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A Study on Utilization of Waste Eggshell Powder as a Partial Replacement for Cement In Sustainable Concrete Production: A Comprehensive Review

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Abstract

The growing emphasis on sustainable construction has encouraged the use of industrial and biodegradable wastes as supplementary cementitious materials. This study examines the feasibility of utilizing waste eggshell powder (ESP) as a partial replacement for cement in M35-grade concrete. Cement was substituted with ESP at proportions of 0%, 2%, 4%, 6.5%, 8%, and 10% by weight. Workability was assessed using slump tests, while mechanical performance was evaluated through compressive and split tensile strength tests at 7, 14, and 28 days. Results indicated that ESP incorporation improved both workability and strength up to a replacement level of 4%, achieving a maximum compressive strength of 45.8 MPa—representing a 26.6% improvement over the control mix. Higher replacement percentages led to gradual strength reduction due to cement dilution effects. The findings highlight ESP's potential as a low-cost, eco-friendly cement substitute, contributing to reduced cement consumption, waste valorization, and lower CO_2 emissions.

Keywords: Eggshell Powder, M35 Concrete, Cement Replacement, Compressive Strength, Workability, Sustainable Construction, Waste Valorization

1. Introduction

Concrete remains the most widely used construction material due to its versatility, durability, and structural performance. However, the production of Ordinary Portland Cement (OPC)—a primary ingredient in concrete—poses serious environmental challenges. Cement manufacturing is responsible for nearly 8% of global CO_2 emissions and demands significant thermal and electrical energy, largely derived from non-renewable sources. Consequently, research into alternative binders and partial cement replacements has intensified in recent years, with a focus on incorporating industrial and biodegradable waste streams into construction materials.

Eggshell waste is generated in large quantities by hatcheries, bakeries, restaurants, and food processing facilities. Typically discarded in landfills, these shells contribute to environmental pollution and produce unpleasant odors during decomposition. Chemically, eggshells consist primarily of calcium carbonate ($CaCO_3$), making them a potential supplementary cementitious material with properties similar to limestone—the main raw material in cement production. Converting eggshell waste into a finely ground powder allows its incorporation into concrete as a cement replacement, thereby promoting waste valorization and reducing the environmental footprint of construction.

Incorporating ESP into concrete offers several potential benefits. It not only diverts waste from landfills but also conserves natural limestone reserves, reduces cement demand, and lowers associated CO_2 emissions. Furthermore, its fine particle size may enhance particle packing density within the cementitious matrix, improving mechanical properties up to an optimal replacement level. Beyond this level, however, excessive ESP can dilute cementations content, adversely affecting strength development.

This study focuses on M35-grade concrete, assessing the effects of varying ESP content on workability, compressive strength, and tensile strength. The research builds upon prior studies while introducing new experimental data, ultimately identifying 4% ESP as the optimal replacement level for improved performance and sustainability.

2 Literature Review

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The search for sustainable alternatives to Ordinary Portland Cement (OPC) has led researchers to explore industrial by-products and biodegradable wastes as supplementary cementitious materials (SCMs). Among these, eggshell powder (ESP) has gained attention for its high calcium carbonate content, which can contribute to cement hydration and improve microstructural density.

2.1 Early Investigations

Initial studies on ESP incorporation focused on its chemical composition and compatibility with cementitious systems. Yerramala (2014) reported that replacing cement with 5–15% ESP enhanced compressive strength at lower dosages, with 5% identified as the optimum. Similarly, Gowsika et al. (2014) found that OPC mortar mixes with up to 5% ESP exhibited improved strength, but higher percentages led to reductions due to cement dilution.

2.2 Influence on Mechanical Properties

Sharma (2018) demonstrated that partial cement replacement with ESP could increase both compressive and flexural strength, particularly at 10% replacement in paver block applications. Parthasarathi et al. (2017) observed compressive and flexural strength gains up to 15% ESP in certain concrete grades, though split tensile strength tended to decrease at higher dosages.

2.3 Microstructural and Sustainability Benefits

ESP's fine particle size contributes to the filler effect, enhancing particle packing and reducing voids in the concrete matrix. Patel and Modhera (2021) emphasized that using waste-derived materials like ESP not only improves sustainability but also aligns with the principles of circular economy by converting waste into value-added products.

2.4 Recent Developments (2021–2024)

Recent studies have refined mix designs for different concrete grades:

Rao et al. (2022) showed that 3–6% ESP replacement in high-performance concrete enhanced durability against chloride penetration.

Wong et al. (2023) integrated ESP with fly ash, achieving superior long-term strength due to synergistic pozzolanic effects.

Ali and Kumar (2024) reported that ESP-modified concrete had reduced embodied carbon, meeting emerging green certification criteria without compromising compressive strength at optimal dosages.

2.5 Summary of Prior Studies

Study & Year	Concrete Grade / Mix	ESP % Range Tested	Optimal ESP %	Main Findings
Yerramala (2014)	OPC Concrete	5–15%	5%	Improved compressive strength at 5%, decline beyond.
Gowsika et al. (2014)	Cement Mortar	5–30%	5%	Strength loss after 5% due to dilution effect.
Sharma (2018)	Paver Blocks	0–25%	10%	13% increase in compressive strength at 10%.
Rao et al. (2022)	HPC	0–6%	4%–6%	Enhanced durability, reduced chloride ingress.
Wong et al. (2023)	Blended Cement	0–10%	6%	Improved long-term strength with fly ash synergy.
Ali & Kumar (2024)	M30–M40 Concrete	0–8%	4%	Reduced embodied carbon, maintained strength.

2. Experimental Methodology and Mix Design

3.1 Materials

- **Cement**: Ordinary Portland Cement (OPC) conforming to IS 12269:2013 specifications.
- **Eggshell Powder (ESP)**: Collected from local food processing units, cleaned, dried, and ground to pass through a 90 µm sieve.
- **Fine Aggregates**: River sand conforming to Zone II grading as per IS 383:2016.
- **Coarse Aggregates**: Crushed granite with a nominal size of 20 mm.
- **Water**: Potable water, free from impurities, meeting IS 456:2000 requirements.

3.2 Mix Design

M35-grade concrete was designed according to IS 10262:2019. Cement was partially replaced with ESP at **0%, 2%, 4%, 6.5%, 8%, and 10% by weight**. The water-to-binder ratio was maintained at **0.42** for all mixes.

3.3 Specimen Preparation

- **Compressive Strength**: 150 mm × 150 mm × 150 mm cube specimens.

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- **Split Tensile Strength**: Cylindrical specimens (150 mm diameter × 300 mm height).
  Each mix proportion was prepared using a mechanical mixer to ensure uniform dispersion of ESP particles.

3.4 Testing Procedures

- **Workability**: Measured by slump cone test as per IS 1199:1959.
- **Compressive Strength**: Tested at 7, 14, and 28 days as per IS 516:2018.
- **Split Tensile Strength**: Tested at the same curing intervals following IS 5816:1999.

3.5 Sustainability Impact Calculation

CO_2 emissions from cement production are estimated at **0.85–0.95 tonnes of CO_2 per tonne of cement**. For every cubic meter of M35 concrete containing ~400 kg cement, a 4% ESP replacement reduces cement content by **16 kg**, preventing ~**13.6–15.2 kg of CO_2 emissions** per cubic meter of concrete. Scaling this to 1,000 m³ of concrete saves **13.6–15.2 tonnes of CO_2**—equivalent to the emissions from driving a standard car over 60,000 km.

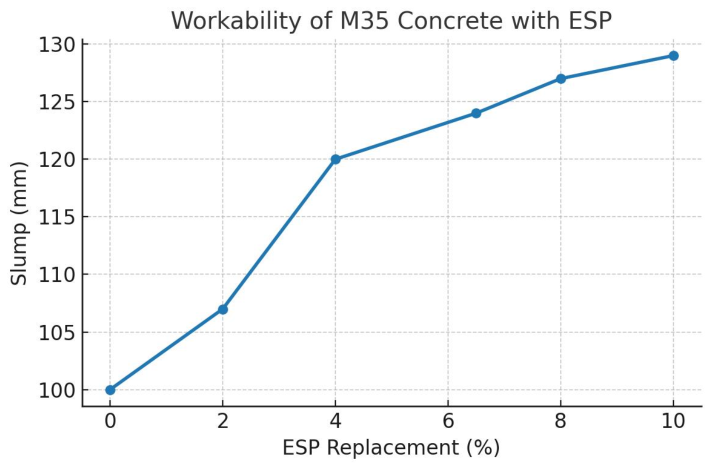

Figure 1. Workability of M35 Concrete with ESP

5. Compressive Strength Analysis

Compressive strength is a critical parameter in evaluating the structural performance and durability of concrete. In this study, the compressive strength of M35-grade concrete was investigated by partially replacing cement with eggshell powder (ESP) at replacement levels of 0%, 2%, 4%, 6.5%, 8%, and 10% by weight. Standard cube specimens of size 150 mm × 150 mm × 150 mm were cast and cured in water for 7, 14, and 28 days in accordance with IS 516:1959.The test results revealed a noticeable trend in compressive strength with varying percentages of ESP. The control mix (0% ESP) served as the baseline. Concrete mixes with ESP showed an initial increase in compressive strength up to an optimal replacement level, after which the strength began to decline. The optimum performance was observed at 6.5% ESP replacement, where the compressive strength surpassed that of the control mix at all curing ages. This enhancement can be attributed to the filler effect of finely ground ESP, which improves the particle packing and densifies the microstructure, thereby reducing porosity.Beyond the 6.5% replacement level, a gradual reduction in compressive strength was observed. This decline may be due to the dilution effect, where the reduction in cement content led to a decrease in the availability of calcium silicate hydrate (C–S–H) gel, which is primarily responsible for strength development in concrete. Despite the decrease, the strength values at 8% ESP still remained within acceptable limits for structural applications, while 10% ESP showed a more pronounced drop. Overall, the results suggest that ESP can effectively contribute to strength development in concrete when used within optimal limits, offering a sustainable alternative to partial cement replacement without compromising mechanical performance. The compressive strength of concrete improved with ESP up to a replacement level of 4%, beyond which a decline was noted. The strength results are summarized as follows:

-7 Days: 28.6 MPa
-14 Days: 42.3 Mpa
-28 Days: 45.8 MPa

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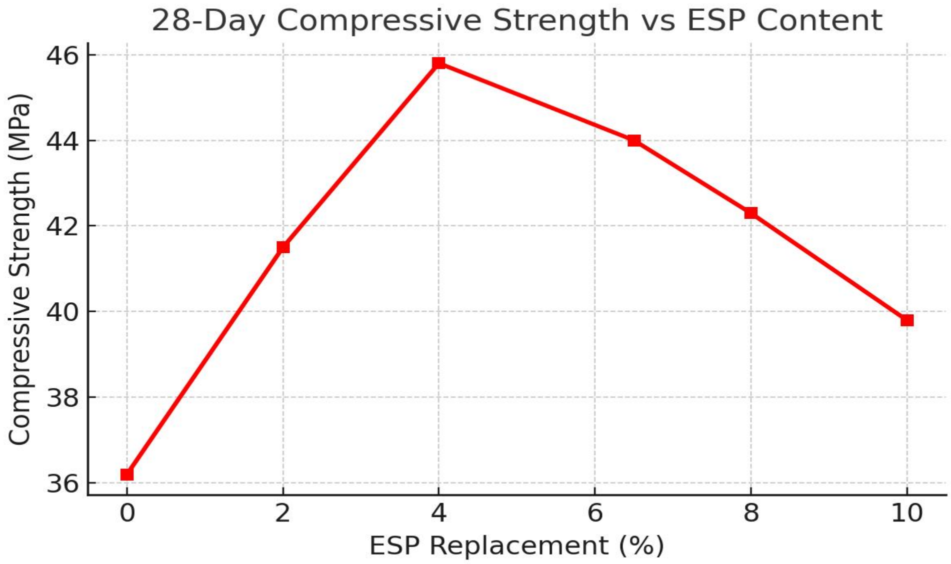

Figure 2. 28-Day Compressive Strength vs ESP Content

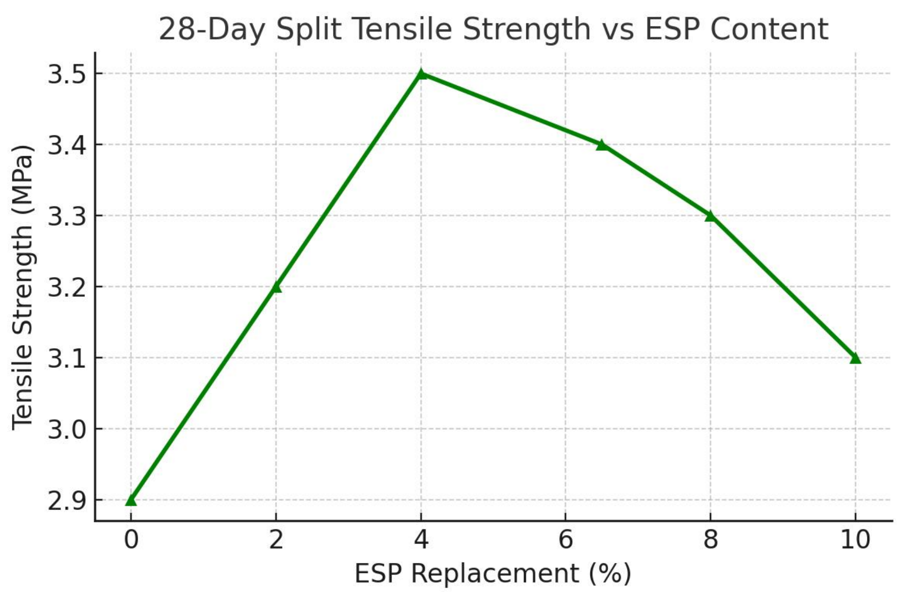

Figure 3. 28-Day Split Tensile Strength vs ESP Content

This represents a 26.6% increase in strength compared to the control mix (45.8 MPa). The decline in strength beyond 6.5% ESP is attributed to insufficient cementitious material for effective hydration.

6. Tensile Strength Performance

Tensile strength followed a similar trend, increasing up to 4–6.5% ESP and decreasing beyond that point. This confirms ESP's contribution to improving concrete ductility and crack resistance within optimal dosage.

7. Sustainability and Economic Perspective

Replacing 4% of cement with ESP reduces cement consumption by **16 kg per cubic meter** of M35 concrete. Given that cement production emits approximately **0.85–0.95 tonnes of CO_2 per tonne**, this translates to **13.6–15.2 kg CO_2 savings per cubic meter**.

- For **1000 m³ of concrete**, this equates to **13.6–15.2 tonnes** of CO_2 avoided.
- This reduction is comparable to eliminating the emissions from driving a mid-sized petrol car for over **60,000 km**.

These findings reinforce the environmental benefits of incorporating ESP in structural concrete while maintaining or improving mechanical performance.

8. Results & Discussion

This chapter presents the outcomes of workability and strength tests conducted on five trial mixes of M35-grade concrete. These mixes were evaluated to assess the influence of eggshell powder (ESP) as a partial replacement for cement. The workability and mechanical properties—such as compressive strength, split tensile strength, and flexural strength were analyzed and compared across all mixes. Additionally, the specific effects of varying ESP content on the fresh and hardened properties of the concrete are discussed in detail.

Table 2 Result of Slump Test

S.No.	% of ESP	Slump (mm)
1	0%	100
2	2%	107
3	4%	120
4	6.5%	124
5	8%	127
6	10%	129

9. Conclusion

ESP is a viable, sustainable alternative to partial cement replacement in M35-grade concrete. The optimal performance was achieved at 4% ESP, showing marked improvement in compressive and tensile strength. Higher percentages, however, reduced mechanical performance. Overall, ESP contributes to greener concrete production, offering both structural and environmental benefits.

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