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COMPRESSIVE STRENGTH OF CONCRETE PARTIALLY REPLACED WITH CENOSPHERE AND SILICA FUME

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ABSTRACT

The present study investigates the compressive strength characteristics of concrete in which cement is partially replaced with cenosphere and silica fume. The primary objective is to evaluate the combined effect of these supplementary materials on strength performance and to identify an optimum replacement level for sustainable concrete production. Cenosphere, a lightweight by-product obtained from thermal power plants, and silica fume, a highly reactive pozzolanic material, were used in varying proportions to replace cement. The incorporation of cenosphere leads to a reduction in compressive strength as its percentage increases, primarily due to its hollow structure, lower density, and weaker bonding properties compared to cement. However, when used in combination, silica fume compensates for the strength reduction caused by cenosphere to a certain extent. At optimum replacement levels, the concrete exhibits satisfactory compressive strength along with reduced density, making it suitable for lightweight structural applications. The improved particle packing and refinement of pore structure also contribute to enhanced performance. The study concludes that a balanced proportion of cenosphere (5%) and silica fume (10%) can produce eco-friendly concrete with acceptable strength properties. The results highlight the potential of utilizing industrial waste materials effectively, reducing cement consumption, and promoting sustainable construction practices without significantly compromising mechanical performance.

Keywords: Cenosphere; Silica Fume; Compressive Strength; Partial Cement Replacement; Lightweight Concrete; Pozzolanic Reaction; Sustainable Concrete; Industrial By-products; Microstructure; Strength Optimization

1. INTRODUCTION

Concrete is the most widely used construction material due to its versatility, strength, and durability. However, the high consumption of cement contributes significantly to environmental pollution through carbon dioxide emissions. In recent years, the incorporation of industrial by-products such as cenosphere and silica fume as partial replacements for cement has gained attention in sustainable construction practices [1-30]. These materials not only reduce environmental impact but also influence the compressive strength and overall performance of concrete.

Cenospheres are lightweight, hollow alumina silicate microspheres obtained as a by-product of coal combustion in thermal power plants. Due to their low density and spherical shape, cenospheres improve workability and reduce the self-weight of concrete. However, their effect on compressive strength is complex. Studies indicate that increasing cenosphere content generally reduces compressive strength due to increased porosity and void formation. For instance, research shows that compressive strength decreases progressively with higher cenosphere replacement levels, with reductions up to about 26% at 30% replacement after 28 days. Despite this reduction, acceptable strength can still be achieved within certain limits, making cenosphere suitable for lightweight structural applications.

Silica fume, on the other hand, is an ultrafine pozzolanic material obtained from silicon and ferrosilicon alloy production. It is highly reactive due to its high silica (SiO_2) content and fine particle size. Numerous studies have confirmed that silica fume significantly enhances compressive strength by filling micro-voids and promoting the formation of additional calcium silicate hydrate (C-S-H) gel. Experimental investigations reveal that the inclusion of silica fume increases compressive strength and elastic modulus, with strength improving as the dosage increases. This improvement is attributed to its pozzolanic reaction and densification of the microstructure.

The combined use of cenosphere and silica fume creates a synergistic effect in concrete. While cenospheres tend to reduce density and strength, silica fume compensates for this loss by enhancing the microstructure. Research indicates that when silica fume is used along with cenosphere, the internal structure becomes denser and bonding between particles improves. This combination helps maintain adequate compressive strength while achieving weight reduction.

Several studies have explored this hybrid replacement approach. One investigation reported that up to 20–30% cenosphere replacement with constant silica fume content can produce concrete with acceptable compressive strength for structural use. Another study on ultra-high-performance concrete found that mineral admixtures like silica fume enhance mechanical properties despite reducing workability. Additionally, silica fume-based concrete has shown long-term strength gain due to continued pozzolanic activity and improved hydration. Furthermore, research on artificial silica fume confirms its role in enhancing early strength development in concrete mixes. Mathematical models have also been developed to predict compressive strength variations based on silica fume content and curing time.

Overall, the compressive strength of concrete incorporating cenosphere and silica fume depends on the proportion of replacement, curing conditions, and mix design. While excessive cenosphere content may reduce strength, the presence of silica fume effectively counteracts this drawback. Thus, an optimized combination of these materials can produce lightweight, sustainable, and high-performance concrete suitable for modern construction applications.

2. LITERATURE REVIEW

The incorporation of cenosphere and silica fume as partial replacements in concrete has been widely investigated to improve sustainability while maintaining adequate compressive strength. Several studies provide quantitative insights into their performance.

Guo et al. (2023) reported that cenosphere-based lightweight concrete achieved compressive strength greater than 25 MPa at 30% replacement, but strength decreased by about 26.88% compared to control mixes at 28 days. Similarly, another study by Mahato et al. (2022) showed that increasing cenosphere content reduces compressive strength due to increased porosity, with values dropping progressively as replacement increases. This indicates that optimized systems can overcome strength reduction.

Silica fume has consistently shown positive effects on compressive strength. Li et al. (2023) reported compressive strengths of 51.3 MPa and 61 MPa at 28 days for silica fume concrete, significantly higher than conventional mixes. Similarly, Ahmed et al. (2020) found that 10% silica fume replacement increased compressive strength to 33.6 MPa at 28 days compared to 30.7 MPa at higher replacement levels. Kumar and Singh (2019) observed that silica fume improves compressive strength due to pore refinement and enhanced C-S-H gel formation. Likewise, Bozkurt and Yazıcıoğlu (2010) reported significant strength enhancement in lightweight concrete containing silica fume. Kenai et al. (2021) further noted that silica fume contributes to long-term strength gain due to continued pozzolanic reactions.

The combined use of cenosphere and silica fume has shown synergistic behaviour. Mehta and Monteiro (2014) emphasized that silica fume improves microstructure and compressive strength through densification. Further studies by Singh and Bansal (2015) indicated that silica fume replacement up to 15% significantly enhances compressive strength, while higher replacement levels may lead to marginal reductions.

Experimental observations by Ramesh et al. (2020) showed that the inclusion of cenospheres reduces compressive strength by 10–20%, depending on replacement level, but improves workability and reduces density. Similarly, Patel and Shah (2021) found that hybrid mixes produced strengths between 30–40 MPa at 28 days, suitable for structural applications. Rao et al. (2022) reported that mixes containing 10–20% cenosphere and constant silica fume-maintained target compressive strength while reducing density. An experimental study by Kumar et al. (2023) revealed that concrete with 20% silica fume and 4% cenosphere achieved a compressive strength of 38.43 MPa at 28 days, representing a 5% increase over conventional concrete. This demonstrates that silica fume compensates for the strength loss caused by cenospheres.

Overall, the literature confirms that cenosphere reduces compressive strength due to increased voids, whereas silica fume enhances strength through pozzolanic activity and microstructure refinement. The combined use of these materials results in optimized concrete with compressive strength typically ranging between 25 MPa and 40 MPa for structural applications, and even higher in advanced composites. Proper proportioning is therefore essential to achieve a balance between lightweight characteristics and mechanical performance.

3. EXPERIMENTAL INVESTIGATIONS

Materials and Properties

The experimental investigation was carried out to evaluate the compressive strength of concrete with partial replacement of cement using cenosphere and silica fume. The methodology involved material selection, mix design, casting, curing, and testing of specimens. Ordinary Portland Cement (OPC 53 grade) was used as the primary binder. Fine aggregate (River sand) and coarse aggregate (20 mm size) were selected as per standard specifications. Fig.1 represents the materials involved in the present study and Table 1 presents the important properties of materials.



Fig.1(a). Cenosphere



Fig.1(b). Cement



Fig.1(c). River sand



Fig.1(d). Silica fume

Fig.1(e). Coarse aggregate

Fig.1(f). Super plasticizer

Fig.1(a-f). Materials involved in the present study

Table 1. Materials involved in the study and their important physical properties

Material	Properties	Values / Remarks
Cement (OPC 53 Grade)	Specific gravity	3.15
	Fineness (Blaine)	225–300 m ² /kg
	Setting time	30 minutes
Cenospheres	Specific gravity	0.8
	Particle size	10–100 µm
Silica Fume	Specific gravity	2.4
	Particle size	<1 µm
Fine Aggregate (River Sand)	Specific gravity	2.65
	Fineness modulus	2.8
	Water absorption	1.5%
	Grading	Zone II as per IS 383:2016
Coarse Aggregate (Crushed Stone)	Specific gravity	2.80
	Maximum size	20 mm
	Water absorption	1%
Water (Potable)	pH	7
	Impurities	Free from harmful salts, oil, and organic matter
Superplasticizer (PCE-based)	Specific gravity	1.10
	Solid content	25%
	Dosage	1.2% by weight of binder
	Function	Improves workability, reduces water demand, disperses cement & cenospheres

Mix Design

Concrete mix design was carried out for M25 and M40 grade as per IS 10262-2019 guidelines. Cement was partially replaced with cenospheres and silicafume at varying percentages. Proper batching by weight was adopted to maintain uniformity. Dry materials (cement, silica fume, cenosphere, fine aggregate, and coarse aggregate) were thoroughly mixed in a mechanical mixer. Water was then added gradually, and mixing continued until a uniform and workable mix was obtained. The fresh concrete was checked for workability using a slump test. Table 2. depicts the mixing proportion of materials and Fig.2 Presents the procedure of making cubes.

Table 2. Quantity of Materials (kg/m³)

S.No	Cement	FA	CA	Water	SP	Mix Proportion
M25	400	584	1080	180		1 : 1.46 : 2.7 : 0.45
M40	450	594	1071	171	1.2%	1 : 1.32 : 2.38:0.38



Fig 2. Cube casting and curing

Experimental Setup and Procedure

Concrete cubes of size 150 mm × 150 mm × 150 mm were cast in steel moulds. The moulds were filled in three layers, and each layer was compacted using a tamping rod to remove entrapped air. After casting, the specimens were kept undisturbed for 24 hours at room temperature. The cubes were then demoulded and cured in a water tank for 7 and 28 days. Compressive strength testing was conducted using a Compression Testing Machine (CTM) as per IS 516:1959 (Methods of Tests for Strength of Concrete). The cubes were placed centrally in the machine, and load was applied gradually at a rate of 140 kg/cm²/min until failure. The maximum load at failure was recorded, and compressive strength was calculated. Fig.3 exhibits the compressive strength tests and Table 3 shows the Compressive strength results of different cubes.



Fig 3. Testing cubes

Table 3. Compressive Strength Results

Mix ID	Cenosphere (%)	Silica Fume (%)	M25 (MPa)	M40 (MPa)
M0	0	0	26.50	42.00
M1	5	0	30.00	46.00
M2	10	0	26.80	43.00
M3	15	0	25.00	40.00
M4	20	0	23.50	38.00
M5	5	5	32.60	48.60
M6	5	10	35.40	52.20
M7	5	15	31.20	50.60
M8	5	20	28.20	46.00

4. DISCUSSION OF RESULTS

The results indicate that the addition of silica fume and Cenosphere significantly enhances compressive strength due to its pozzolanic reaction and pore-filling effect.

The results show that 5% cenospheres in place of cement is the optimal dosage for concrete. The concrete grades M25 and M40 achieved a compressive strength at this level that was 9.5% and 13.2% higher than the control mix, respectively, indicating effective use of cenospheres. The strength increase is caused by a reaction between calcium hydroxide and reactive silica present in cenospheres, which results in more C-S-H gel formation. Additionally, the tiny and spherical structure of cenospheres promoted a micro-filling action that decreased voids and enhanced particle packing. Strength reduced at higher replacement levels because of increased porosity and lower cementitious content. Therefore, 5% cenosphere replacement offers the best possible balance between sustainability, workability, and strength.

As the percentage of cenosphere increased beyond 10%, a reduction of 10.6% and 6.5% in compressive strength for M25 and M40 were observed. This is mainly due to the hollow and lightweight nature of cenospheres, which increases voids and reduces density. At 20% replacement, the strength dropped to 17 % in both grades of concrete, which is still acceptable for certain structural and non-structural applications. The mix M6 (5% cenosphere + 10% silica fume) exhibited the highest compressive strength of M25 and M40 concrete which were found to be 35.4 MPa and 52.20 MPa at 28 days, for about 33.6 and 24.2% higher than conventional concrete. Table 4 presents the Comparison table of Present and Past Compressive strength Results. Overall, the experimental study shows that an optimum combination of 5–10% cenosphere with 10% silica fume provides the best balance between strength and lightweight properties. Silica fume effectively compensates for the strength reduction caused by cenospheres, making the mix suitable for sustainable and high-performance concrete applications.

Table 4. Comparison of Present and Past Compressive strength Results

Authors & Year	Replacement		Compressive Strength Result	Key Findings / Reasons
	Materials	Level		
Zhang & Malhotra (1996)	Silica Fume	5%–15%	Strength increased significantly (15–25%)	Dense microstructure and improved cement hydration
Kearsley & Wainwright (2001)	Fly Ash (lightweight behavior similar to cenosphere)	20%–50%	Reduced compressive strength but improved workability	Increased void content and lower specific gravity affect load-bearing capacity
Bhanja & Sengupta (2005)	Silica Fume	5%–15%	Strength increased up to 20% at 10% replacement	High pozzolanic activity forms additional C–S–H gel; micro-filling improves density and ITZ
Nochaiya et al. (2010)	Fly Ash + Silica Fume	SF: 5%–10%	Significant strength gain at later ages	Improved pore refinement and reduced permeability due to silica fume reaction
Kumar & Sharma (2018)	Cenosphere	10%–30%	Strength decreased with increase in	Hollow spherical particles reduce density and bonding

Authors & Year	Replacement		Compressive Strength Result	Key Findings / Reasons
	Materials	Level		
			cenosphere content	strength
Present Study (2026)	SF (10%)and Cenosphere (5%)		Strength increases by 33.6 % (M25)and 24.2%(M40)	pozzolanic reaction and pore-filling effect

5. CONCLUSIONS

The current study on the compressive strength of concrete partially replaced with cenosphere and silica fume demonstrates that the incorporation of these industrial by-products significantly influences strength characteristics, both positively and negatively, depending on the replacement levels.

Cenosphere, being a lightweight and hollow spherical material, reduces the density of concrete. At lower replacement levels, it contributes to improved workability and may not significantly affect strength. However, as the percentage of cenosphere increases, the compressive strength decreases due to its lower intrinsic strength and weak bonding characteristics compared to conventional cementitious materials. The hollow structure of cenosphere introduces additional voids, leading to reduced load-carrying capacity.

The improvement in compressive strength with 5% Cenosphere and 10% silica fume was attributed to its high pozzolanic reactivity and extremely fine particle size. Silica fume reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, which enhances the density and bonding within the concrete matrix. Furthermore, the micro-filling effect of silica fume reduces voids and improves the interfacial transition zone (ITZ), resulting in higher strength.

Overall, the study concludes that partial replacement of cement with silica fume and controlled amounts of cenosphere can produce sustainable and structurally viable concrete. The findings highlight the importance of optimizing replacement percentages to achieve a balance between strength, density reduction, and environmental benefits, making it suitable for lightweight and eco-friendly construction applications.

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