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Experimental investigation on the influence of cenosphere on mechanical and rheological properties of Portland cement pastes

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ABSTRACT

Cenosphere is a captivating material in the realm of cementitious materials. Its unique properties, such as being superfine, spherical, and hollow, make it a suitable additive in concrete. Fine cenosphere particles can efficiently bridge the gap among the cement particles. This increases the density and reduces porosity, thereby enhancing the performance of the concrete. The experimental results suggest that incorporating cenosphere up to 15% can lead to notable improvements in the properties of the concrete. This optimal content ensures the enhancements without detriment to the other significant characteristics of concrete. In the present scenario, cenospheres offer a sustainable solution for enlightening the characteristics of cement paste and reducing the environmental footprint of waste accumulation.

Keywords: Cenosphere; Industrial by-product; Additive; Sustainable material.

1. INTRODUCTION

Concrete is the most affordable and reliable construction material. Even though the construction industry meets the requirement of concrete for a changing marketplace, still the industry requires essential improvements in cost reduction, energy efficiency, product performance and eco-friendliness. The industry will need to face the technical and environmental challenges for improvisation [1–5]. Presently, the most alarming environmental problem is waste accumulation and disposal. Especially, thermal power plants worldwide generate a significant volume of fly ash [6–8].

In the present era, fly ash is largely produced and accumulated. In India, yearly around 110–112 million tonnes of fly ash is accumulated. The yearly production of fly ash is much high than its usage. The devious component produced along with fly ash is the cenosphere [9–13]. Cenospheres are lightweight free flowing powders consisting of hollow, hard-shelled, and petite spheres. Cenosphere constitutes 2–3% of fly ash and is extremely of low density (300–500 kg/m^3). Cenosphere can be easily transmitted through air and water due to its low density [14–18]. Transit of cenosphere through the air may pose a threat to living things because inhaling this minute particle results in respiratory problems. If it mixes with water bodies, it may extremely affect aquatic living also [19–21].

Inappropriate disposal may cause an unadorned environmental impact. Hence it should be scrupulously handled in an effective manner [22–23]. The cementitious properties of the cenosphere show a great scope to utilize it as a substitute for cement in concrete. Instead of considering it as a waste, Cenosphere can be utilized as a valuable product in construction [24–26]. Cenosphere consists of thin-walled and spherical particles of size 10–400 mm which may enrich the rheological properties of the concrete. Prior studies have exhibited that the cenosphere may augment the flowability of the cement matrix and enhance its strength [27–31].

Previously, many investigations have been done by researchers to develop cost-effective concrete by blending industry by-products with cement [32–34]. Hence this study is envisaged to develop a new eco-sustainable composite by using cenosphere as an alternative material for cement [35–39]. The potential of cenosphere as a cement replacement material clearly shows its significance in future construction. Replacing cement with cenosphere not only reduces waste accumulation but also considerably reduces the cost and over-exploitation of resources [40–42].

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The rheological characteristics of concrete strongly depend on flow properties of cement paste which in predominantly influenced by the water/cementitious materials (W/C) ratio [43–46]. Besides, the quantity and quality of binding material also play a key role. In a cement mantle, sufficient water should be incorporated to seal the voids present among solid particles [47–55]. If the voids are unfilled, the air may entrain into the concrete and that may result in strength reduction [56–61]. Hence in this research, the cenosphere content is varied for different W/C ratios to assess the mechanical and rheological properties. Three different W/C ratios have been used in this study to ascertain the influence of the cenosphere in the cement mantle.

2. MATERIALS AND EXPERIMENTAL PROGRAM

In this study, cenosphere is substituted with OPC in the cement mantle. The chemical constituent details of OPC and cenosphere are furnished in Table 1 and Figure 1.

The solid density of OPC and cenosphere were assessed as 1449 kg/m^3 and 759 kg/m^3, respectively. Several mix ratios were used to assess the influence of cenosphere in the mix for different water-to-binder ratios. The flow characteristics were evaluated to gauge the rheology of the cement paste. The XRD pattern of cenosphere is shown in Figure 2.

In this study, three W/CM ratios of 0.42 to 0.48 in the rise of 0.3 by mass of cement were used. Mixes comprising different ratios of cenosphere were assigned with codes of CNS-5, CNS-10, CNS-15, CNS-20 and CNS-25, which represents mixes, consisting of 5, 10, 15, 20 and 25 percentage of cenosphere respectively. The influence of the cenosphere were test-verified and compared with the control mix.

The flowability of cenosphere infused mixes has been determined by the Cone flow test. Figure 3a–c show the dimensions of the molds used for preparation of samples for flow, compressive and flexural strength tests. Sample were prepared and tested as per IS 4031-8 [62] and the properties were assessed [63].

Table 1: Chemical composition of the OPC and cenosphere.

CONSTITUENT	PROPORTIONS (%)	
	OPC	CENOSPHERE
CaO	65.1	3.2
SiO_2	20.9	59.5
Al_2O_3	4.7	25.9
Fe_2O_3	3.4	6.7
MgO	2.2	1.7
Na_2O	0.9	1.9
SO_3	1.9	0.8
LOI	0.9	0.3

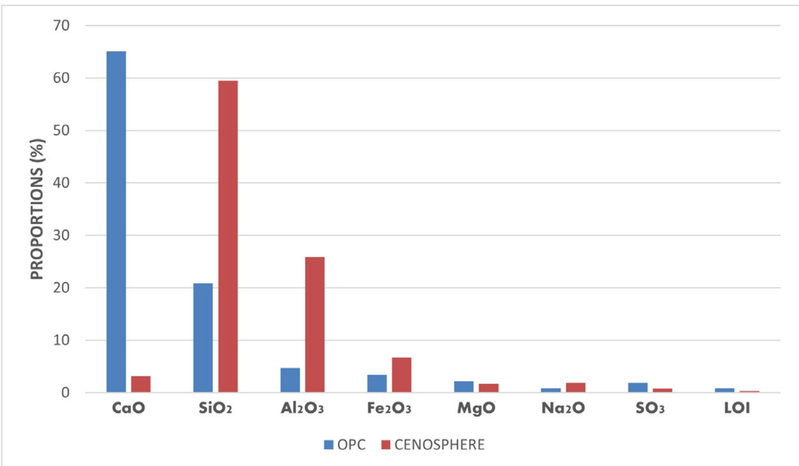


Figure 1: Chemical properties of OPC and cenosphere.

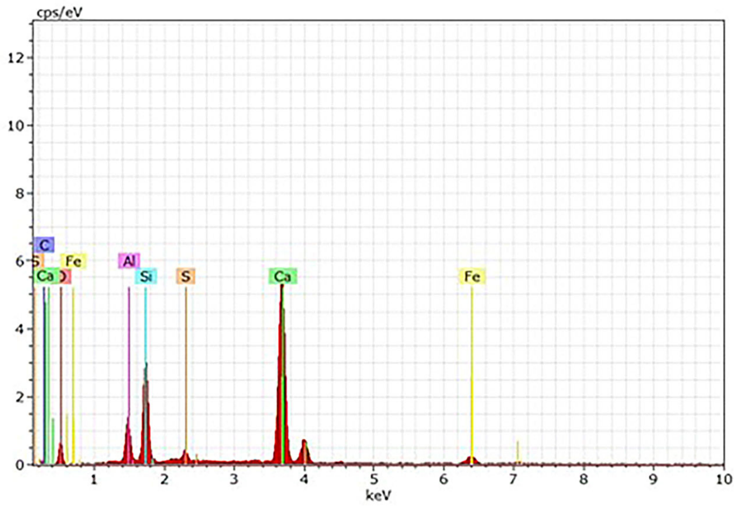


Figure 2: XRD of cenosphere.

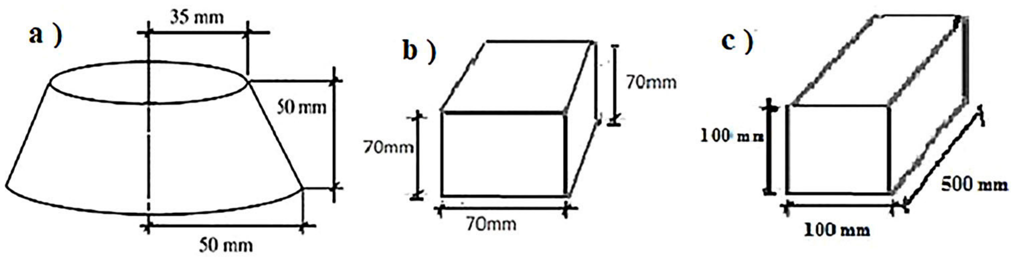


Figure 3: Dimensions of the moulds for flow, compressive and flexural strength tests.

3. RESULTS AND DISCUSSIONS

3.1. Compressive strength of CNS mixes

The compressive strength at 28 days of cubes comprising different proportions of cenosphere has been evaluated. Figure 4 indicates the compressive strength difference of mixes. Reduction in W/CM ratio substantially enriched the compressive strength of the cubes up to 15% incorporation of cenosphere. Beyond 15% addition of cenosphere reduces the strength of the mix. Therefore, the incorporation of cenosphere up to 15% with a lower W/CM ratio would increase the strength. The strength achievement is due to the pozzolanic effect thick shell surface of the cenosphere present in the composite.

It was noted that 15% is the optimal percentage to replace cement with cenosphere. However, based on the cenosphere content present in the mix, the optimal W/CM ratio may vary. In case if the water is not uniformly distributed in the past, some voids might be filled by air and this air entrainment may cause a reduction in strength irrespective of the W/CM ratio. The presence of air content in the mix cause notable variations in the strength. Hence the strength not only depends on the cenosphere content and W/CM ratio, it depends on the through mixing of constituents also.

3.2. Flexural strength of CNS mixes

The test verification related to the flexural strength of prisms containing cenospheres has been deliberated over 28 days. The lower water-to-cement (W/CM) ratio resulted in higher flexural strength values. Specifically, this trend persisted up to a 15% addition of cenospheres. Conversely, a reduction in flexural strength was exhibited in the mixes containing more than 15% cenospheres. This diminution is due to the altered composition and density of the concrete with the existence of cenospheres beyond this threshold. Besides, a marginal variation in strength characteristics was revealed up to 15% replacement of cement with cenospheres. It is evident that within this range, the substitution of cement with cenospheres does not significantly compromise the flexural strength of the concrete.

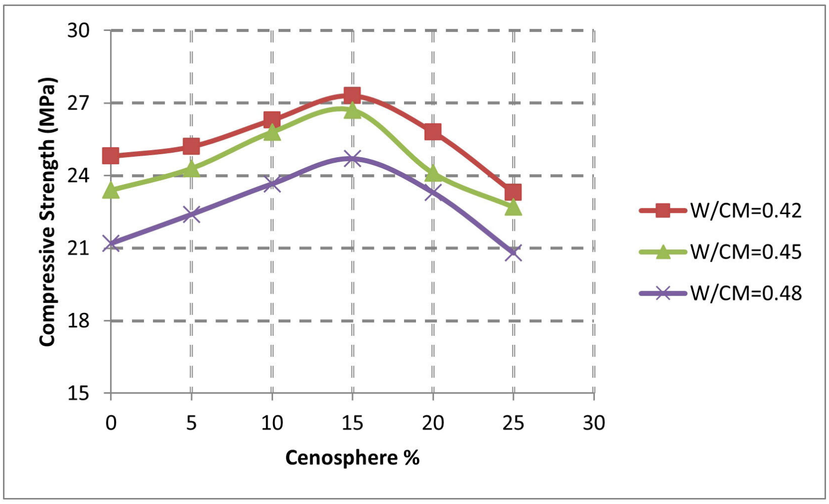


Figure 4: Cube compressive strength vs cenosphere content.

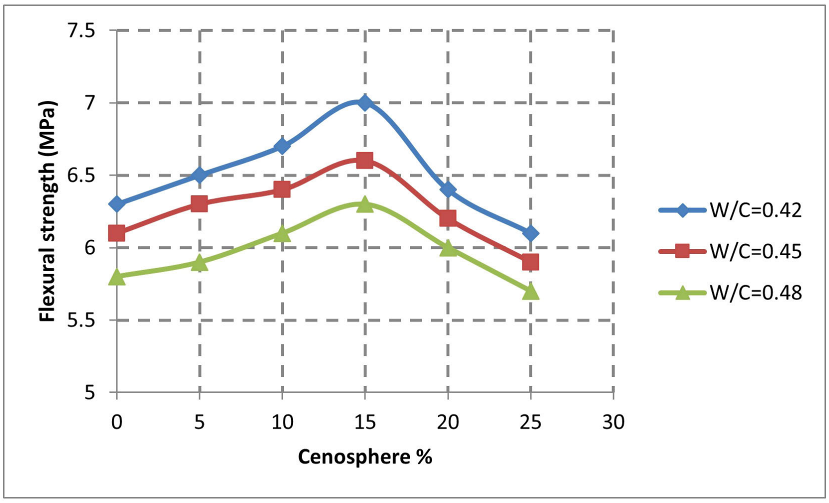


Figure 5: Flexural strength vs cenosphere content.

The strength increase is attributed to the pozzolanic properties of the cenosphere. Pozzolanic materials, such as cenospheres, can interact with $Ca(OH)_2$, forming additional calcium silicate hydrate (C-S-H) gel. This gel is dense and monolithic, providing enhanced structural integrity to the composite. Additionally, the proliferation of C-S-H gel serves to seal the micro-pores. By reducing the presence of these micro-pores, the composite becomes more compact and less liable to crack propagation. Figure 5 illustrates the variations in flexural strength of concrete mixes having cenospheres (CNS mixes).

3.3. Empirical relationship for assessment of compressive strength of cenosphere concrete

Apropos of previous discussions, an empirical correlation was established among flexural and compressive strength of infused cenosphere-infused concrete to assess the flexural strength of concrete. In line with the test data, the below-expressed relationship in Equation (1) was developed using regression analysis to predict the 28 days' flexural strength of cenosphere concrete.

$$\rho c = 8.895\ (f) 0.615\ (\rho f)\text{MPa} \quad (1)$$

Where ρc and ρf denote the compressive and flexural strength of cenosphere imbibed concrete in terms of MPa, respectively. The developed empirical equation with a correlation dependence of 92.91% shows the level of confidence of the equation in the assessment of flexural strength in tandem with compressive strength.

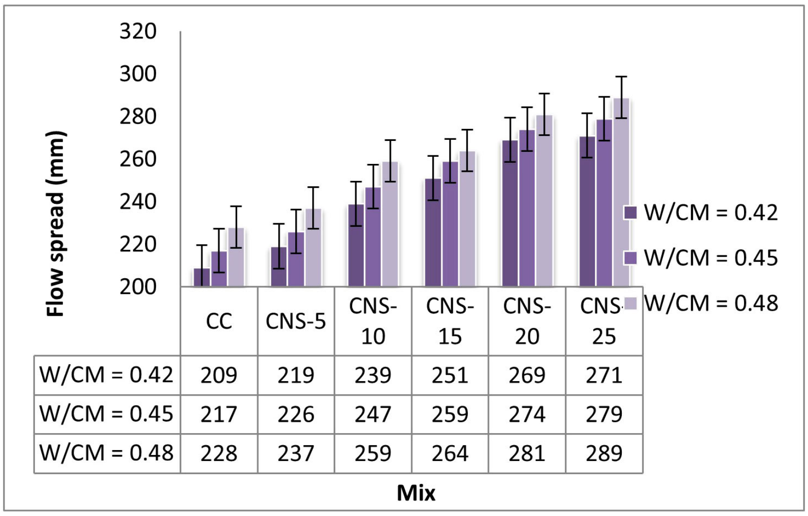
3.4. Flow spread of CNS mixes

The flow spread of the mix is mainly influenced by the W/CM and cenosphere content. The maximum flow rate was exhibited at a W/CM ratio of 0.48. Conversely, the W/CM ratio alone is not the major factor prevailing the flow spread. Precisely, the addition of 15% cenosphere content caused a substantial escalation in flow spread from 0 to 276 mm. Besides, for a mix comprising 25% cenosphere, the flow spread value increased to 291 mm. This specifies that there is a prominent effect of cenosphere content on flow spread, with higher percentages leading to greater flowability.

However, it was noticed that only a minor upsurge in flow spread beyond the 15% addition of cenosphere. This nominal increase could be attributed to a thinner water film thickness resulting from the higher cenosphere replacement percentages. This thinner water film might restrict the flowability of the mix at higher cenosphere content, thereby limiting the further increase in flow spread. Figure 6 illustrates the variations in flow spread for different cenosphere content and W/CM ratios, providing a visual representation of how these factors interact to influence the flow characteristics of the mix.

3.5. Flow rate of CNS mixes

Flow spread test was performed and the flow rate of the cenosphere concrete was determined. The increase in the W/CM ratio increases the flow rate but the W/CM ratio alone not governs the flow rate. The highest flow rate was obtained at a W/CM ratio of 0.48 and the flow rate has expressively upgraded for the mixes comprising 5 to 25% ceneosphere.



	CC	CNS-5	CNS-10	CNS-15	CNS-20	CNS-25
W/CM = 0.42	209	219	239	251	269	271
W/CM = 0.45	217	226	247	259	274	279
W/CM = 0.48	228	237	259	264	281	289

Figure 6: Flow spread values of CNS mixes.

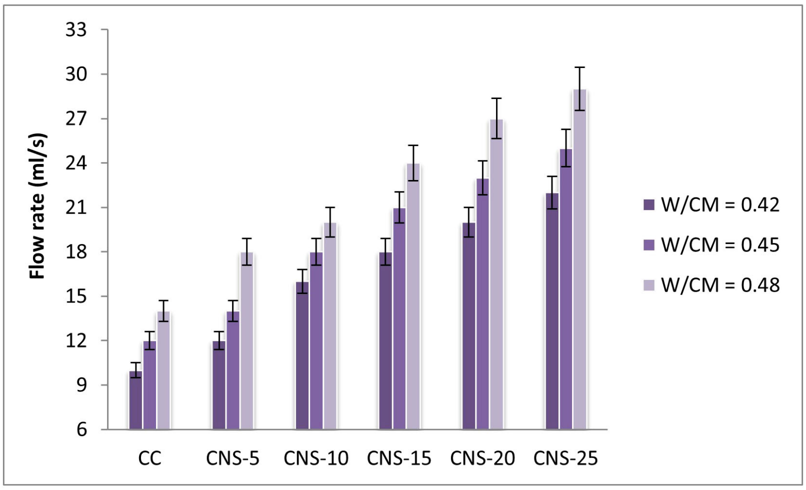


Figure 7: Flow rate of CNS mixes.

The addition of 5% to 25% ceneosphere content in the cement paste escalates the flow rate for all the water-to-cement ratios ml/s. The higher increase in flow spread was observed for the mixes comprising more than 15% cenosphere content due to less WFT of the cement paste. Higher cenosphere content intensifies the flow rate of the mix. It is an added advantage from the point of view of workability. Figure 7 shows the Flow rate of CNS mixes for different cenosphere content and W/CM ratios.

3.6. Rapid Chloride Penetration of CNS mixes

The results of the RCPT for both the control concrete and the cenosphere-incorporated concrete were compared. The findings revealed that the control concrete exhibited the highest level of chloride penetration, with a coulomb passed value of 1697. In contrast, the concrete mixes containing cenosphere displayed significantly lower coulomb passed values. Specifically, for CNS mixes incorporating different percentages of cenosphere (5%, 10%, 15%, 20%, and 25%), the coulomb passed values were observed to decrease progressively. For instance, the lowest value of 1398 was recorded for the mix CNS-25. Mix CNS-15 obtained the coulomb value of 1459. Figure 8 illustrates the percentage reduction in the ingress of chloride ions of CNS mixes concerning control mix. Compared to the control mix, 14.02% less chloride ingress was found for the mix CNS-15.

The notable reduction in chloride ingress in cenosphere blended concrete indicates that the incorporation of cenospheres contributes to enhancing the chloride resistance of the concrete. This is due to the pozzolanic effect of the cenosphere, which may produce stable Calcium Silicate Hydrate (C-S-H) gel. This gel formation helps to densify the concrete microstructure, reducing the permeability and consequently restricting the entrainment of chloride ions into the concrete. Hence, the presence of cenospheres leads to a more durable and corrosion-resistant concrete material.

4. CONCLUSION

- It is evident that the incorporation of cenosphere considerably increases the compressive and flexural strength of the mix by 9.15% and 10.2% than the control mix. Mix CNS-15 is considered as the optimal mix.
- Higher cenosphere content in the mixes enhanced the flow spread. Mix CNS-15 exhibited a flow spread of 251 mm for the W/CM of 0.42. Intensification in flow spread was exhibited in the mixes concerning ceneosphere content.
- Enhancement in flow rate was attained for the mixes comprising the cenosphere. Mix CNS-15 obtained a flow rate of 22.9 ml/s. An increase in ceneosphere content and W/CM ratio enhanced the flow rate of mixes.
- RCPT test results indicated that the chloride ingress of mix CNS-15 is 14.02% less than that of the control mix due to the dense microstructure of the mix.
- Cenosphere has the potential to improve the rheology and strength characteristics of the cement paste. Utilization of the cenosphere significantly endorses sustainable development and waste reduction.

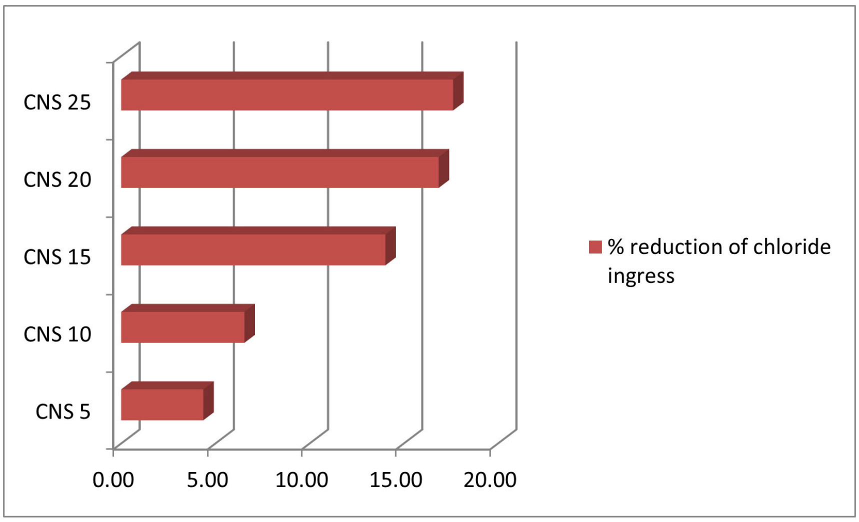


Figure 8: Percentage in the ingress of chloride ions of CNS mixes.

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