

## From Waste to Strength: Hybrid Binder Approach for Sustainable M25 Concrete

Tanushree Dalai<sup>1\*</sup>, Bitishree Patel<sup>2</sup>, Madhusmita Biswal<sup>3</sup>

### Abstract

*The growing demand for concrete in infrastructure development has led to increased cement consumption, raising serious environmental concerns due to high energy use and carbon dioxide emissions correlated with cement manufacturing. In this context, the use of industrial residues as partial substitutions for cement has achieved deep focus as a sustainable construction strategy. The current investigations experimentally explore the strength and quality performance of concrete produced using a hybrid binder system incorporating silica fume and fly ash cenospheres. In this investigation, silica fume was used as a constant partial replacement of cement at 12%, while fly ash cenospheres were introduced at varying replacement levels of 0%, 5%, 10%, 15%, and 20%. Concrete mixes were prepared using a fixed mix proportion, and standard specimens were cast to evaluate compressive and split tensile strength at 7 and 28 days of curing. In addition to destructive testing, non-destructive evaluation was carried out using the rebound hammer and ultrasonic pulse velocity test to assess surface hardness and internal quality of the concrete. The experimental results indicated that the incorporation of cenospheres up to an optimum level significantly enhanced the structural behavior of concrete. The mix containing 10% cenosphere replacement exhibited the highest strength values in all mechanical tests, which was attributed to improved particle packing and the synergistic pozzolanic action of silica fume. Beyond this level, a gradual reduction in strength was observed due to decreased cementitious content and increased porosity. The non-destructive test results showed good correlation with compressive strength, confirming improved surface hardness and internal uniformity of the optimized mixes. Overall, the study demonstrates that the integrated use of shear force (SF) and freeform additive construction system (FACS) can produce structurally efficient and environmentally sustainable concrete, while reducing dependence on conventional cement.*

**Keywords:** Fly ash cenospheres, hybrid binder system, mechanical properties, non-destructive testing, partial cement replacement, silica fume, sustainable concrete

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### INTRODUCTION

Concrete is essential in modern construction because of its strength, versatility, and long service life. From residential buildings to large-scale infrastructure, it continues to be the material of choice worldwide. However, the increasing demand for concrete has led to a rapid rise in cement production, which has become a serious environmental concern. The manufacture of cement requires large amounts of energy and is a major source of carbon dioxide emissions, mainly because of the calcination of limestone and the use of fossil fuels. Consequently, reducing the dependency on cement has become an important step toward achieving sustainable construction [1–5].

In response to this challenge, researchers and engineers have focused on using industrial spin-offs as partial replacements for cement. Materials such as fly ash and silica fume have already proven effective in improving concrete performance while lowering its environmental impact. Among the various components derived from fly ash, cenospheres are particularly interesting because of their lightweight and hollow structures. Despite their favorable characteristics, cenospheres have not been widely used in concrete applications [6–10].

Cenospheres are rich in silica and alumina and exhibit pozzolanic behavior when blended with cement. Their spherical shape improves workability and particle packing, resulting in a more uniform and denser concrete matrix. In addition, silica fume, with its extremely fine particles, fills microvoids inside the concrete and strengthens the adhesion between cement paste and aggregates. When used together, silica fume and cenospheres can complement each other and enhance both strength and durability [11–13].

The performance of concrete containing these materials depends on their proportions. Excessive cement replacement may reduce strength, whereas an optimized combination can produce concrete with improved mechanical properties and reduced environmental impact. With this understanding, the present study focused on developing M25 grade concrete using a hybrid binder system consisting of a constant percentage of silica fume and varying amounts of cenospheres. The objective was to identify an optimum binder composition that delivers reliable strength performance while promoting sustainable and eco-friendly construction practices [14–17].

## LITERATURE REVIEW

A literature review by Senthamarai et al. (2016) examined the intensification of concrete containing cenospheres and silica dust as pozzolanic replacements. The results showed significant improvements in compressive and flexural strength owing to enhanced microstructural densification. The study confirmed the synergistic effect of using cenospheres with highly reactive materials [14].

Aparna and Reshmi (2018) investigated the use of industrial waste materials in high-strength concrete and reported that partial replacement of cement can improve mechanical performance when properly proportioned. Their study highlighted the importance of optimizing replacement levels to avoid strength reduction. The findings demonstrated the feasibility of using industrial by-products for sustainable concrete production [1].

Gupta et al. (2020) evaluated the mechanical and environmental performances of cementitious composites containing lightweight industrial by-products. The authors observed that such materials significantly reduce concrete density and carbon footprint while maintaining acceptable strength. The study emphasized the need for a balanced mixed design to achieve both structural efficiency and sustainability [3].

Arel et al. (2021) presented a detailed review on sustainable concrete incorporating industrial waste materials. Their work concluded that hybrid binder systems generally perform better than single-material replacements in terms of strength and durability. The authors stressed that improper proportioning can negatively affect performance, highlighting the need for systematic experimental studies [2].

Kumar (2020) conducted an experimental study on concrete containing fly ash cenospheres as a partial replacement for cement. The results showed improved compressive, split tensile, and flexural strengths at lower replacement levels owing to better particle packing. However, excessive cenosphere content led to a reduction in strength because of lower cementitious bonding [7].

Li et al. (2022) investigated the mechanical behavior and microstructural characteristics of cenosphere-based lightweight concrete. Their findings indicated that moderate incorporation of

cenospheres enhances strength and reduces micro-cracking. The study also reported that higher replacement levels increase porosity, which adversely affects mechanical performance [8].

Singh et al. (2024) experimentally studied lightweight concrete produced using fly ash cenospheres. The authors reported that optimized replacement levels resulted in improved strength and reduced the self-weight of concrete. The study recommended combining cenospheres with reactive pozzolanic materials to enhance the structural performance of sustainable construction [15].

### OBJECTIVES OF THE STUDY

1. The objectives of this study were to develop M25 grade concrete using a hybrid binder system incorporating silica fume and fly ash cenospheres.
2. To investigate the effect of constant silica fume replacement (12%) on the mechanical properties of concrete
3. To evaluate the influence of varying cenosphere contents (0%–20%) as a partial replacement for cement.
4. To determine the optimum cenosphere percentage that yields maximum strength performance.
5. To assess the suitability of the proposed concrete mix for sustainable and eco-friendly construction

### EXPERIMENTAL PROGRAM

#### Mix Design for M25 Grade Concrete

A concrete mix design was performed for M25 grade concrete in accordance with IS 10262 and IS 456 guidelines. Based on the target mean strength and workability requirements, the final mix proportion adopted for the experimental investigation was

#### 1:1.44:2.91 (Binder:Fine Aggregate:Coarse Aggregate)

In this study, the term *binder* refers to a modified cementitious system comprising ordinary Portland cement (OPC), silica fume, and fly ash cenospheres.

#### Binder Composition and Replacement Strategy

To develop a sustainable and high-performance concrete, experimental studies were conducted using different binder mixes, including.

1. Constant partial alternative of cement by silica fume, and
2. Variable replacement of cement by fly ash cenospheres.

Silica fume was maintained at a constant replacement level of 12% by weight of cement in all mixes, owing to its well-established pozzolanic efficiency and micro-filling capability.

Cenospheres were used as a partial replacement for cement at varying proportions to evaluate their influence on the mechanical properties of concrete.

#### Concrete Mix Combinations

Five different concrete mixes were prepared using the same mix proportion (1:1.44:2.91), but with varying cenosphere contents. The percentage replacement levels are summarized in Table 1.

**Table 1.** Concrete mix combinations.

Mix ID	Silica fume (%)	Cenosphere (%)
M 0	12	0
M 5	12	5
M 10	12	10
M 15	12	15
M 20	12	20

### Specimen Preparation

A total of 80 specimens were cast:  
 50 cubes (150 × 150 × 150 mm)  
 30 cylinders (150 mm × 300 mm)

All specimens were compacted manually and cured in water after 24 hours.

### Testing Procedures

- Compressive Strength: IS 516:1959
- Split Tensile Strength: IS 5816
- Rebound Hammer Test: IS 13311 (Part 2): 1992
- Ultrasonic Pulse Velocity (UPV) Test: IS 13311 (Part 1): 1992

Destructive tests were conducted at 7 and 28 days, and non-destructive tests were conducted at 28 days.

### Curing of Specimens

After remolding, the specimens were cured in clean water at ambient laboratory temperature until testing. Curing periods of 7 and 28 days were adopted to study early-age and long-term strength development, respectively.

### Objective of Strength Evaluation

The strength tests were carried out to:

- Aim: To identify the *optimum cenosphere content* in the presence of constant silica fume, evaluate the combined effect of *silica fume and cenospheres* on strength enhancement, and assess the feasibility of using this *hybrid binder system* for M25 grade structural concrete.

## RESULTS AND DISCUSSION

### Compressive Strength of Concrete

The compressive strength results of M25 grade concrete containing a constant 12% silica fume and varying percentages of cenospheres are presented in Table 2. The tests were conducted at 7 and 28 days of curing.

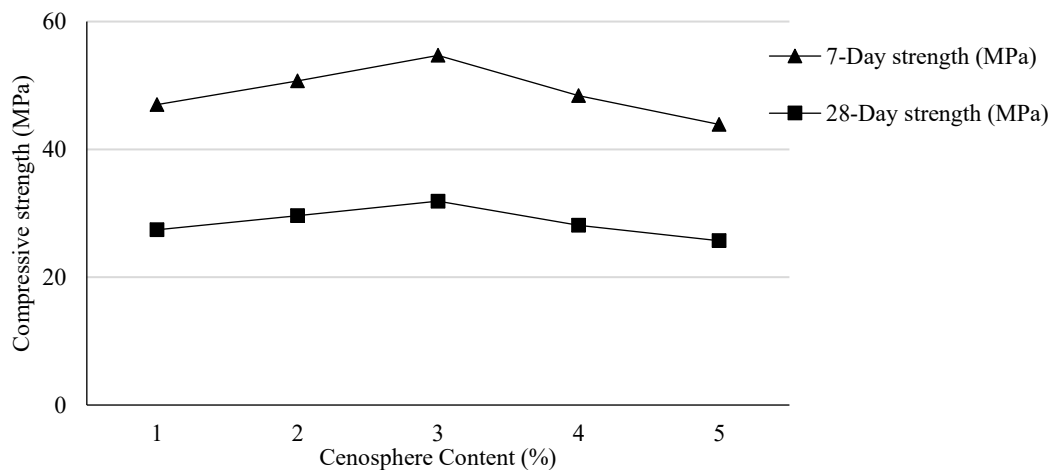
### Discussion

An increasing trend in compressive strength was observed up to 10% cenosphere replacement, after which a gradual reduction occurred. The improvement in strength at lower replacement levels can be attributed to the synergistic effect of silica fume and cenospheres, wherein silica fume contributes to pore refinement and cenospheres improve particle packing efficiency.

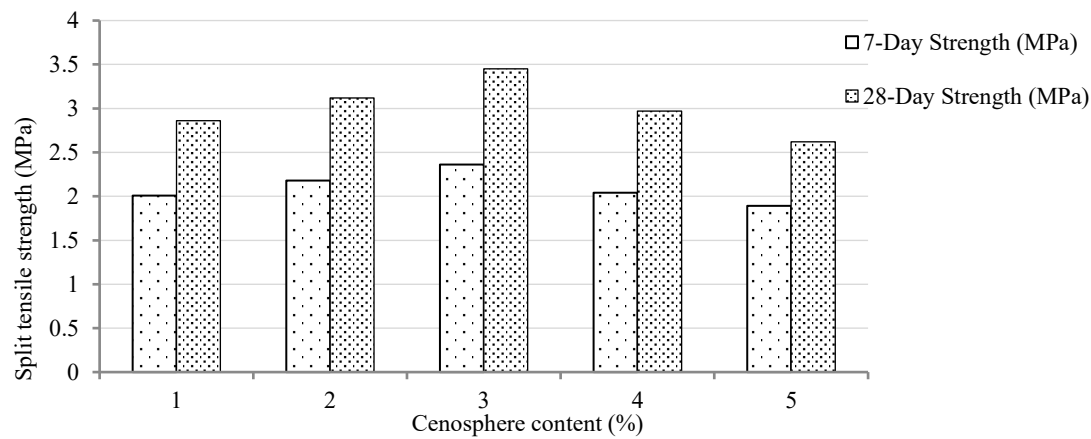
At higher replacement levels (15% and 20%), the reduction in strength was primarily due to insufficient cementitious material and increased internal voids caused by the lightweight nature of cenospheres. Nevertheless, all mixes achieved the characteristic strength requirement of M25 grade concrete at 28 days (Figure 1).

**Table 2.** Compressive strength of M25 concrete with silica fume and cenospheres.

Cenosphere content (%)	7-day strength (MPa)	28-day strength (MPa)
0	19.6	27.4
5	21.1	29.6
10	22.8	31.9
15	20.3	28.1
20	18.2	25.7



**Figure 1.** Illustrates the variation of compressive strength with increasing cenosphere content, showing a peak strength at 10% replacement.



**Figure 2.** Depicts the variation of split tensile strength with cenosphere percentage, highlighting the optimum performance at 10% replacement.

**Table 3.** Split tensile strength of M25 concrete.

Cenosphere content (%)	7-day strength (MPa)	28-day strength (MPa)
0	2.01	2.86
5	2.18	3.12
10	2.36	3.45
15	2.04	2.97
20	1.89	2.62

### Split Tensile Strength of Concrete

The split tensile strength results are summarized in Table 3.

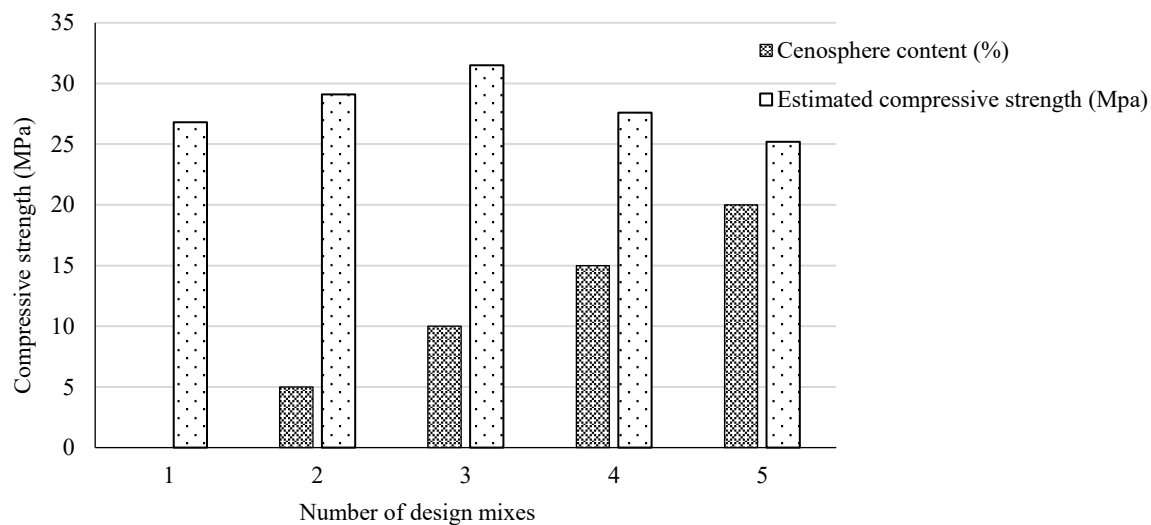
### Discussion

Split tensile strength followed a trend similar to compressive strength. The maximum tensile strength was recorded for the mix containing 10% cenospheres, indicating improved bonding between the binder matrix and aggregates.

The presence of silica fume enhances the interfacial transition zone, whereas cenospheres contribute to better stress distribution under tensile loading. However, excessive replacement levels reduce the tensile resistance owing to weaker cementitious continuity (Figure 2).

**Table 4.** Rebound hammer test results (28 days).

Cenosphere content (%)	Average rebound number	Estimated compressive strength (MPa)	Concrete quality
0	33	26.8	Good
5	36	29.1	Good
10	39	31.5	Very good
15	34	27.6	Good
20	31	25.2	Fair

**Figure 3.** Shows the variation of rebound number with cenosphere content, indicating peak performance at 10% replacement.

## Rebound Hammer Test

### Test Procedure

The rebound hammer test was conducted in accordance with IS 13311 (Part 2): 1992. The test was performed on 28-day-cured concrete cube specimens. Before testing, the concrete surface was cleaned and dried. For each specimen, multiple readings were taken, and the average rebound number was recorded to minimize surface irregularities (Table 4).

### Discussion

The rebound hammer test results indicated an increase in surface hardness with the incorporation of cenospheres up to a 10% replacement, which corresponded well with the compressive strength test results. The mix containing 10% cenospheres exhibited the highest rebound number, indicating a denser and stronger surface layer.

Beyond this level, a reduction in the rebound number was observed because of the lower cementitious content and increased porosity caused by the higher cenosphere replacement. Nevertheless, all the mixes demonstrated acceptable surface quality for structural concrete (Figure 3).

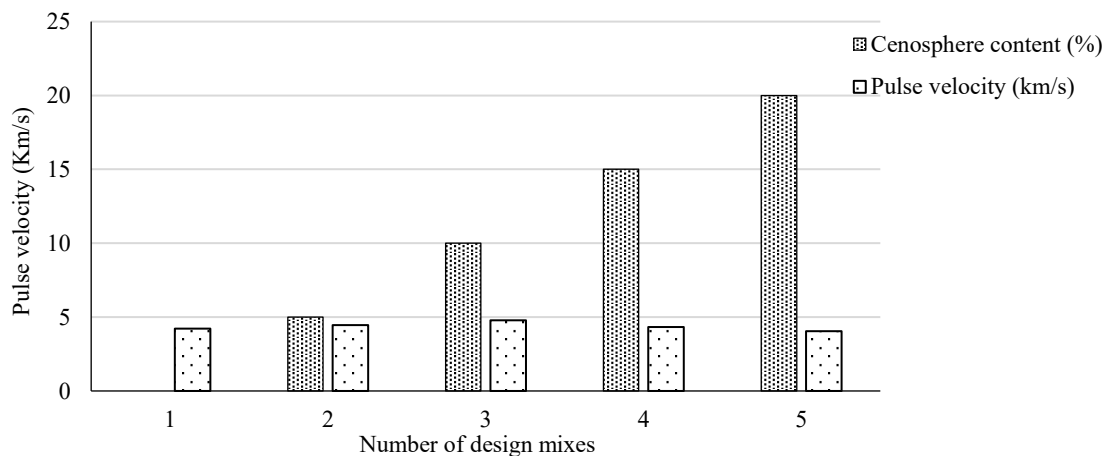
## Ultrasonic Pulse Velocity Test

### Test Procedure

The ultrasonic pulse velocity test was conducted as per IS 13311 (Part 1): 1992. The test measures the velocity of ultrasonic waves passing through concrete, which reflects its internal structure, density, and homogeneity. The test was performed on cube specimens at 28 days of curing using the direct transmission method, as shown in Table 5.

**Table 5.** Ultrasonic pulse velocity test results (28 days)

Cenosphere content (%)	Pulse velocity (km/s)	Concrete quality grade
0	4.21	Good
5	4.45	Good
10	4.78	Excellent
15	4.32	Good
20	4.05	Medium



**Figure 4.** Illustrates the variation of ultrasonic pulse velocity with cenosphere content, showing maximum velocity at 10% replacement.

### Discussion

The UPV results demonstrate a clear improvement in pulse velocity up to 10% cenosphere replacement, indicating enhanced density and reduced internal voids. The presence of silica fume contributes to pore refinement, whereas the optimized cenosphere content improves particle packing and matrix continuity.

At higher replacement levels (15% and 20%), the pulse velocity decreased slightly owing to increased porosity and reduced cement paste volume. However, all mixes exhibited pulse velocities above 4.0 km/s, confirming satisfactory internal quality and the absence of major defects (Figure 4).

### Correlation Between NDT and Destructive Test Results

A strong correlation was observed between:

- Rebound hammer values and compressive strength
- UPV values and internal concrete quality

The concrete mix containing 10% cenospheres and 12% silica fume consistently showed superior performance in both destructive and non-destructive tests. This confirms the reliability of NDT methods for predicting the strength and quality of hybrid binder concrete.

## CONCLUSIONS AND FUTURE SCOPE

### Conclusions

The present study investigated the performance of M25 grade concrete using a hybrid binder system incorporating 12% silica fume and varying percentages of fly ash cenospheres. The results show that silica fume significantly enhances matrix densification and strength development.

An optimum cenosphere replacement level of 10% was identified, at which the maximum compressive, split tensile, and flexural strengths were achieved. Beyond this level, a reduction in

strength was observed owing to the decreased cementitious content and increased porosity.

The non-destructive test results obtained from the rebound hammer and ultrasonic pulse velocity tests were well correlated with the destructive strength tests, confirming the improved surface hardness and internal quality of the optimized mix. All mixes satisfied the strength requirements of M25 grade concrete, demonstrating the feasibility of using cenospheres and silica fume for sustainable construction.

### Future Scope

Future research may focus on long-term durability studies, microstructural analysis using advanced techniques, and performance evaluation under aggressive environmental conditions. Further investigations can also explore higher-strength grade concrete, lightweight concrete applications, and life-cycle environmental assessments to support large-scale practical implementation.

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