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Influence of Cenosphere on Mechanical Properties and Rheological Behavior of Portland Cement

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Abstract

Cenosphere is a superfine hollow material spherical in shape with good cementitious properties. It is predominantly composed of alumino-silicate. Being finer than cement, these particles can distribute effectually throughout the cement paste and it can fill the micro-voids. This stuff enriches the overall particle packing performance in the mix. The mechanical and rheological properties have been studied for cementitious suspensions containing varying cenosphere contents (0–50%) with various water-to-cement ratios. The tests evaluated the parameters such as flowability, packing density, and compressive strength. Results signposted that incorporating up to 30% cenosphere considerably upgraded both fresh and hardened properties of mix. Besides, cenosphere increased the water film thickness without any additional water, sustaining with better workability. These findings highlight cenosphere as a capable additive for enriching the performance of cement paste in the mix.

*Keywords:*Cenosphere, Rheology, Flowability, Particle packing, Sustainable material

1. **Introduction**

In the present era, the need for sustainable concrete production has become increasingly critical. Traditional concrete trusts greatly on raw materials mined from non-renewable geological sources, posing environmental challenges. One

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active approach to address this issue is the incorporation of industrial by-products as alternative materials in concrete production [Brooks et.al (2021), Nithyanandam and Deivarajan (2021), Haustein (2020), Chen et.al (2020)]. Thermal power plants generate vast amounts of flyash as a by-products. However, from the production quantity only about 80% being reused. The remaining ash is disposed in ash ponds on in open yards results in environmental degradation. [Danish and Mosaberpanah (2020), Satpathy et.al (2019), Yoriya et.al (2019), Strzałkowska (2021)]. Cenospheres are hollow particles consist of alumino-silicate with spherical shape. They are free-flowing, and light in weight. Approximately 2–3% of cenosphere present in fly ash with density between 450 to 820 kg/m^3 [Kushnoore et.al (2020), Agrawal and Wanjari (2017), Arunvivek et.al (2020)]. Owing to their low mass, cenospheres may transported from one place to another place and cause health issues in humans and animals, as well as ecological harm to aquatic life. Indecorous dumping of cenospheres poses a severe environmental impact. Thus, sustainable utilization of cenospheres remains indispensable [Asad Hanif Zeyu Lu et.al (2017), Kan and Demirboga (2009), Kwan and Chen (2013)].

Cenosphere should be considered as a valuable material rather than waste. The particle size range between 10 and 400 microns. Hence the particles may considerably augment the rheological properties of concrete [Arunvivek et.al (2015), Fenelonov et.al (2010), Blanco et.al (2000)]. Rheological performance, particularly the flowability of concrete, is heavily influenced by the water content and the shape of the cementitious material. The addition of cenosphere expands the packing density, decreasing the voids and increasing the amount of free water. This develops water film because of lubrication that boosts workability [Blissett and Rowson (2012), Arunvivek et.al (2015), Nadesan and Dinakar (2017), Fomenko et.al (2013), Kristombu et.al (2019)].

Packing density plays a major role in strength enhancement. Incorporating cenosphere can reduce water demand and improve strength characteristics. Some researchers reported that ultrafine cenospheres can improve both packing density and early-age strength [Senthamarai Kannan et.al (2016), Luong et.al (2016), Adesina (2020)]. Hence this study emphases on evaluating the effects of cenosphere on the rheological behavior, mechanical performance, and packing characteristics of cement paste through detailed experimental investigations**.**

2. Materials

Ordinary Portland cement (OPC) was used to produce mortat cubes and cenosphere was replaced with OPC in different percentage proportions. The solid density of cenosphere and OPC were tested and the values found to be 1449 kg/m^3 and 756 kg/m^3, respectively. The grain size distribution of OPC and cenosphere are shown in Fig.1.

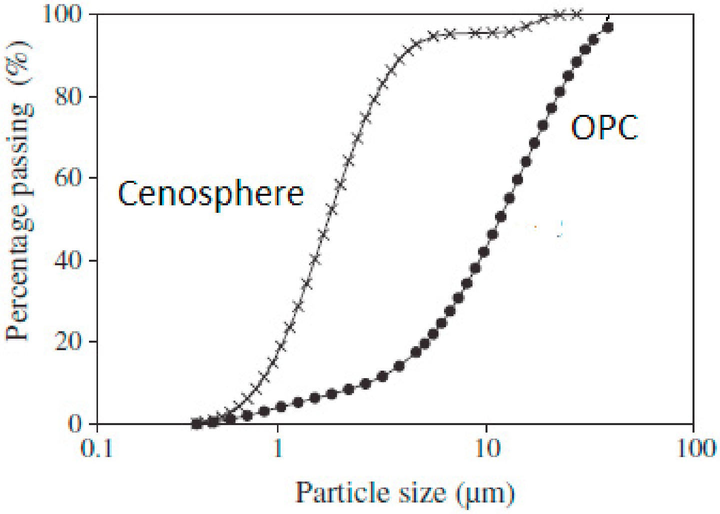


Fig.1 Particle size distribution of cenosphere and OPC

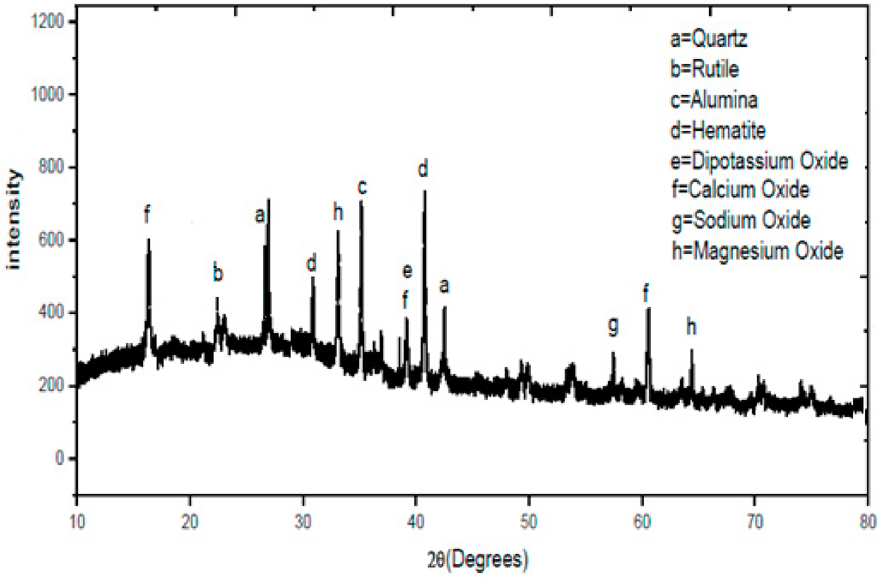


Fig. 2 XRD pattern of cenosphere

XRD analysis has been carried out and the pattern is shown in Fig. 2. The surface areas were calculated as 1559 m^2/kg and 356 m^2/kg for OPC and cenospheres, respectively. In order to improve workability super plasticizer has been used. Various trials had been conducted and the dosage of 0.5% by mass of the cement has been identified as optimal dosage.

3. Experimental program

Cenosphere content has been varied from 0% to 50% in increments of 10% by the mass of cement. Packing densities and rheology of the mix have been calculated. The compressive strength variations of mortar were studied. The W/CM has been varied to assess the influence of cenosphere on rheology. In general, the packing density of cement in dry packed form is lower than that of its paste form. Hence wet packing method proposed by Wong and Kwan (2008) [59] was adopted in this study. To evaluate the mechanical and flowability properties of the mixes, the water-to-cementitious materials (W/CM) ratio was varied from 0.36 to 0.40, in increments of 0.02 by mass of the cementitious material. Mixing has been done as per the guidelines given in IS 10262:2019.

Cone flow test was conducted to determine the flowability of the mix. Fig.3 and Fig.4 shows the molds used to cast the samples to conduct the experiments.

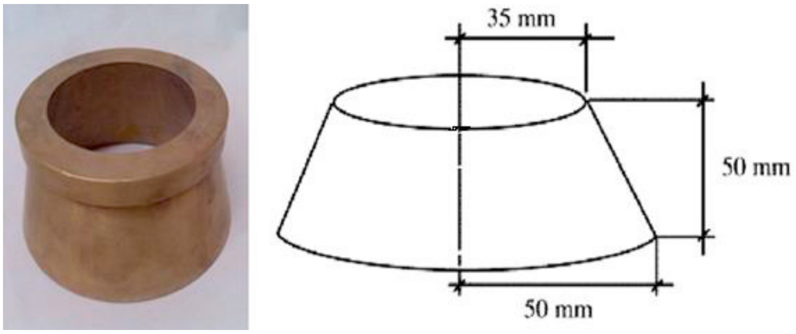


Fig. 3 Mini slump cone used for flow test

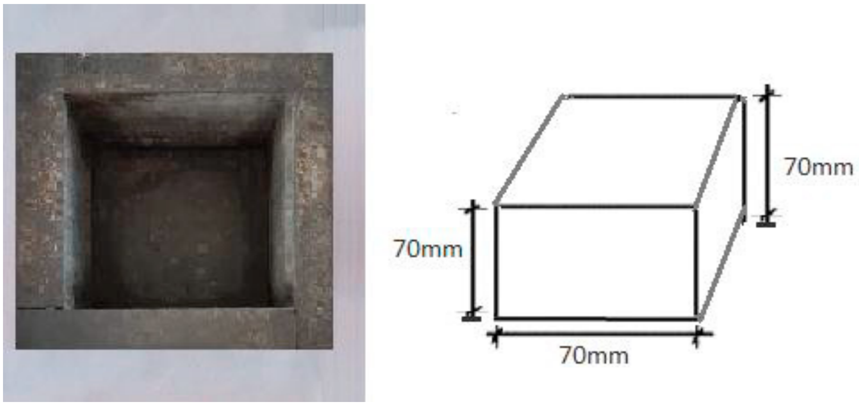


Fig. 4 Cubical mold used for preparing specimens

4. Results and discussions

4.1 Packing density and void ratio

Packing density refers to the maximum solid concentration attainable when particles are compactly arranged. To determine this parameter, varying water-to-cementitious materials (W/CM) ratios are essential. Three W/CM ratios ranging from 0.36 to 0.40 were used. The bulk density of the mix has been measured for each ratio to calculate the corresponding solid content. Typically, the concentration of solid touches the peak if water content is more and then begins to decrease. The highest solid concentration (**ρ**max) is considered the packing density, as suggested by Kwan and Chen (2013). Figure 4 illustrates the variation in packing density of cementitious suspensions containing cenosphere across different W/CM ratios.

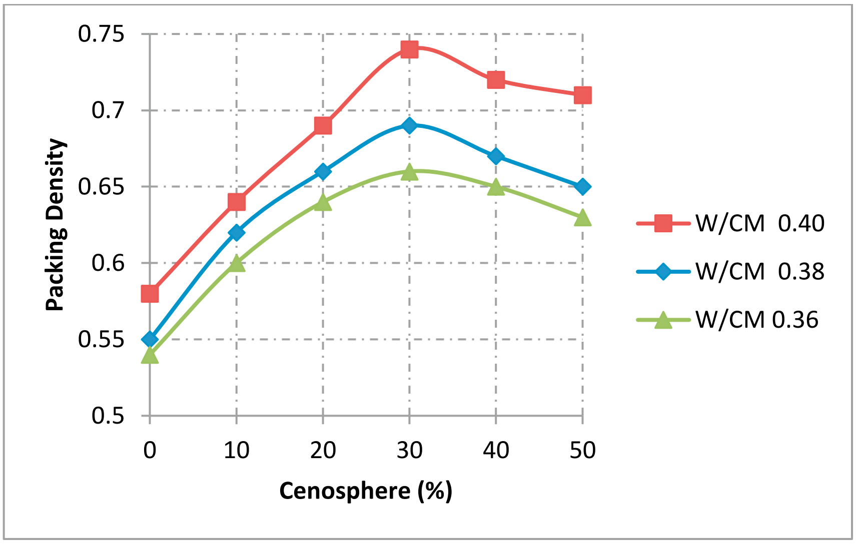


Fig. 4 Packing density variations of samples with cenosphere

The results show that the inclusion of cenosphere with Ordinary Portland Cement (OPC) significantly enhances packing density. For instance, the control mix (PC-0-0.40) without cenosphere exhibited a packing density of 0.587. With 10% and 20% cenosphere replacement, the packing densities increased to 0.643 (PC-10-0.40) and 0.672 (PC-20-0.40), respectively. The highest packing density of 0.749 was observed at 30% replacement (PC-30-0.40). However, beyond this level, a slight decrease was noted, with values of 0.716 and 0.703 for the 40% and 50% replacement samples (PC-40-0.40 and PC-50-0.40), respectively.

By considering data from packing density test, the voids ratio E and the excess water ratio E' have been calculated as:

$$E = (1- \boldsymbol{\rho}\text{max})/ \boldsymbol{\rho}\text{max} \quad \text{---(1)}$$

$$E' = E_w - E \quad \text{---(2)}$$

E_w represents water ratio of the cement paste. (volume of water to volume of solid). E' is the amount of excess water in the cement paste per solid volume of the cementitious materials (Kwan and Chen, 2013). Variations in the voids ratios of the cenosphere incorporated cementitious materials are shown in Fig. 5. Experimental data ensured that infusing of cenosphere substantially reduced the voids ratio. Uniting the packing density differences with related voids ratios, the upper rise in packing density was found to be 18.9%, the void ratio reduction for the corresponding packing density was found to be 43.7%. Greater decrease in voids ratio considerably improve the free water. This would form expands lubrication due to formation of water films.

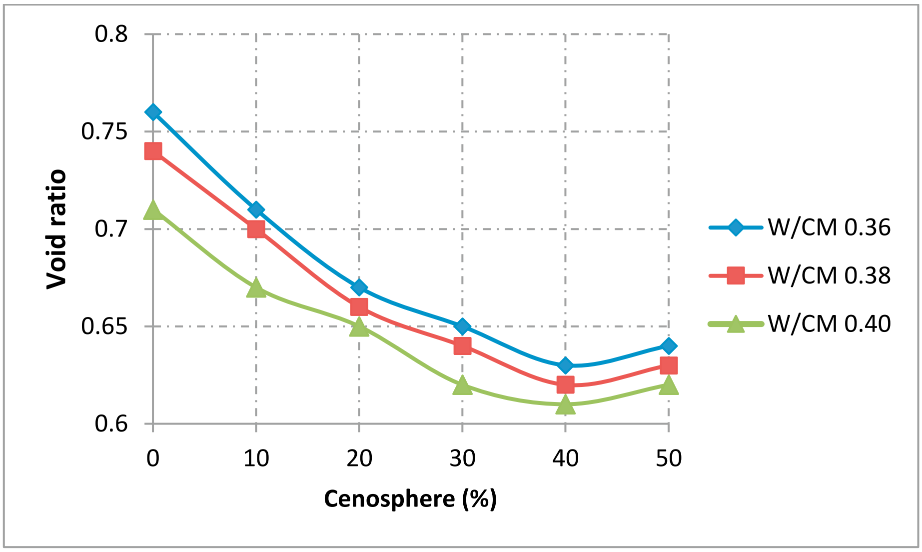


Fig. 5 Void ratio variations of samples with cenosphere

4.2 Water film thickness

In order to assess the water film thickness (WFT), the specific surface area of the cementitious material (solid surface area per solid volume) has been calculated using the following formula:

$$SSA_{CM} = SSA_1 + SSA_2 + SSA_3 \quad \text{----(3)}$$

Where, SSA_1, SSA_2, and SSA_3 are the specific surface areas of the particulate material in the cementitious composite. Based on the obtained values of E' and SSA_{CM}, WFT can be calculated as:

$$WFT = E'/SSA_{CM} \quad \text{---(4)}$$

Test results indicated that the increase in cenosphere content tends to increase the WFT up to a certain percentage. It was observed that addition of cenosphere up to 30% increased the WFT and the WFT decreased if the cenosphere content exceeds 30% in the cement paste. This may be due to high packing density and large surface area of the cenosphere because WFT is the net effect of the increase in solid surface area and excess water. Higher fineness of the SCM proportionally increases the solid surface area. If the surplus water increase is higher than the surface area increase, then the WFT would be increased or else decreased. Filler which improves the packing density may be considered as the ideal filler to enhance the WFT. Fig 6 shows the variations in WFT of the cement paste comprising different proportions of cenosphere for different W/CM ratios.

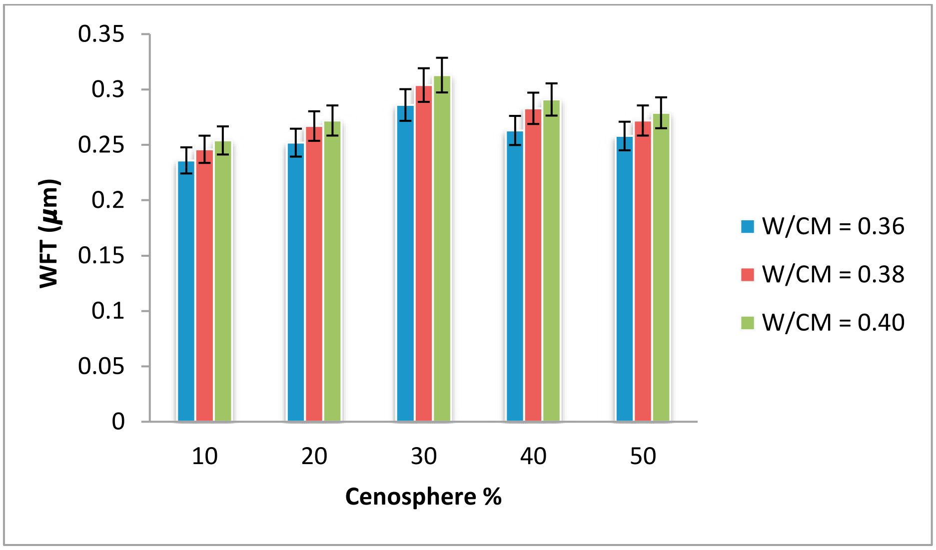
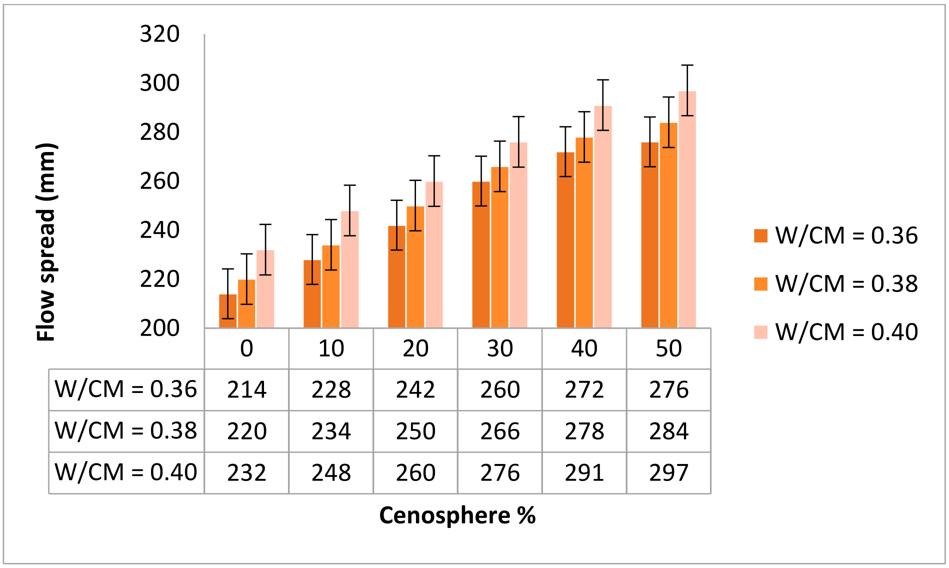


Fig. 6 Variations in WFT for different cenosphere contents and W/CM ratios

4.3 Flow spread

Test results signposted that with respect to cenosphere content and W/CM ratio significant improvement in flow spread was observed in the mix. Highest flow rate obtained at W/CM ratio of 0.40. However, W/CM ratio is not a predominant factor which governs flow spread.



	0	10	20	30	40	50
W/CM = 0.36	214	228	242	260	272	276
W/CM = 0.38	220	234	250	266	278	284
W/CM = 0.40	232	248	260	276	291	297

Fig. 7 Flow spread of mixes for different W/CM ratios

Addition of 30% ceneosphere content escalates the flow spread from 0 to 276 however mix encompassing 40% ceneosphere showed flow spread value of 291 mm. Minor escalation beyond 30% addition of the cenosphere may be due to the minimal water film thickness that inclines to confine the flowability of the mix at higher cenosphere replacement percentages. Fig. 7 shows the flow spread variations of the mixes for varying water to cement ratios and cenosphere content.

4.4 Compressive strength

Fig. 9 shows the 28-day compressive strength variations of different mixes. Compressive strength increase was observed with respect to reduction in W/CM ratio for 30% addition of cenosphere. It was noted that up surging the cenosphere content beyond 30% causes reduction in compressive strength. Hence, 30% considered as optimal replacement with lower W/CM ratio. Higher strength accomplishment in the cementitious system is due to pozzolanic effect of the cenosphere particles.

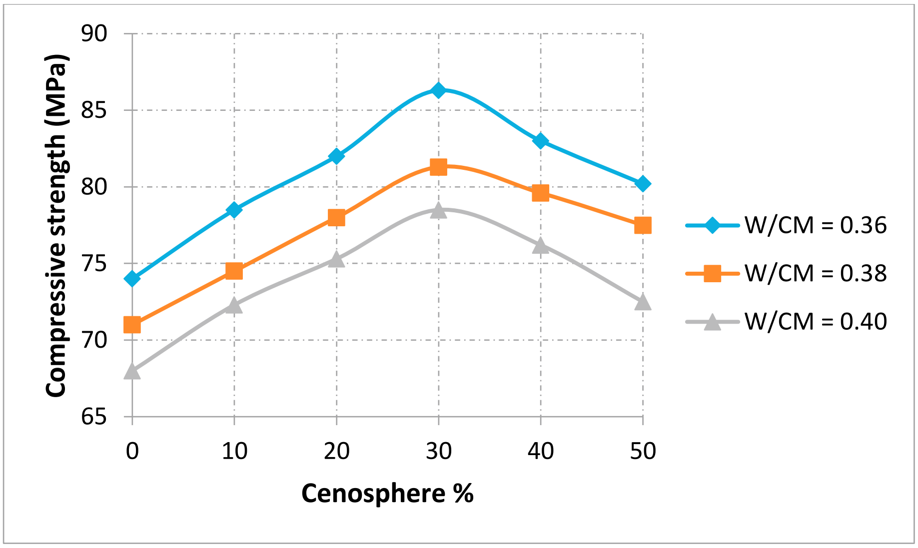


Fig. 9 Compressive strength variations for different W/CM ratios

The ideal substitution percentage of cenosphere is 30%. However, the ideal water-to-cementitious materials (W/CM) ratio may reliant on the cenosphere content in the mix. If water is not evenly dispersed throughout the paste, voids may become filled with air, leading to air entrainment. This, in turn, can reduce the compressive strength, regardless of the W/CM ratio. The air content significantly affects the strength of the cement paste. Therefore, cenosphere content alone not deciding the strength, but also by the W/CM ratio and thorough mixing of the constituents in the mix.

5. Conclusion

The following conclusions are drawn from the experimental investigation:

- Packing Density: The results clearly indicate that increasing the cenosphere content enhances the packing density of the cementitious mix. A significant improvement was observed up to a 30% replacement level, beyond which only marginal gains were noted.
- Optimal Packing at 30% Replacement: At a W/CM ratio of 0.40, the mix with 30% cenosphere replacement (PC30-0.40) exhibited an 18.9% increase in packing density compared to the control mix. Correspondingly, the void ratio was reduced by 43.7%.
- Water Film Thickness (WFT): The inclusion of cenospheres also increased the water film thickness. The highest WFT of 0.32 µm was recorded for the mix PC30-0.40. Mixes containing more than 30% cenosphere showed a reduction in WFT.
- An upsurge in cenosphere content enhanced the flow ability of the mixes. The PC30-0.40 mix achieved the maximum flow spread of 276 mm. Slight improvements in flow spread were also observed in mixes with cenosphere content exceeding 30%, though the increase was less pronounced.

- Compressive Strength: The highest compressive strength of 86.3 MPa was achieved by mix PC30-0.36. Based on the compressive strength data, 30% cenosphere replacement is identified as the optimum level for enhancing mechanical performance.

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