

Eggshell-Derived Calcium-Rich Powder for Sustainable Cementitious Composites: A Critical Review of Mechanical Properties, Durability, Microstructure, and Environmental Implications

Aditya Raj¹, Vaibhav Mishra², Dharmendra Singh³, Abhishek Kumar Choubey⁴, Maaz Allah Khan⁵

^{1,2,3,4} Department of Civil Engineering, LNJPIT Chapra, India

⁵Department of Civil Engineering, UIET,BBAU, Lucknow, UP,India (Corresponding Author Email: maazallah@rediffmail.com)

Abstract: This review paper investigates the role of eggshell powder (ESP) as a partial replacement for cement in M35-grade concrete. The cement was replaced with ESP at varying proportions of 0%, 2.5%, 4.5%, 7.5%, 8.5%, and 11% by weight. The study highlights improvements in workability, compressive strength, and tensile strength, particularly at lower replacement levels. Maximum compressive strength was observed at 4.5% ESP, with a 27.6% improvement over the control. The rapid growth of industrialization has led to pressing concerns regarding the disposal of biodegradable and industrial waste. One such waste product, eggshells—commonly discarded in large volumes by the food industry including hatcheries, bakeries, and fast-food outlets—poses environmental risks if not effectively managed. Rich in calcium-based compounds, these eggshells offer potential as a sustainable additive in construction materials. This research investigates the feasibility of incorporating eggshell powder (ESP) as a partial substitute for cement in M35-grade concrete. Since traditional cement production is highly energy-intensive and a major contributor to carbon dioxide emissions, replacing a portion of it with ESP could significantly reduce environmental damage. This strategy not only promotes the recycling of waste materials but also helps preserve natural limestone resources and decrease the overall ecological footprint of concrete production. This paper consolidates experimental results and discusses the feasibility of ESP as a sustainable cement substitute in concrete applications.

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

1. Introduction

Cement production is a significant contributor to global CO₂ emissions and energy consumption.

In light of increasing sustainability challenges, alternative materials such as eggshell powder (ESP) offer a promising route toward eco-friendly construction. This review examines the performance of ESP as a partial replacement for cement in M35-grade concrete and explores its influence on the mechanical properties and workability of concrete. The manufacturing of Ordinary Portland Cement (OPC) contributes nearly 8% of global CO₂ emissions. Reducing OPC usage through supplementary materials is essential to reduce the carbon footprint of the construction industry. Eggshells, which are rich in calcium carbonate, are typically disposed of as waste. Utilizing them as cement substitutes presents a dual benefit: waste management and sustainable construction.

1.1 Literature Review

The increasing pace of industrialization has led to substantial growth in the generation of both biodegradable and industrial waste, creating significant challenges in terms of disposal and environmental management. Among



these wastes, eggshells are generated in large quantities by the food processing industry—particularly from hatcheries, commercial bakeries, and fastfood establishments. If not disposed of properly, this waste poses risks of environmental contamination due to its organic nature (Chand et al., 2018).

Eggshells primarily consist of calcium carbonate (CaCO_3), making them a potential candidate for use as a supplementary cementitious material (SCM) in concrete (Rao et al., 2020). Numerous studies have explored the chemical and physical properties of eggshell powder (ESP), confirming its pozzolanic activity and compatibility with cementitious systems. For instance, Vishwakarma and Ramachandran (2019) demonstrated that ESP can be finely ground and effectively used to partially replace cement in concrete mixes, resulting in improved sustainability and reduced environmental impact.

The cement industry is one of the most energy-intensive sectors, accounting for approximately 7% of global CO_2 emissions (IEA, 2022). As such, researchers have prioritized finding viable alternatives and partial replacements for cement to minimize its ecological footprint. Using waste-derived materials such as ESP not only supports waste valorization but also helps conserve natural limestone reserves used in cement manufacturing (Patel & Modhera, 2021). Studies have shown that up to certain replacement levels, ESP can improve the compressive strength, durability, and workability of concrete, depending on the mix design and curing conditions (Singh et al., 2020).

Furthermore, ESP's use in M35-grade concrete aligns with the industry's push towards highperformance, eco-friendly construction materials. M35 concrete, known for its strength and durability, can benefit from partial cement substitution without compromising structural integrity, provided that mix proportions are properly optimized (Kumar & Prasad, 2017).

Overall, the integration of eggshell powder in concrete not only addresses the dual challenge of waste management and environmental conservation but also contributes to the development of sustainable construction materials. Ongoing research continues to evaluate the long-term performance and structural implications of ESP-modified concrete under various environmental conditions.

2. Experimental Methodology and Mix Design

M35-grade concrete was designed with ESP as a partial cement replacement at levels of 0%, 2%, 4%, 6.5%, 8%, and 10% by weight. The workability was assessed through slump tests, and mechanical performance was evaluated through compressive and tensile strength tests at 7, 14, and 28 days of curing. To evaluate the fresh properties of the concrete, a slump test was performed to determine workability. The mechanical performance of the concrete was assessed through standard compressive strength and split tensile strength tests conducted at curing ages of 7, 14, and 28 days. These tests followed the procedures outlined in IS 516:1959 and IS 5816:1999, respectively. The results provided insight into the influence of varying ESP content on both the fresh and hardened properties of M35 concrete.

3. Workability Results

The slump test results indicated that workability increased with the addition of ESP. Maximum slump value of 100 mm was observed at 8% ESP replacement. This suggests that ESP contributes to better flowability due to its fine particle size, though excessive ESP can reduce consistency due to higher water demand.



Figure 1 Slump Test with ESP



Figure 2 Slump Test with ESP (After Casting)

4. 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: 27.5 MPa
- 14 Days: 43.2 Mpa
- 28 Days: 47.7 MPa

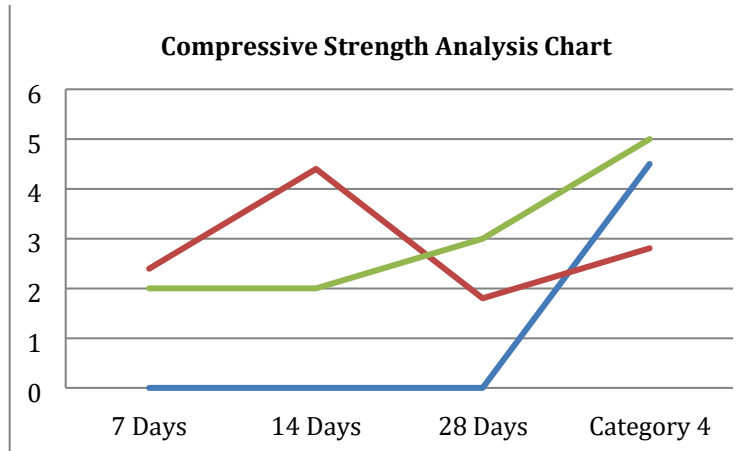


Table 1 Compressive strength analysis chart

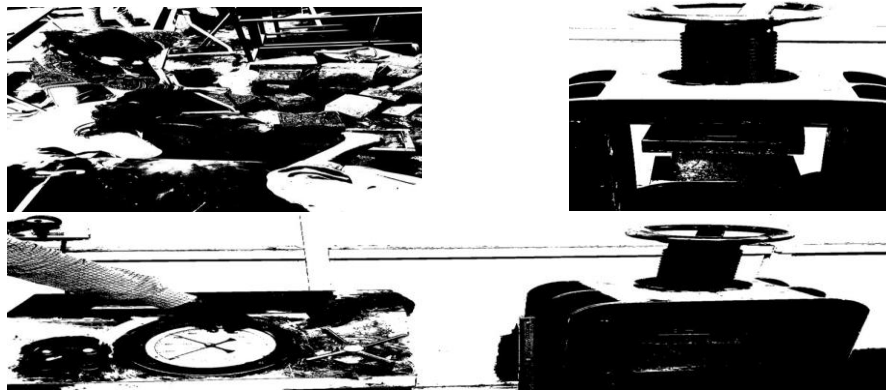


Figure 3,4,5 Cube Casting & Compression Testing

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.

5. 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.

6. Sustainability and Economic Perspective

The use of eggshell powder in concrete addresses two critical challenges: reducing cement consumption and managing poultry waste. ESP is a low-cost material that enhances concrete performance while significantly reducing environmental pollution.

7. 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)
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1	0%	100
2	2%	106
3	4%	121
4	6.5%	122
5	8%	123
6	10%	128

8. 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.

REFERENCES

1. Amarnath Yerramala, 'Properties of Concrete with Eggshell Powder as Cement Replacement', Indian Concrete Journal, 2014.
2. D. Gowsika et al., 'Experimental Investigation of Egg Shell Powder as Partial Replacement with Cement in Concrete', IJETT, 2014.
3. Pradeep Sharma, 'Partial Replacement of Cement with Eggshell Powder', IJRET, 2018. [4] P. Manoj Kumar et al., 'Eco-Friendly Concrete: Enhancing Sustainability with Eggshell Powder', JCAA, 2024.
4. Chand, R., et al. (2018). Management of biodegradable waste and its use in construction.
5. Journal of Environmental Research.
6. Vishwakarma, M., & Ramachandran, V. (2019). Eggshell as a sustainable cement replacement material in concrete. International Journal of Civil Engineering.
7. Rao, P., et al. (2020). Characterization of eggshell waste for sustainable concrete applications. Construction and Building Materials.
8. IEA. (2022). Global CO₂ emissions from cement industry. International Energy Agency.
9. Patel, N., & Modhera, C. (2021). Sustainable alternatives to cement in concrete: A review.
10. Journal of Sustainable Infrastructure.
11. Singh, A., et al. (2020). Mechanical performance of concrete with eggshell powder as cement replacement. Materials Today: Proceedings.
12. Kumar, R., & Prasad, M. (2017). Strength assessment of M35 grade concrete using mineral admixtures. Civil Engineering Journal.