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Behavioral Analysis of HDPE-Infused Bubble Beams with Ceramic and Industrial Waste-Based Concrete

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Abstract

This research investigates the structural behavior of conventional and modified bubble-reinforced beams incorporating ceramic waste powder, fly ash, and ground granulated blast furnace slag (GGBS). The bubble beam approach involves embedding hollow plastic spheres within the tensile region of concrete beams—an area where concrete's contribution to strength is minimal. This strategy reduces the volume of concrete required, consequently lowering the beam's self-weight. High-density polyethylene (HDPE) spheres of varying sizes and shapes were used to form cavities in the beam core. M30 grade concrete was used to cast a series of beams, some incorporating these spheres and others serving as control specimens, to compare flexural performance and weight. Additionally, the study assessed the use of ceramic waste powder as a fine aggregate substitute, replacing 15% of the sand in the mix. Fly ash and GGBS were employed as supplementary cementitious materials, replacing cement at 10%, 20%, and 30%, with each proportion maintaining a 1:1 blend of the two materials. These modifications aimed to explore environmentally sustainable alternatives to traditional concrete components. Experimental results revealed that beams with ceramic waste and partial cement replacements achieved mechanical performance on par with traditional beams. Notably, the combination of fly ash and GGBS at a 20% substitution level provided the highest compressive strength among the modified mixes. Including HDPE spheres resulted in a 4.4% reduction in overall weight without compromising flexural strength, highlighting the technique's potential for lightweight, sustainable construction.

Keywords: *Bubble Beam; Ceramics Waste Powder; Flexural strength; Fly ash; GGBS*

1. Introduction

Beams play a critical role in structural systems, particularly in supporting slab loads in buildings. These elements are typically constructed using materials such as timber, steel, or concrete, with concrete being especially prevalent in commercial applications.[1-2] Due to its inherent characteristics, concrete performs well under compressive forces but lacks tensile strength. Therefore, in the design of reinforced concrete (RC) beams, engineers generally disregard the tensile capacity of concrete and rely on steel reinforcement to resist tension forces (Asalkar et al., 2018; Kolge et al., 2022). An alternative technique known as the bubble beam method focuses on minimizing the volume of concrete in the central zone of the beam—an area [3] that contributes little to load-bearing performance—thereby reducing the beam's self-weight significantly (Kumar & Dhiman, 2022; Nadeem et al., n.d.). Research has demonstrated that inserting hollow HDPE spheres with a diameter of 50 mm into this region can

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decrease concrete usage by approximately 2.07% without reducing structural capacity. After 28 days of curing, [4] bubble-reinforced concrete exhibited compressive and flexural strengths of 32.97 N/mm² and a 6% improvement, respectively, compared to 30.17 N/mm² for standard concrete. These results indicate a strength gain of roughly 9.28% in compression (Nadeem et al., n.d.). The behavior of RC deep beams is governed by several variables, including the shear span-to-effective depth ratio (a/d), the clear span-to-overall depth ratio (Ln/h), as well as the properties of the concrete, reinforcement, and load placement (Hasan et al., 2018). Shear failure is a primary concern in their design, but flexural failure can occur due to insufficient tensile reinforcement or corrosion, potentially leading to catastrophic failure (Kuchma et al., 2011). For beams with minimal reinforcement and a shear span-to-depth ratio of 1.11-1.67, flexural failure is common. Bubbles within deep beams reduce weight and deflection but do not change the failure mode. Weight reductions of 9.35% [5] and 18.7%, and mid-span deflection reductions of 7.7.5% and 17. 6% are noted for beams with shear span-to-depth ratios of 1.11 and one or two layers of bubbles, respectively. Bubble deck slabs, which use HDPE hollow bubbles, reduce dead load by one-third compared to solid slabs of the same depth without significantly affecting deflection behaviour or bending strength (Hasan et al., 2018). These slabs exhibit up to 40% less stress and internal forces than solid slabs(Kumar & Dhiman, 2022). Concrete production significantly contributes to global CO2 emissions, with cement alone accounting for 7% of these emissions (Daniel & Sangeetha, 2023). Fine aggregates, which constitute 30-35% of the concrete's volume, are crucial in providing workability and strength (Liang et al., 2022). A possible alternative to fine aggregates is ceramic tile waste powder (CWP) (Abou Rachied et al., 2023; Siddique et al., 2018). While replacing fine aggregates with CWP at 5%, 15%, and 20% levels tends to reduce compressive strength, a 10% replacement has been found to improve strength compared to conventional concrete (Daniel & Sangeetha, 2023). Incorporating industrial by-products such as Ground Granulated Blast-Furnace Slag (GGBS) and fly ash as partial substitutes for cement in natural fibre-reinforced concrete contributes to both sustainability and cost efficiency (Sheral et al., 2016; S.M & M, 2019; Wan et al., 2004). Studies have shown that GGBS can enhance early compressive strength, with increases of up to 21.5% at 7 days and 8.86% at 28 days, though excessive amounts of fly ash may negatively affect strength development (Kumar & Dhiman, 2022). Geopolymer concrete, which utilizes GGBS and fly ash either partially or entirely in place of cement, has demonstrated compressive strength levels comparable to those of standard concrete mixtures (Hasan et al., 2018). In addition to environmental benefits, the financial cost of integrating GGBS and fly ash aligns closely with conventional concrete production, offering a viable and greener alternative to traditional construction materials (Desale et al., n.d.). This research evaluates the structural efficiency and environmental impact of concrete beams modified with industrial by-products. It compares standard reinforced concrete beams with bubble beams that use hollow HDPE spheres to reduce weight. The study assesses the effects of replacing 15% of fine aggregate with ceramic waste powder and partially substituting cement with equal parts fly ash and GGBS at levels of 10%, 20%, and 30%. The goal is to evaluate flexural performance and material weight to assess the feasibility of producing lightweight, sustainable concrete elements. [6]

2. Experimental Program

Table 1 outlines the materials utilized along with their respective properties. Nine concrete cubes (150 mm × 150 mm × 150 mm) were cast with 15% fine aggregate replaced by ceramic waste powder (CWP). The cement was partially substituted with fly ash and GGBS at 10%, 20%, and 30%. Curing durations of 7, 21, and 28 days were applied, and compressive strength tests were conducted according to IS 516 (Part 1/Section 1):2021 to assess the mechanical properties. A total of nine reinforced concrete beams, each with dimensions of 150 mm × 150 mm × 700 mm, were prepared for this study. Three of these beams, made using standard concrete materials, were designated as control specimens and cured for 7, 21, and 28 days. Another set of three beams was

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produced by partially substituting cement with a 1:1 blend of fly ash and GGBS at replacement levels of 10%, 20%, and 30%. The remaining three beams combined a 15% replacement of fine aggregate with ceramic waste powder (CWP) and incorporated the same SCM blend (fly ash and GGBS in equal parts) at the same replacement levels of 10%, 20%, and 30%. (Table 1) [7] Each beam specimen was constructed with a 25 mm concrete cover on all sides, as illustrated in Figure 1. The longitudinal reinforcement consisted of 10 mm diameter steel bars, while 8 mm diameter bars were used for the stirrups. In the bubble beam configurations, hollow plastic spheres measuring 60 mm in diameter were integrated and held securely using a steel mesh framework, as depicted in (Figure 2) [8]

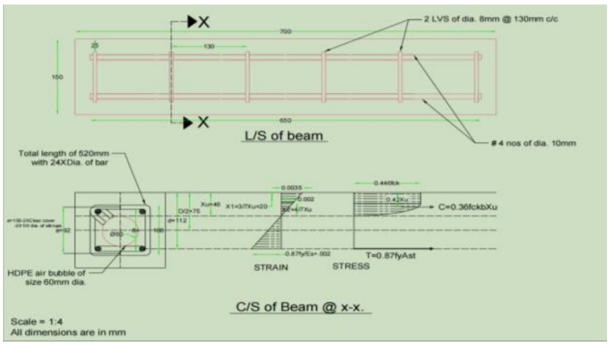

Figure 1 **Details of the Beam Specimen**


Figure 2 **Casting of the Beam Specimen**

Flexural strength testing was carried out on all nine reinforced concrete beams following IS 516 (Part 1/Section 1):2021. The tests were performed at 7, 21, and 28 days after casting. Each beam was supported at both ends and subjected to a two-point loading setup, with a 200 mm distance between the applied loads, as illustrated in Figure 3. The load at failure and the effective span were recorded for each specimen to determine its flexural strength. [9]

Table 1 **Materials Used and their Properties**

Materials	Description
Cement	OPC 53 Grade Testing done as per the IS code: Fineness (IS 4031-1988): 9.2% Specific gravity (IS 2720-part 3): 3.14 Consistency (IS 4031-1988): 31% Setting Time (IS 4031-1988): Initial- 29 min, Final- 600 min
Coarse aggregate	Size: 12mm down Testing done as per the IS code: Crushing value (IS 383-1970): 34.75% Impact Value (IS 283-1970): 15.5% Los Angeles Abrasion: 26.2% Specific Gravity: 2.92 Water Absorption: 1.96%
Fine aggregate	M sand Testing done as per the IS code Size: 4.75 mm down Specific Gravity (IS 2386-1963): 2.92 Water Absorption: 2.4% Moisture content: 1.6% Sieve Analysis: Zone II (As per IS 383-1970, Table 9)
	Ceramics Waste Powder (CWP): Size-4.75 mm down Specific Gravity (IS 2386-1963): 2.7 Sieve Analysis: Zone II (As per IS 383-1970, Table 9)
Water	Potable water conforming to IS 456: 2000
HDPE (-CH2-CH2-) n	Relative Density 950 kg/m^3 Melting point: 135˚C Softening point: 123˚C Solubility: Insoluble in water
Fly Ash	Class C
GGBS	Grade 100 GGBS
Reinforcement	Fe 500 for both top and bottom reinforcement. 10 mm Ø bars for the main reinforcement, 8 mm Ø bars for stirrups.
Concrete (M30)	Concrete mix design as per IS 10262: 2009 Slump value: 72mm

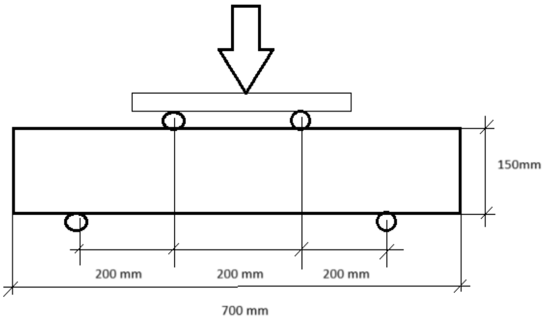

Figure 3 Flexural Strength Test Setup

3. Results and Discussion

3.1. Effect on Workability

The workability of fresh conventional concrete and with partial replacements of 10-30% cementitious material with SCM and 15% CWP was maintained within the slump range of 68-81 mm, as indicated in Table 2. The slump test results revealed a noticeable pattern in the workability of concrete modified with supplementary cementitious materials (SCMs) and ceramic waste powder (CWP). When compared to the conventional mix, which had a slump of 72 mm, the mixes containing 10% and 20% SCM exhibited enhanced workability, reaching slump values of 77 mm and 81 mm, respectively. This enhancement is primarily due to the spherical shape and smooth texture of fly ash particles and the filler effect of GGBS, which reduces internal friction and improves particle packing. However, at 30% replacement, the slump decreased to 74 mm, likely due to increased fineness and water demand of the SCMs, which start absorbing more water and reducing flowability. When 15% ceramic waste powder was added to each of these combinations, a noticeable reduction in slump was observed across all mixes, down to 70 mm, 72 mm, and 68 mm, respectively. This decline in workability is attributed to the angularity and high surface area of ceramic waste powder, which increases water demand and reduces the mix's ease of flow. Overall, moderate replacement with SCMS improves workability, but excessive SCMs and the addition of ceramic waste reduce the slump due to higher water absorption and reduced lubrication among particles (Abou Rachied et al., 2023; Daniel & Sangeetha, 2023; Desale et al., n.d.; Sheral et al., 2016; Siddique et al., 2018; Wan et al., 2004) [10]

Table 2 Slump of Different Mixes

MIX	SLUMP, mm
Conventional	72
Mix with 10% SCM	77
Mix with 20% SCM	81
Mix with 30% SCM	74
Mix with 10% SCM & 15% CWP	70
Mix with 20% SCM & 15% CWP	72
Mix with 30% SCM & 15% CWP	68

3.2. Effect on Compressive Strength

As illustrated in Figure 4, the compressive strength results demonstrate that incorporating SCMs along with CWP contributes positively to concrete performance. All mix variations showed a consistent increase in compressive strength with longer curing durations. The standard mix achieved a strength of 32.56 MPa at 28 days, while the mixes with 10% and 20% SCM substitutions produced strengths of 29.6 MPa and 32.5 MPa, respectively. However, using 30% SCM resulted in a substantial decrease in strength to 21.4 MPa, suggesting that excessive SCM content can be detrimental as it delays hydration and weakens strength. The introduction of 15% CWP significantly improved strength across all mixtures, with the combination of 20% SCM and 15% CWP achieving the highest strength of 38.05 MPa at 28 days. This later-age enhancement is linked to the synergistic effects of SCMs and CWP, which boost pozzolanic activity and improve the concrete's microstructure. CWP acts as a filler and additional pozzolanic material, promoting secondary gel formation and refining pore structure, which explains the enhanced strength (Daniel & Sangeetha, 2023; Desale et al., n.d.; Liang et al., 2022; Sheral et al., 2016; Siddique et al., 2018; Wan et al., 2004). [11]

3.3. Effect on Flexural Strength

The flexural behaviour and corresponding deflection at failure of three types of concrete beams—conventional, conventional with bubbles, and bubble beams incorporating 20% SCM and 15% CWP—were analysed at 7, 21, and 28 days, with results shown in Figure 5 At 7 days, the conventional beam

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exhibited the highest deflection (0.231 mm) and load at failure (27,857 N), while the bubble beam with SCM and CWP showed a slightly lower deflection (0.210 mm) and comparable load (27,300 N), indicating early strength development due to supplementary materials. By 21 days, all beams displayed reduced deflections, with the bubble beam containing SCM and CWP achieving the lowest deflection (0.172 mm) and demonstrating superior stiffness compared to the conventional beam (0.19 mm). At 28 days, the trend continued, with the SCM and CWP-modified bubble beam recording the smallest deflection (0.1795 mm) while maintaining a high load-bearing capacity (32,689 N). [12]

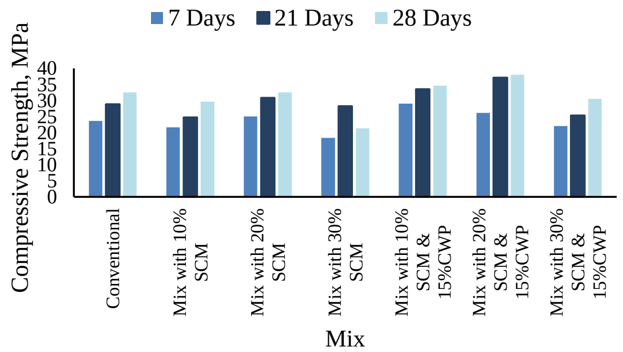

Figure 4 Compressive Strength of Different Mixes

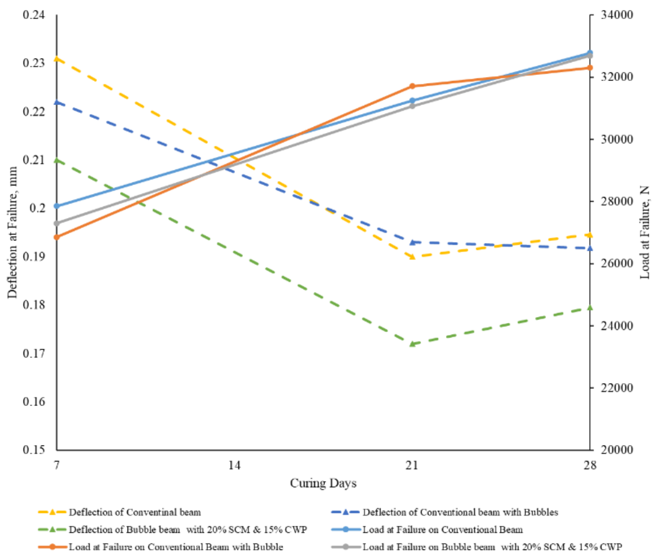

Figure 5 Variation of Deflection and Load at Failure for Different Beams with Age

Including SCM and CWP improved flexural strength, significantly enhanced the stiffness, and reduced deformation under load. These findings confirm that moderate use of industrial by-products can effectively strengthen concrete while promoting sustainability without compromising structural performance. The flexural strength development of the three beam types over 7, 21, and 28 days, as presented in Figure 6, provides valuable insights into their structural performance. The conventional beam demonstrated the highest flexural strength after 28 days (6.8 MPa), demonstrating consistent strength gain with age due to effective cement hydration and matrix formation. The conventional beam with bubble showed the lowest initial strength (5.6 MPa at 7 days), likely due to the internal voids introduced by the bubble structure, which may slightly weaken the early-age matrix (Ali & Manoj Kumar, 2017; Hasan et al., 2018). However, it displayed a significant improvement by 21 and 28 days, reaching 6.7 MPa, indicating that proper curing mitigates the initial weakness. Notably, the bubble beam with 20% SCM and 15% CWP delivered a strong early performance (5.7 MPa at 7 days) and nearly matched the conventional beam by 28 days with a flexural strength of 6.78 MPa. This implies that the inclusion of supplementary cementitious materials and ceramic waste powder can sustain, and possibly improve, long-term strength, while also contributing to more sustainable practices. [13]

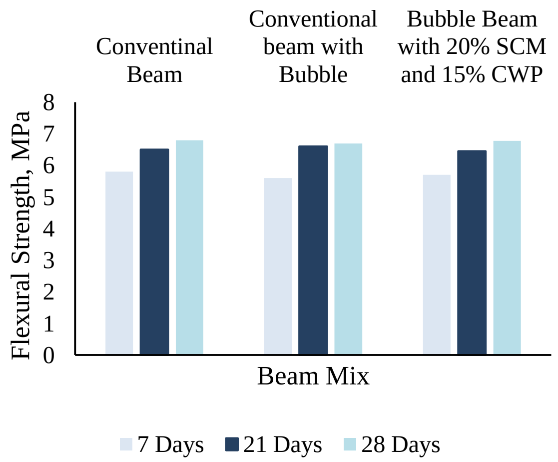

Figure 6 Variation of the Flexural Strength of Different Beams with Age

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Conclusion

- Partial substitution of cement with up to 20% SCM significantly enhances workability, with the highest slump (81 mm) observed at 20% SCM due to improved particle packing and reduced internal friction. [14]
- The incorporation of 15% ceramic waste powder consistently lowered the workability, suggesting that its increased water demand and angular texture adversely impact the slump, particularly when paired with higher levels of SCMs.
- The highest compressive strength of 38.05 MPa at 28 days was observed with a combination of 20% SCM and 15% CWP, attributed to the improved pozzolanic reaction and the resulting refinement of the concrete's microstructure.
- While moderate SCM replacement improves strength, excessive SCM (30%) without CWP significantly reduces compressive strength, highlighting the importance of balanced substitution levels for optimal performance.
- Incorporating 20% SCM and 15% CWP in bubble concrete beams significantly improved flexural performance, achieving high load-bearing capacity and the lowest deflection at all curing ages, indicating enhanced stiffness and early strength development. [15]
- Flexural strength of the SCM- and CWP-modified beams nearly matched that of conventional beams by 28 days, confirming that industrial by-products can effectively substitute a portion of cement without compromising structural integrity.
- The use of SCM and CWP promotes sustainable concrete development, offering a balance between performance and environmental responsibility by improving mechanical properties while reducing cement usage and incorporating waste materials.

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