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# INCORPORATING FLY ASH CENOSPHERE (FAC) AS A PARTIAL REPLACEMENT FOR FINE AGGREGATES INTO CEMENT MORTAR

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**Abstract:** An experimental investigation is carried out to assess the properties of Fly Ash Cenosphere (FAC) based cement mortar in producing Lightweight cement mortar. The physical, morphological, chemical, and mineralogical properties of FAC are analyzed from the lab investigations. FAC's impact on cement mortar properties with varying percentages of FAC replacing manufactured sand and with varying curing duration is studied. The strength of FAC-based cement mortar is analyzed in terms of a specific strength which provides a comparable relation of compressive strength and density of mortar in the production of lightweight mortar. The density of the cement mortar gradually reduces with the increase in the FAC content. At the same time, the initial decrease in strength was observed, followed by an increase in strength up to 15% replacement. A further reduction in strength occurred up to 30%. However, there was a significant increase in strength after 30% replacement, reaching an optimal level at 60% replacement. No considerable increase in strength was observed at later-age of cement mortar.

***Keywords:*** *Fly Ash Cenosphere, Cement mortar, morphology, Specific strength.*

## 1. Introduction

Various waste materials have been explored for their viability in substituting natural sand with alternative materials as fine aggregates. Some waste materials studied include manufactured sand (M-sand), steel slag, copper slag, and sheet glass powder. Out of these, M-sand has emerged as a favourable alternative due to its suitability and widespread availability. An elevation in the percentage of M-sand was associated with a corresponding increase in elastic modulus and compressive strength. M-sand is recommended as an alternative to natural fine aggregate manufacturing high-strength mortar [1].

[2] Showcased improved workability and drastic bleeding of blended sand (M-sand + offshore sand) compared to conventional mortar. More paste will be needed to achieve adequate flowability and strength when crushed fine aggregates are used instead of natural sand [3, 4, 5]. [6] Concluded that the increase in the cement replacement led to an increase in the apparent porosity and a decrease in the strength of the mortar after 28 days of curing. [7] Concluded that the compressive strength of the ternary blend cement mortar mix is higher

than the binary and control cement mortar due to the packing of finer particles and the pozzolanic reaction.
Fly Ash Cenospheres (FAC) are extracted from fly ash, a by-product of coal-powered thermal plants. The color of FAC is greyish-white, and the chemical composition is almost similar to that of fly ash [8]. The properties of FAC may vary from batch to batch, even from the same power plant [9]. Various authors studied the extraction process of FAC from fly ash [10, 11] and found that a combination of wet sieve and air classification is efficient. The quality of the cenospheres can be improved by an acetone-water mixture [12].
There have been numerous studies [13, 14, 15, 16, 17, 18, 19, 20, 21] carried out to understand the physical properties of FAC indicating the Bulk density and specific surface area of FAC to be in the range of 400-800 kg/m3 and 2.50–6.02 m2/g respectively. The investigation by [13] and [17] reveals that a noteworthy portion of the particles falls within the 50–400 μm range, while close to 5% of particles exceed 400 μm in size [13]. The bulk density of FAC was compared with the lightweight aggregate by [22, 23], who ascertained that FACs could be used to produce structural lightweight concrete with a unit weight of less than 1900 kg/m3. Many have investigated the chemical composition of FAC [24, 14, 15, 25] using X-ray fluorescence (XRF), it was discovered that Silicon Dioxide and aluminium oxide composed a predominant part together (81-93.08 %).
The specific strength of FAC-based cement composite ranged from 34.69 – 24.11 kPa-m3/kg, and the compressive, flexural, and tensile strengths over a 28-day curing period, yielded values within the ranges of 55.92–30.38 MPa, 9.29–5.38 MPa, and 3.51–1.66 MPa, respectively [13,14] observed elevated specific strength (18.39 - 26.65 kPam3/kg), increased flexural strength (14.47 - 28.13 MPa), and enhanced tensile strength (5.69 - 11.06 MPa) through the inclusion of FAC. Even though the microstructure of the FACC is porous, the lack of interconnectivity among the pores results in a decrease in overall permeability [15, 26] stated that, with a 10 wt. % filler addition, there was a reduction of nearly 7.5% in tensile strength and nearly 20% in flexural strength compared to composites without filler loading. The density, compressive strength, and flexural strength of the ULCC were found to be 1474 kg/m3, 68.2 MPa, and 8 MPa, respectively [27]. The natural frequency was reduced with the increase in the FAC content, and Young's modulus increased with the FAC content by up to 35% and gradually decreased beyond 35% [15]. Polymer composite reinforced with 35% FAC has given good results. The adequate weight fraction of FAC was 55% [28]. The addition of FAC effectively reduced the thermal conductivity and density and enhanced the rheological characteristics of the concrete. Robust FAC shells acted as barriers to impede the propagation of cracks [29].
Among various alternative materials, FAC proves to be a suitable filler material in the manufacture of cement composite with a lightweight formulation. Studies on FAC procured from thermal power plants located in India are limited. Studies on the appropriateness of using FAC as a substitute for fine aggregates within cement mortar are limited. The behavior of Indian FAC within the cement composites has not undergone a thorough investigation completely.

## 2. Material properties

This study employed the use of Ordinary Portland cement (OPC), Fly ash cenosphere (FAC), and Manufactured sand (M-sand). The physical properties of FAC along with morphology, and chemical and mineral composition of FAC are investigated. Further, the methodology to investigate the effect of replacing M-Sand with FAC on the properties of cement mortar with varying mix proportions is presented.

**2.1. Physical properties of FAC and M-sand.**

The physical properties of FAC as well as M-Sand are summarised in Table 1. A major observation from the lab test was the low specific gravity and bulk density of FAC in comparison to M-sand. This property of FAC will impact the density of FAC-incorporated cement composites. The compacted bulk density of FAC was found to be 454 kg/m$^3$ which is less than that of M-sand.

Table 1: Physical properties of FAC and M-sand

| Sl. No. | Characteristics | FAC | MSand |
|---|---|---|---|
| 1 | Fineness modulus | 2.68 | 4.47 |
| 2 | Specific gravity | 0.698 | 2.65 |
| 3 | Bulk density<br>• Loose bulk density<br>• Compacted bulk density | <br>387.3 kg/m$^3$<br>424.6 kg/m$^3$ | <br>1564 kg/m$^3$<br>1900 kg/m$^3$ |
| 4 | Voids percentage<br>• Loosely packed FAC<br>• Compacted FAC | <br>44.5<br>35.77 | <br>40.9<br>28.3 |

The particle size distribution of FAC and M-sand were determined and the particle size distribution curves are shown in Fig 1 and 2. From the particle size distribution curve obtained from the sieve analysis, FAC contained a higher percentage of fines compared to M-sand.

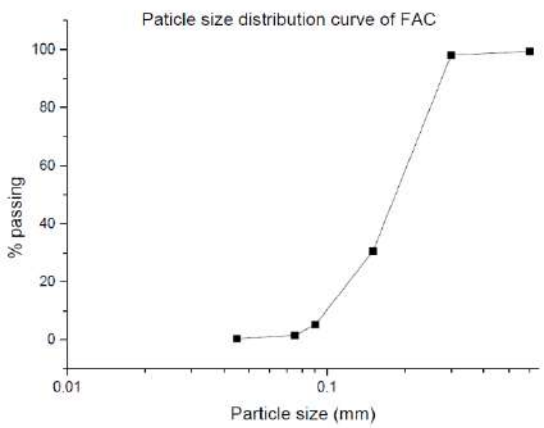


Fig. 1: Particle size distribution of FAC.

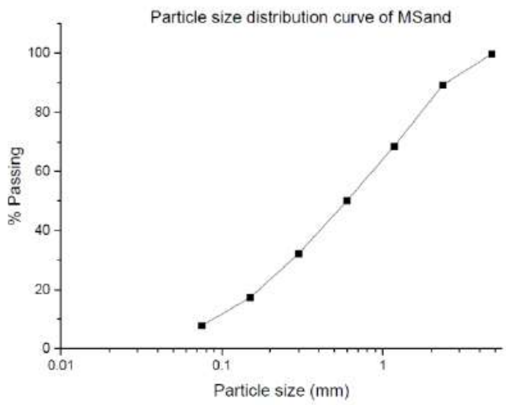


Fig. 2: Particle size distribution of M-Sand

**2.2. Morphology of FAC**

To understand the shape and size of FAC, the material was subjected to SEM analysis and the microscopic images at our lab as displayed in Fig. 3 (a, b, and c). It was observed that FAC particles exhibit a spherical shape and possess a smooth texture. From SEM images and results of sieve analysis, the size range of FAC was noted to fluctuate from 1–600 µm.

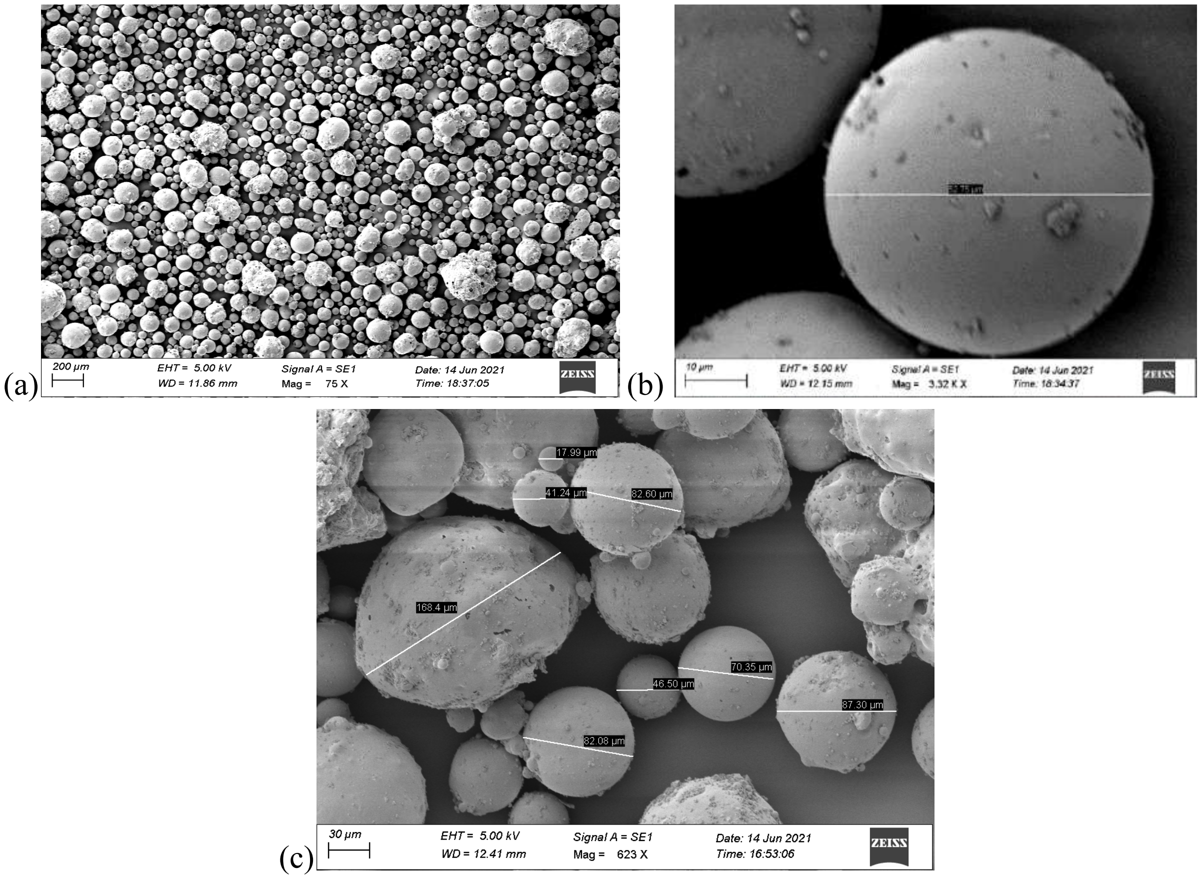



Fig. 3: SEM image of FAC at (a) 75x, (b) 3320x and (c) 623x

### 2.3. Chemical and mineral composition of FAC

A sample of FAC was subjected to energy-dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) analysis to obtain and study the chemical composition of FAC as well as phase mineral composition. The obtained results are presented in Tables 2 and fig. 3. From the results of the EDS analysis, it was noted that the presence of aluminium oxide and silicon dioxide are predominant in FAC. From the XRD results (fig. 4) it was observed that mullite and quartz were predominant compounds in FAC indicating the major portion of alumina and silica minerals in FAC.

Table 2: Chemical composition of FAC

| **Description** | | **Percentage content (%)** |
|---|---|---|
| $Al_2O_3$ | Aluminium oxide | 36.55 |
| $SiO_2$ | Silicon dioxide | 50.08 |
| $K_2O$ | Potassium oxide | 6.26 |
| $Fe_2O_3$ | Ferric oxide | 3.70 |
| $Na_2O$ | Sodium oxide | 1.52 |
| MgO | Magnesium oxide | 1.27 |

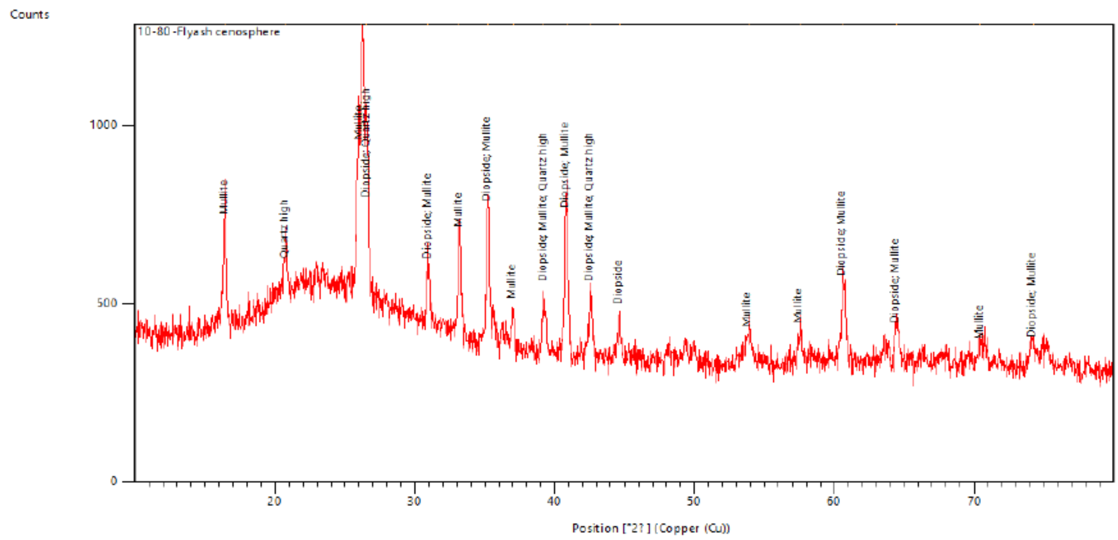



Fig. 4: XRD analysis of FAC.

## 3. Methodology

To examine the impact of FAC on the properties of cement mortar having a cement-fine aggregate ratio of 1:3 and water-cement ratio of 0.6, seven distinct mixes were prepared with varying percentages of FAC replacing manufactured sand (M-sand). The experimentation began with a baseline mix containing 0% FAC, progressively introducing FAC in 5% increments (5%, 10%, 15%, 20%, 25%, and 30%). 168 mortar cubes with 70.6 mm sides were cast and cured for 3, 7, 14, 28, 56, 90, 180, and 365 days. The workability of fresh mortar mixes with different percentages of FAC replacement was assessed by performing a flow table test. Each cube was weighed to determine the density of hardened specimens. Subsequently, the cubes were subjected to testing under a Universal Testing Machine (UTM) for the determination of compressive strength.

Similarly, 18 distinct mixes were formulated by altering the cement-to-mortar ratio (1:1, 1:2, 1:3, 1:4, 1:5, and 1:6) and the percentage replacement of FAC (0, 5, and 10) to examine the impact of FAC on mixes with different cement-to-mortar ratios. The compressive strength of the water-cured specimens was determined. Furthermore, an additional 18 mixes were prepared to recognize the water-to-cement ratio necessary to accomplish a 110% flow for various combinations of cement-to-mortar ratios (1:1, 1:2, 1:3, 1:4, 1:5, and 1:6) and percentage replacement of FAC (0, 5, and 10).

To investigate the behaviour of cement mortar incorporating high volumes of FAC, M-sand was progressively replaced with FAC at intervals of 10%, ranging from 0% to 100% replacement. The study examined compressive strength, flow variation, density variation, specific strength, water absorption, and thermal conductivity.

## 4. Results and discussions

The results of the investigation carried out on the workability, density, compressive strength, and specific strength carried out on the FAC-based cement mortar are presented in the following sections.

### 4.1. Workability and Density

It was observed that the flow rate initially decreased with the increase in the % of replaced fine aggregate up to 5% FAC content (Fig. 5). Thereafter, the workability gradually increased with the increase in the % of FAC content. At 30% FAC content replacement, the flow rate exceeded that of the cement mortar without FAC. The initial decline in flow rate in cement mortar mixes with lower FAC replacement percentages may be ascribed to the higher fine content in the FAC. Similarly same trend was observed while studying 100% replacement of FAC as shown in Fig. 6, gradually the flow rate increased till 60% and declining further after. The study investigated the water-cement ratio needed to achieve a 110% flow rate in various mortar mixes with different cement-to-fine aggregate ratios (Fig. 9). The findings revealed that the water-cement ratio increased proportionally to the increased fine aggregate content in the mortar mix. The density of the cement mortar cubes was measured, and for the interpretation, the density of the cubes cured for 28 days was chosen since the density variation was found to be consistent across all other curing durations (Fig. 7). It was observed that incorporating FAC in mortar mixes led to a reduction in the density making it a lightweight cement mortar, mainly attributed to the low specific gravity of FAC, thereby reducing the weight of the mix. Similar trend war observed while studying 100% replacement of FAC (Fig. 8). The study examined how the density changes with different cement-to-fine aggregate ratios (Fig. 10), revealing that the density of cement mortar decreases as the fine aggregate content increases. The graph below illustrates the variations in flow rates and density for cement mortar mixes with varying percentages of fine aggregate content as shown in Figs. 9 & 10.

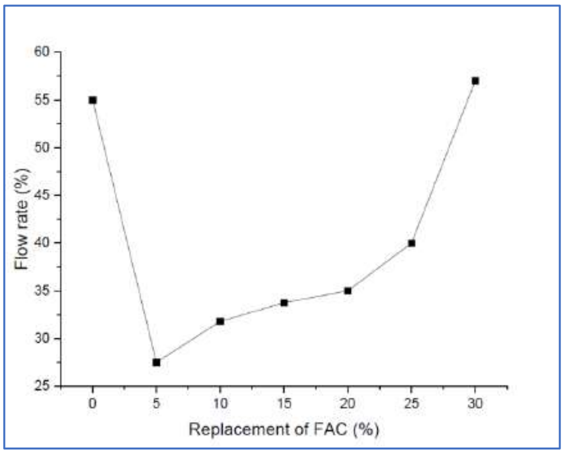



Fig 5: Variation of flow rate (upto 30%)

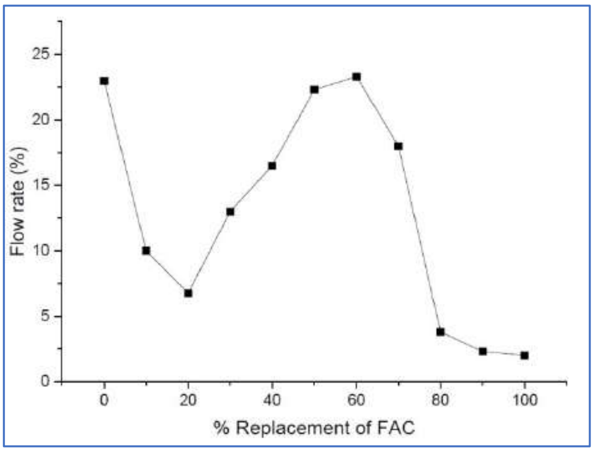
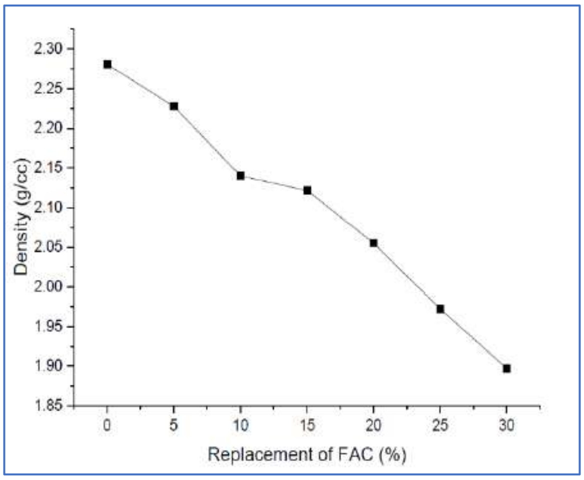



Fig 6: Variation of flow rate (upto 100%)



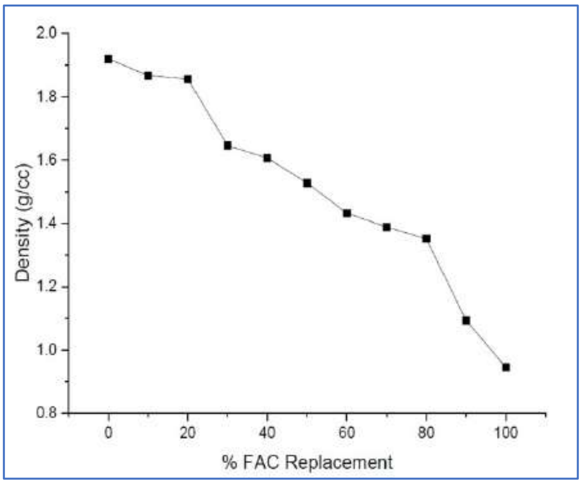



Fig 7: Variation of density (upto 30%)

Fig 8: Variation of density (upto 100%)

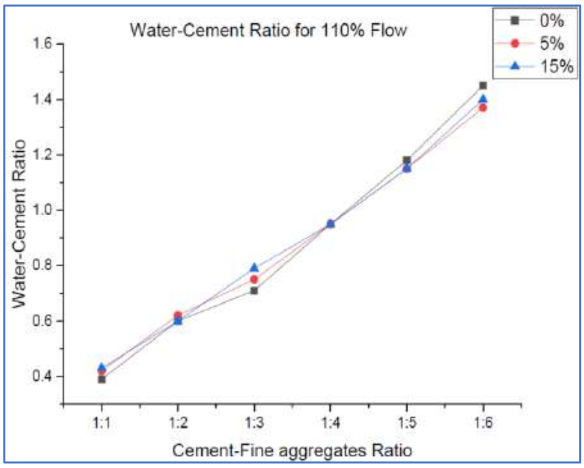



Fig 9: Water-cement ratio for 110% flow

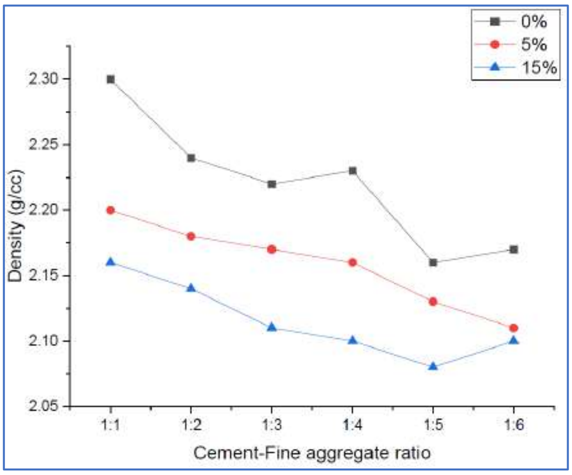



Fig 10: Variation of density (C-FA ratio)

### 4.2. Compressive strength

It was observed that including FAC resulted in a reduction in compressive strength. Though there was a decrease in strength when replaced at 5%, the compressive strength exhibited a considerable rise at 10% and 15%, only to decrease once more with higher FAC content (Fig. 11). Notably, the 15% replacement demonstrated better results in comparison with other variations. The initial decrease in compressive strength can be attributed to the higher percentage of fines present in FAC and the decrease in the later-on strength can be attributed to the increase in pores in the mix. During the investigation of cement mortar with full replacement of M-sand by FAC, a similar trend was observed up to 30% replacement. Beyond that, a gradual increase in strength was noted from 30% to 70%, followed by a decline in the strength thereafter (Fig 12).

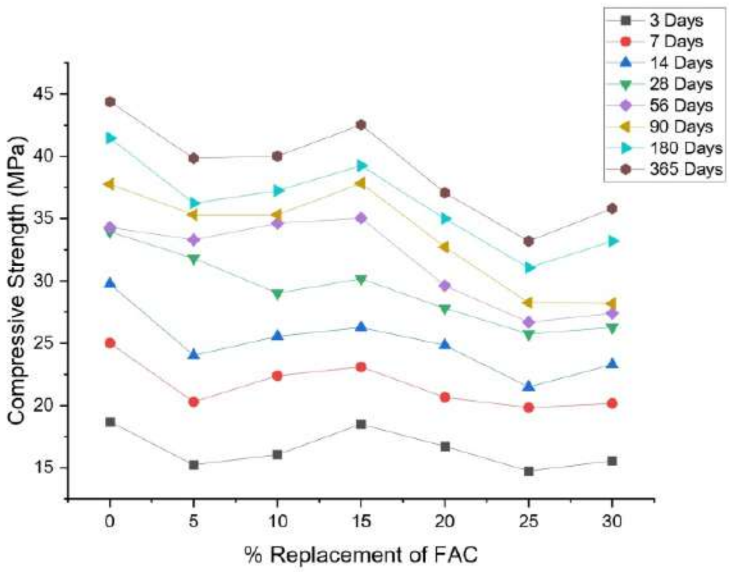



Fig 11: Variation of compressive strength (upto 30%)

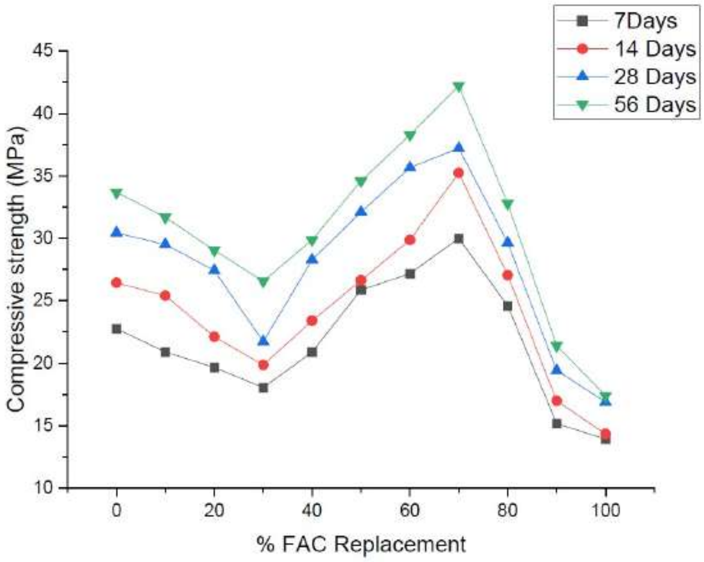
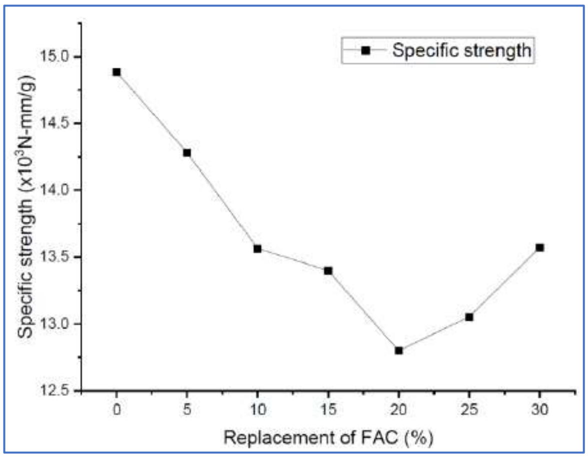



Fig 12: Variation of compressive strength (upto 100%)

**4.3.Specific strength**

The gradual reduction in the specific strength ratio was observed with the increase in the FAC up to 20% replacement thereby increasing the specific strength of cement mortar by more than 20% FAC replacement (Fig. 13). The addition of FAC leads to lighter mortar, reducing the mortar strength considerably. Once the percentage of FAC crossed 20%, the specific strength increased due to the strength of unbroken FAC particles. The impact of FAC on mortar with varying cement to fine aggregate ratio was studied by assessing the strength under compression of mortar cubes with 5% and 15% replacement of FAC (Fig. 15). The tested samples exhibited minimal variation. Specific strength of the specimens with higher replacements of FAC showed similar results till 30% and increased till 70% and further reduction in the specific strength, 70% replacement being the optimum value (Fig. 14).



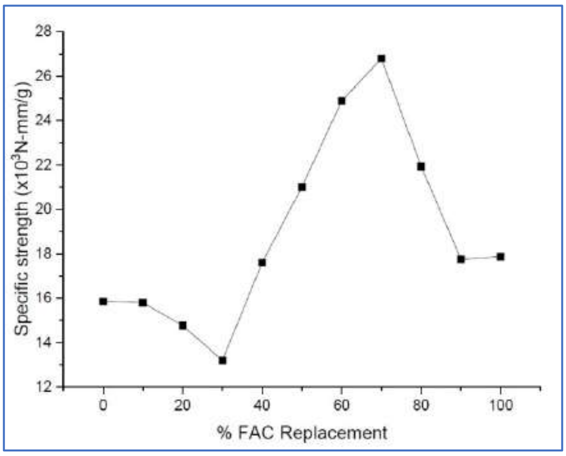




Fig 13: Specific strength (upto 30%). Fig 14: Specific strength (upto 100%).

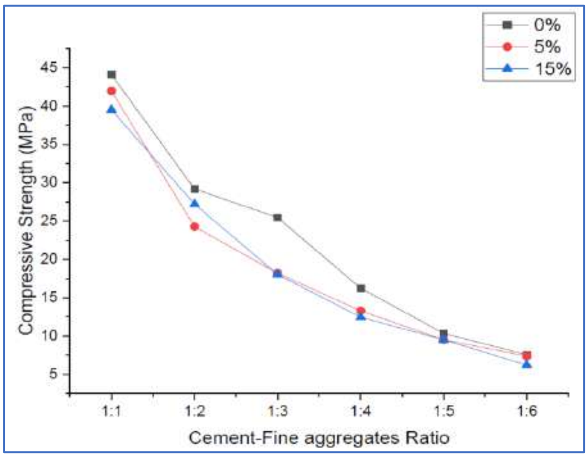
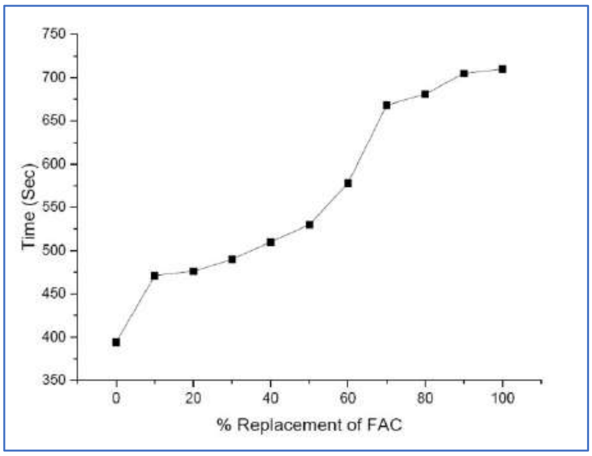



Fig 15: Compressive strength (C-FA ratio).

## 4.4.Thermal conductivity and Water absorption

In terms of thermal conductivity, the cement mortar containing FAC demonstrated favourable outcomes (Fig. 16). As FAC was added to the mortar, the time it took for heat to transfer from one point to another progressively increased. FAC particles have a hollow, spherical shape. When these particles are mixed into the mortar, they create small air pockets or voids, which make the mortar porous. However, the pores are not interconnected, meaning that the air pockets formed by the FAC are isolated from each other. This prevents continuous pathways for heat, moisture, or other materials to easily pass through; contributing to the mortar's insulating properties. This indicates that the incorporation of FAC effectively reduced the mortar's thermal conductivity, making it a more efficient insulator by slowing down heat transfer. This property can be beneficial in applications where thermal resistance is desired, such as in energy-efficient construction materials.



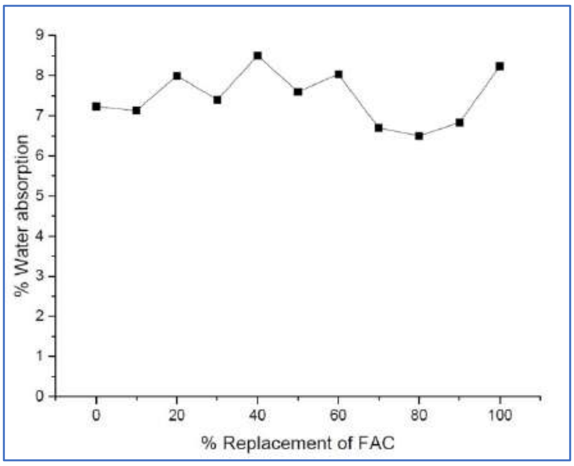




Fig 16: Variation in thermal conductivity Fig 17: Variation in water absorption

There are minor fluctuations, with water absorption slightly increasing and decreasing at different points (Fig. 17), but no drastic changes are observed across the range of FAC replacement. This suggests that while the introduction of FAC makes the mortar more porous (due to its hollow structure), the overall effect on water absorption remains fairly consistent across different FAC replacement levels. The non-interconnected nature of the pores could be a reason why the water absorption remains relatively stable despite the porous structure of the mortar. The isolated pores created by the FAC may limit the amount of water the material can absorb, preventing large variations in water absorption as the percentage of FAC increases.

## 5. Conclusions

The investigation of incorporating Fly Ash Cenosphere (FAC) in cement mortar was carried out for different proportions of fine aggregates replaced with FAC. The physical properties of FAC are analysed by lab testing and its effect on the properties of cement mortar with different percentages of FAC is investigated. The conclusions from the lab investigation are as follows:

- The flow rate is optimal at around 60% FAC replacement, with values peaking near 25%. However, beyond 60% replacement, the flow rate drops dramatically, suggesting that higher FAC replacement negatively affects flowability, attributed to the higher fines content in FAC.
- The density decreases as the percentage of FAC replacement increases, indicating that higher FAC content leads to lower density.
- For all curing times, the compressive strength initially decreases with increasing FAC replacement until around 40-50%, after which it significantly increases and peaks at 70% replacement. 70 % replacement being the optimum value.
- Specific strength calculations from experimental results indicated a decline in specific strength with FAC replacement up to 20%, followed by an increase in specific strength in replacements upto 70%.
- The investigation on the impact of FAC on mortar with varying cement-to-fine aggregate ratios, using 5% and 15% FAC replacement, showed minimal variation in compressive strength in the tested samples.
- The addition of FAC to cement mortar demonstrated favourable effects on thermal conductivity, making it a promising alternative for manufacturing thermal insulating components.
- Addition of FAC in the cement mortar did not influence water absorption property of the mortar.

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