualization, P.K.K. and M.A.K.; methodology, D.Q.; software, A.A.; validation, P.K.K., M.A.K., and D.Q.; investigation, P.K.K.; data curation, M.A.K.; writing—original draft preparation, P.K.K.; writing—review and editing, P.K.K.; supervision, M.A.K.; project administration, P.K.K. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data sharing is not applicable to this article.

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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