iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 12 Issue: XII Month of publication: December 2024

DOI: https://doi.org/10.22214/ijraset.2024.66053

www.ijraset.com

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 12 Issue XII Dec 2024- Available at www.ijraset.com

Eggshell Waste to Wonder: A Novel Approach to Sustainable Cementitious Materials

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Abstract: Eggshells, a widely available byproduct of food consumption, are generated in vast quantities globally, with significant waste accumulation in domestic and industrial settings. Despite their high calcium carbonate content, eggshells are often discarded, leading to environmental concerns such as landfill congestion and methane emissions. This study explores the potential of repurposing powdered eggshells as a partial replacement for cement in concrete production, addressing both waste management challenges and the sustainability of cement manufacturing. In this experimental investigation, cement was replaced by eggshell powder in varying proportions of 2.5%, 5%, 7.5%, and 10%. Concrete mixes were prepared, and the resulting properties, including mechanical strength and durability, were evaluated. The results showed that the mix with 10% eggshell powder replacement exhibited the best performance, demonstrating optimal mechanical strength and durability. This study underscores the feasibility of utilizing eggshells as a sustainable alternative material in concrete, contributing to circular economy practices. By reducing reliance on mined limestone and decreasing carbon emissions associated with traditional cement production, the use of eggshells offers an eco-friendly solution to both waste management and industrial sustainability. The findings support the growing recognition of eggshells as a recyclable resource in various industries, including construction, and highlight their potential to reduce waste accumulation while promoting sustainable development.

Keywords: Cement replacement, Eggshells, Mechanical strength, Sustainability, Water Absorption

I. INTRODUCTION

Eggshells, a readily available and often overlooked byproduct of daily food consumption, are generated in significant quantities worldwide. In domestic kitchens, several eggshells can accumulate weekly depending on household dietary habits, while in industrial settings—such as egg processing plants, bakeries, fast-food chains, and chick hatcheries—the volume of discarded eggshells becomes exponentially larger. Despite their potential utility, a majority of eggshells are discarded as waste, leading to various environmental concerns. Recognizing their inherent chemical composition and material properties, however, has prompted researchers and industries to explore their potential in diverse applications, including agriculture, food production, and construction. The food industry has demonstrated the viability of repurposing eggshells for uses such as animal feed and calcium supplements, where their high calcium content offers nutritional benefits. Eggshells have also been employed as a clarifying agent in the beverage industry, particularly in brewing, and in bakeries, finely ground eggshell powder has been added to enhance the nutritional value of baked goods. These efforts highlight a growing recognition of eggshells as a recyclable resource, emphasizing their potential to reduce waste accumulation and support sustainable practices. India, a major global producer of eggs, underscores the scale of eggshell waste with significant production metrics. In the fiscal year 2023, the per capita availability of eggs in the country reached 101 eggs per annum, with a total production exceeding 138 billion eggs. These figures, reported by SandhyaKeelery (2024), illustrate the considerable quantities of eggshells generated annually. Without proper disposal methods, these eggshells pose environmental challenges. In landfills, eggshells decompose slowly under anaerobic conditions, releasing methane—a potent greenhouse gas—into the atmosphere. Additionally, improperly discarded eggshells can attract pests, such as rodents and insects, creating hygiene and contamination issues in urban and rural environments. Failure to utilize eggshells not only wastes their potential but also exacerbates ecological problems such as landfill congestion and resource depletion. Chemically, eggshells are primarily composed of calcium carbonate ($CaCO_3$), which constitutes 94–97% of their structure. They also contain minor components, including magnesium carbonate ($MgCO_3$), calcium phosphate ($Ca_3(PO_4)_2$), organic compounds such as collagen, trace elements like zinc, iron, and manganese, and a small percentage of water. This composition, dominated by calcium carbonate, makes eggshells a material of significant interest, particularly in industries requiring a sustainable source of lime (CaO), such as cement manufacturing.

The cement industry relies heavily on calcium carbonate, traditionally sourced from mined limestone, for producing lime—a fundamental component in clinker production. Clinker, in turn, is the precursor to cement, which is essential for concrete production. The high calcium carbonate content of eggshells makes them a promising alternative raw material for cement manufacturing. Utilizing eggshells not only reduces the dependence on limestone mining but also addresses waste management challenges by repurposing an agricultural byproduct. This study investigates the use of powdered eggshells as a partial replacement for cement in concrete. A reference concrete mix design was prepared, with cement fractions replaced by eggshell powder in varying proportions of 5%, 10%, 15%, and 20%. The resulting mixes were evaluated for durability, mechanical strength, and other performance parameters. Among these, the mix with 10% eggshell powder replacement exhibited optimal properties, demonstrating both mechanical reliability and durability. The incorporation of eggshells into cement production aligns with the principles of waste valorization, a concept where waste materials are repurposed to create valuable products. This approach not only mitigates the environmental footprint of cement manufacturing but also reduces the carbon emissions associated with traditional processes. By replacing a portion of the cement with eggshell powder, this study contributes to global efforts to promote circular economies, reduce industrial waste, and support sustainable development goals. Ultimately, leveraging eggshells in cement production offers a dual benefit: addressing waste management issues while providing an eco-friendly alternative to conventional materials.

II. LITERATURE REVIEW

[1] Aravind and Ranjith (2022) explored the use of eggshell powder (ESP) as a partial substitute for cement and steel slag as a replacement for coarse aggregates in M30 grade concrete. The study aimed to reduce environmental impacts from cement production and address the demand for sustainable materials. ESP was tested at 10%, 20%, and 30% replacements, with similar levels of steel slag as coarse aggregate replacement. The results showed that 20% ESP improved tensile strength by 30%, but workability decreased due to its finer texture and higher water absorption. Despite this, compressive strength and durability were enhanced. Steel slag replacement led to a 7-8% increase in compressive strength, with improved density and stability. These findings highlight the potential of ESP and steel slag to improve concrete performance, reduce cement use, and support sustainability in construction.

[2] Zhang et al. (2024) investigated the use of eggshell powder (ESP) as a partial cement replacement at substitution levels of 0%, 7.5%, and 15% in cement-based materials. The study assessed hydration properties, compressive strength, and microstructural characteristics to evaluate ESP's feasibility as a sustainable alternative. The findings showed that ESP enhanced localized hydration through a nucleation effect, increasing cumulative hydration heat per gram of cement, but reduced overall hydration due to its diluting action. Compressive strength decreased with higher ESP content, with 28-day strengths of 54.8 MPa, 43.4 MPa, and 35.5 MPa for 0%, 7.5%, and 15% ESP, respectively. Microstructural analyses revealed lower calcium silicate hydrate (CSH) and calcium hydroxide production at higher ESP levels, alongside transformations in hydration products. A numerical hydration model effectively predicted hydration heat and strength development, showing strength as an exponential function of hydration heat.

[3] Bhaskaran et al. (2024) investigated the feasibility of using eggshell powder (ESP) as a partial replacement for cement in concrete, motivated by the need to reduce carbon emissions from cement production and manage eggshell waste sustainably. In their study, ESP was incorporated into concrete at replacement levels of 5%, 10%, and 15%, and its effects on compressive strength, split tensile strength, and flexural strength were examined at 7 days of curing. The results demonstrated that ESP could effectively substitute cement while maintaining satisfactory structural properties. Materials used in the study included Ordinary Portland Cement (53-grade), M-sand conforming to Zone II of IS 383-1970, and 20 mm coarse aggregate. Eggshells were cleaned, sun-dried, crushed, ground, and sieved through a 90-micron sieve before use. The study concluded that ESP is a viable supplementary cementitious material, offering dual benefits of reducing environmental pollution caused by cement production and utilizing waste eggshells sustainably. This work adds to the growing body of research exploring innovative materials for sustainable construction.

[4] Rambabu et al. (2024) investigated the partial replacement of cement with eggshell powder (ESP) at levels of 0%, 10%, 20%, and 30%, highlighting its potential to reduce construction costs and promote waste management. Their study revealed that the optimum strength was achieved at a 10% replacement level, making it an effective substitute while contributing to sustainability. Similarly, HarshaBhaskaran et al. (2024) explored the incorporation of ESP at 5%, 10%, and 15% replacement levels, demonstrating that ESP-enhanced concrete exhibited improved compressive, tensile, and flexural strength within 7 days. These findings underscored the viability of ESP as a supplementary material in concrete.

[5] Gui-Yu Zhang et al. (2024) delved deeper into the microstructural effects of ESP on cement hydration. They observed that while ESP accelerates hydration through its nucleation effect, it reduces compressive strength when used in higher proportions.

Their study also showed that ESP decreases the production of calcium hydroxide, which necessitates careful mix design to balance hydration and strength properties. Aravind and Ranjith (2022) further validated these results, finding that a 20% replacement of cement with ESP improved tensile strength significantly after 28 days of curing, although higher ESP content negatively impacted workability due to its fine texture and increased water demand.

III. RAW MATERIAL

A. Cement

Ordinary Portland Cement (OPC) of 43 Grade, manufactured by the Khyber brand, was selected and utilized for this experimental work. This specific grade and brand were chosen due to its consistent quality, widespread local availability, and compliance with the relevant standards for construction materials. Its use in this study ensured uniformity in material properties and aligned with the experimental requirements for achieving accurate and reproducible results.

B. Fine Aggregate

Natural river sand, sourced from the local market of Nagam, was utilized in this experimental work. The sand was subjected to sieve analysis, which confirmed its compliance with Zone III grading as per IS:383-2016 standards. Prior to its use in the concrete mix, the sand was sieved through a 4.75 mm sieve to eliminate clay, organic matter, vegetative debris, and other impurities. This ensured the sand's suitability for achieving the desired quality and performance of the concrete mix.

C. Coarse Aggregate

Crushed riverbed boulders, procured from the crusher zone at Lasjan, Srinagar, were utilized as coarse aggregates in this experimental work. The aggregates had a nominal size of 20 mm, making them suitable for use in the concrete mix. Their selection was based on their mechanical properties, durability, and adherence to the specifications outlined in IS:383-2016. The use of crushed boulders ensured a consistent and reliable quality of coarse aggregate, contributing to the desired strength and performance of the concrete.

D. Water

Drinking water, sourced from the local supply line, was utilized for mixing the concrete in this experimental work. The water met the standards prescribed by IS:456-2000, ensuring its suitability for concrete production. Using potable water helped maintain the integrity of the mix, as impurities or contaminants in non-potable water could adversely affect the hydration process and the overall strength and durability of the concrete.

E. Plasticizer

FosrocConplast SP430, a high-performance superplasticizer, was utilized as an admixture in the concrete mix. This admixture is commonly employed by local paver block manufacturing units to enhance workability without compromising strength. Its inclusion in the mix was essential to meet the high workability demands of the experimental setup, especially under varying site conditions. FosrocConplast SP430 complies with IS:9103-1999 and ensures improved dispersion of cement particles, reducing water content while maintaining desired slump and workability for efficient placement and compaction.

F. Egg Shell Powder

Converting eggshells into powder for use in concrete involves a systematic process to ensure the material is fine and usable. The first step is to collect and clean the eggshells, removing any organic material or residue. After washing, the eggshells are dried to eliminate moisture, which is crucial for the grinding process. The drying is typically done using sunlight or a low-temperature oven. Once dried, the eggshells are crushed using an Automatic Soil Proctor**,** CBR Rammer**,** andmould Compactor**,** which break the shells into smaller pieces and ensure uniformity. The crushed material is then ground using a high-speed grinder to achieve a fine powder similar to the consistency of cement or fly ash. After grinding, the powder is sieved through a fine mesh to remove any larger particles. Finally, the eggshell powder is stored in airtight containers in a cool, dry place to prevent moisture absorption until it is ready for use in concrete mixing. This process allows the eggshell powder to be effectively utilized as a sustainable additive in concrete, improving its strength and durability.

Table 1-The chemical composition of egg shell powder

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
EPS	44.59%	0.12%	Nil	Traces	Nil	0.42%	Nil	0.16%

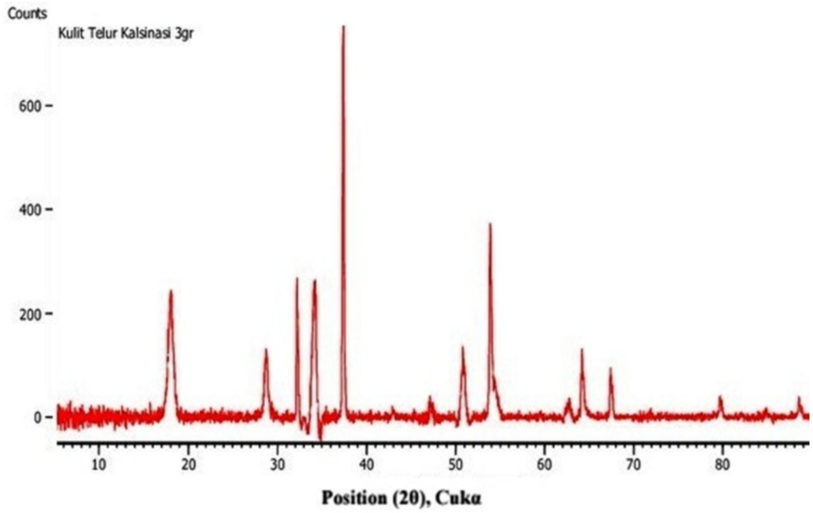


Fig. 1 XRD of Egg shell powder

IV. CONCRETE MIX

The mix ratio was finalized in accordance with the relevant IS Codes; specifically IS 10262:2019 for concrete mix proportioning (guidelines for designing a concrete mix). The batch of ingredients was dry-mixed for 2–3 minutes, followed by the gradual addition of the water fraction. In mixes where egg shell powder was incorporated, it was first thoroughly dry-mixed with cement to ensure uniform blending before combining it with the other concrete ingredients.

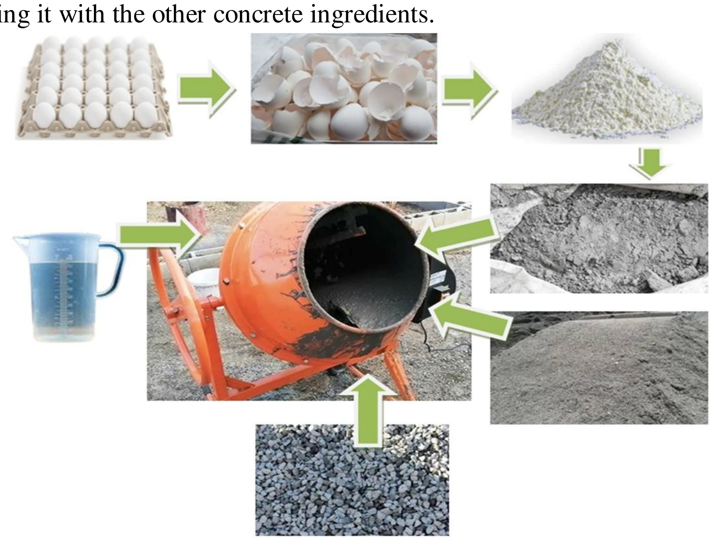


Fig. 2 Mixing of Concrete

The different mix proportions utilized for the investigation are illustrated in Table 2.

Table 2- Different mix proportions

Mix	Egg Shell Powder	Cement	Egg Shell Powder	F A	C A	Water
	%	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)

REFC	0	389.00	0.00	734	1175	154
25EPC	2.5	379.28	9.73	734	1175	154
50EPC	5	369.55	19.45	734	1175	154
75EPC	7.5	359.83	29.18	734	1175	154
100EPC	10	350.10	38.90	734	1175	154

After the ingredients of the concrete are mixed thoroughly to obtain a uniform and homogeneous mixture, a portion of the mix is collected to perform the workability check, typically using the slump test. The remaining mix is then placed into standard molds for cubes and cylinders, conforming to the relevant specifications. These molds are stored in a shaded area for 24 hours to allow initial setting. After this curing period, the specimens are carefully demolded and transferred to a fresh water curing tank, where they are immersed for the duration of the specified curing period, corresponding to the intended testing age.

V. RESULTS & DISCUSSION

A. *Workability*

To check the workability of the concrete mix, a slump test was conducted as per IS 1199: 1959. This test measures the consistency and flowability of the concrete, providing an indication of its workability. The slump test involves filling a standard slump cone with the concrete mix, compacting it in layers, and then lifting the cone vertically. The difference in height between the original cone and the subsided concrete is termed the slump value**,** which helps assess the mix's suitability for placement and finishing.

The slump test results obtained for various concrete mixes with Egg Shell Powder (ESP) as a partial replacement for cement are presented as follows:

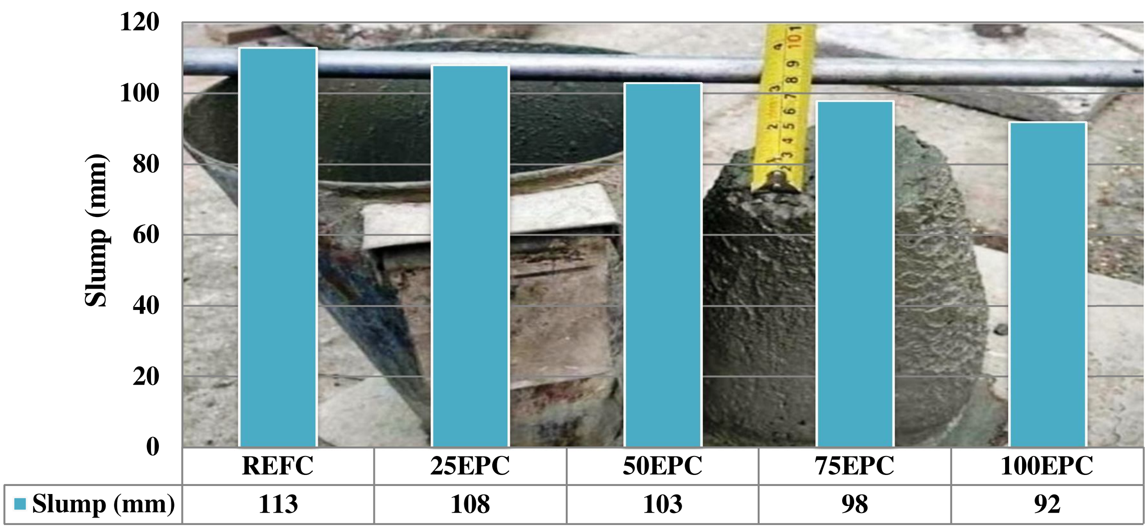
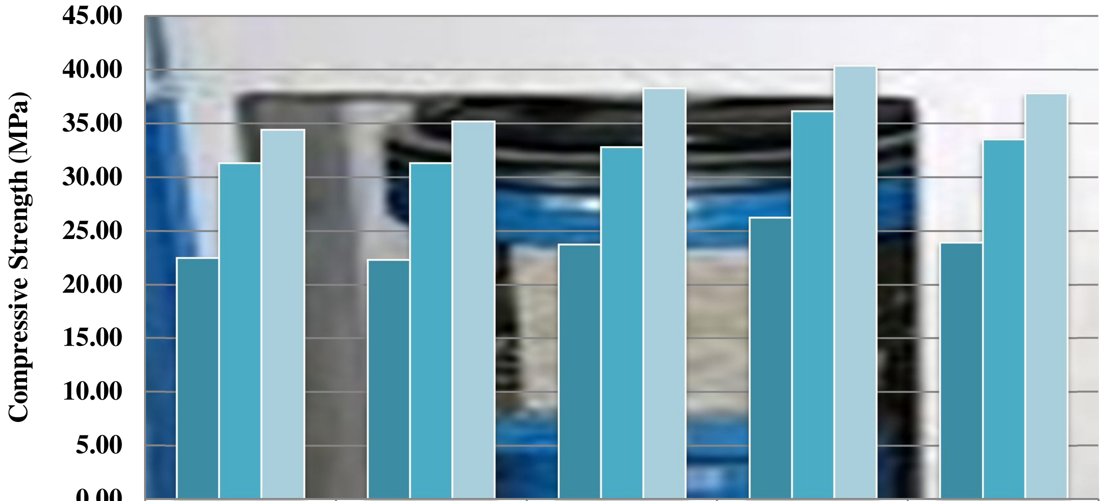


Fig. 3 Slump value for different Concrete Mix

The slump test results for the various concrete mixes with Egg Shell Powder (ESP) as a partial replacement for cement show a clear trend, as the percentage of ESP increases, the slump value decreases. For the reference mix (REFC) with no ESP replacement, the slump value is 113 mm. With 2.5% ESP (25EPC), the slump value drops slightly to 108 mm, and with 5% ESP (50EPC), it further decreases to 103 mm. As the percentage of ESP increases to 7.5% (75EPC), the slump value is reduced to 98 mm, and at 10% ESP replacement (100EPC), the slump value is 92 mm. This reduction in slump indicates a decrease in workability with higher levels of ESP replacement. This behaviour is consistent with the findings in the literature. Siddique (2011) noted that the use of pozzolanic materials like ESP reduces the workability of concrete due to the denser mix they create, which limits the availability of free water for flowability. Similarly, Rattan and Mishra (2020) observed that increased amounts of ESP lead to a stiffer mix, causing a decline in slump. Saeed and Ali (2019) also highlighted that ESP absorbs moisture from the mix, further reducing the available free water and resulting in lower workability. Therefore, the observed reduction in slump with higher ESP content aligns with these studies, demonstrating the impact of ESP on concrete's workability.

B. Compressive Strength Test

The procedure for testing the compressive strength of concrete cubes at 7, 14, and 28 days, as outlined in IS 516: 1959. On the specified testing days, the cubes are taken out of the curing tank, and their dimensions are measured for accuracy. The cubes are then placed in a compression testing machine, which applies a gradual load until the cube fails. The compressive strength is calculated by dividing the maximum load applied to the cube by the cross-sectional area of the cube. The compressive strength is recorded for each testing day, with the average value of three cubes being reported as the final result. The compressive strength of concrete at 28 days for different percentages of Egg Shell Powder (ESP) replacement to cement is presented in Figure 4.



	REFC	25EPC	50EPC	75EPC	100EPC
7 Days	22.51	22.34	23.77	26.25	23.96
14 Days	31.35	31.35	32.81	36.17	33.56
28 Days	34.45	35.22	38.33	40.39	37.85

Fig.4 CompressiveStrength of Different Concrete Mix

The compressive strength results of concrete at 28 days with varying percentages of Egg Shell Powder (ESP) replacement to cement show a positive trend up to a 7.5% replacement level. The compressive strength increased from 34.45 MPa for the control sample (0% ESP) to 40.39 MPa at 7.5% ESP, indicating that ESP has a beneficial effect on concrete strength at moderate replacement levels. However, at 10% ESP, the compressive strength slightly decreased to 37.85 MPa. This suggests that while ESP enhances the properties of concrete at lower replacement levels, excessive amounts might not have the same positive impact. The observed increase in strength is attributed to the pozzolanic properties of ESP, which react with calcium hydroxide in cement to form additional calcium silicate hydrate (C-S-H) gel, leading to a denser and stronger concrete matrix. Studies support this finding: Chandra and Berntsson (2002) demonstrated that pozzolanic materials like ESP improve concrete strength by promoting C-S-H gel formation. Rukzon and Chindaprasirt (2012) also noted that materials like ESP enhance compressive strength by filling voids in the concrete, improving compaction and overall strength. Furthermore, Panyakaew et al. (2013) found that ESP, when used as a partial cement replacement, results in higher strength at lower replacement percentages (up to 7.5%), primarily due to its calcium carbonate content, which contributes to additional gel formation during hydration. These findings indicate that ESP is a promising material for improving concrete strength, especially at moderate replacement levels.

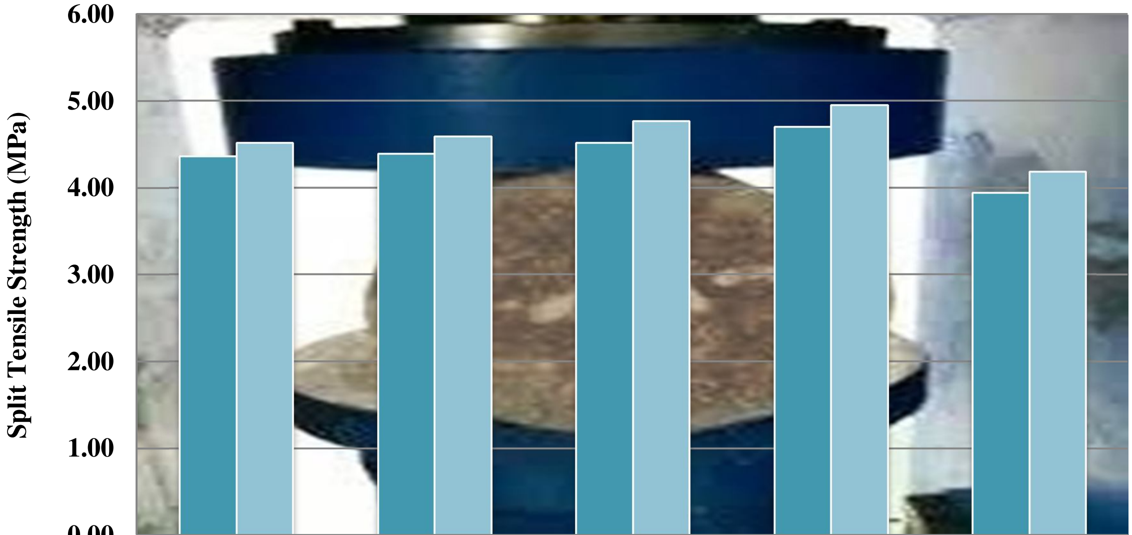
C. Split Tensile Strength

The split tensile strength of concrete is determined using IS 5816: 1999. Concrete cylinders (150 mm diameter and 300 mm height) are cast and cured for 7, 14, o 28 days. The cylinder is placed horizontally in a compression testing machine, and a load is applied gradually along its length until it splits. The split tensile strength Fsp is calculated using the formula

$$Fsp = \frac{2P}{\pi DL}$$

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 12 Issue XII Dec 2024- Available at www.ijraset.com

Where,P is the maximum applied load, L is the cylinder length, and D is the diameter. The test is typically performed on three specimens, and the average result is reported.The results for split tensile strength of concrete with varying percentages of Egg Shell Powder (ESP) replacement to cement, along with references on the increase in strength is presented in Figure – 5.



	REFC	25EPC	50EPC	75EPC	100EPC
7 Days	4.36	4.39	4.51	4.70	3.94
28 Days	4.52	4.59	4.77	4.95	4.19

Fig.5 Split Tensile Strength of Different Concrete Mix

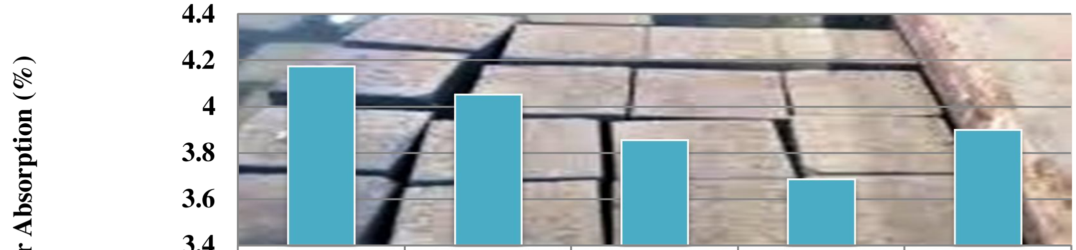
The split tensile strength of concrete at 28 days was tested with varying percentages of Egg Shell Powder (ESP) replacing cement, and the results show a positive trend up to 15% replacement. The reference mix (REFC) with no ESP exhibited a split tensile strength of 4.52 MPa. With the addition of 5% ESP (25EPC), the split tensile strength slightly increased to 4.59 MPa, and further improvements were observed at 10% ESP (50EPC), where the tensile strength reached 4.77 MPa. The highest split tensile strength was recorded at 15% ESP (75EPC) with a value of 4.95 MPa, indicating that this level of ESP replacement enhances the tensile properties of concrete. However, at 25% ESP (100EPC), the tensile strength decreased to 4.19 MPa, suggesting that higher percentages of ESP may not yield the same positive effects. The observed increase in split tensile strength can be attributed to the pozzolanic properties of Egg Shell Powder, which reacts with calcium hydroxide in cement, leading to the formation of additional calcium silicate hydrate (C-S-H) gel, thereby enhancing the overall tensile strength. Similar findings have been reported in the literature, such as by Rukzon and Chindaprasirt (2012), who observed improvements in the mechanical properties of concrete with ESP as a partial cement replacement, particularly at moderate replacement levels. Panyakaew et al. (2013) also found that lower to moderate replacement of cement with Egg Shell Powder enhances the tensile strength due to its fine particle size, which fills voids in the matrix and promotes better bonding.

WATER ABSORPTION

The water absorption test involves drying a concrete specimen at 100°C to 110°C until a constant weight is achieved. The specimen is then immersed in water for 24 hours, and its weight is recorded after removal. The water absorption percentage is calculated using the formula:

$$\text{Water Absorption (\%)} = \frac{Wt.of\ Saturated\ Specimen - Wt.of\ Oven\ Dried\ Specimen}{Wt\ of\ Oven\ Dried\ Specimen}$$

This test assesses the permeability and durability of concrete, with lower absorption indicating better performance. The procedure is outlined in IS 1199: 1959 and IS 516: 1959.The results in Figure 6indicate the variation of water absorption percentage observed by the Egg Shell Powder (ESP) replacement to cement.



	REFC	25EPC	50EPC	75EPC	100EPC
Water Absorption (%)	4.176	4.05346	3.85646	3.68567	3.901

Fig. 6 Water Absorption for Different Concrete Mix

The observed variation in water absorption with increasing Egg Shell Powder (ESP) replacement in cement can be attributed to several well-documented factors in the literature. Initially, up to 7.5% ESP replacement, water absorption decreases due to the pozzolanic reaction of ESP. Egg Shell Powder, being rich in calcium carbonate ($CaCO_3$), reacts with calcium hydroxide (a byproduct of cement hydration) to form additional cementitious compounds, filling voids in the cement matrix and refining the pore structure. This leads to a denser microstructure with fewer capillary pores, which in turn reduces water absorption (Makar, 2010; Hossain et al., 2016). However, at higher ESP replacement levels, particularly at 10%, the trend reverses, and water absorption increases. This is likely due to the non-hydraulic nature of ESP at higher quantities. While it may initially contribute to a better microstructure, beyond a certain threshold, the excessive amount of non-reactive material fails to participate in the hydration process, leaving unreacted particles that can increase the porosity of the mix. As a result, the concrete becomes more porous, leading to higher water absorption. This pattern is consistent with findings in similar studies that emphasize the importance of balancing the pozzolanic and non-reactive content in concrete mixtures (Padmini et al., 2009).

VI. COST ANALYSIS

A cost comparison was conducted to evaluate the economic feasibility of incorporating egg shell powder (ESP) as a partial replacement for cement in concrete production in the Nagam, Chadoora district of Budgam, Jammu and Kashmir. The analysis compared the traditional concrete mix, using 100% cement, with a modified mix containing 7.5% ESP, which yielded optimal strength and performance.

Table 3- Cost Comparison

S. No	Raw Material	Rate (₹)	Unit	Reference Concrete		75EPC	
				Quantity (Kg)	Amount (₹)	Quantity (Kg)	Amount (₹)
1	Cement	9.5	Kg	389	3695.5	359.83	3418.39
2	Fine Aggregate	2	Kg	734	1468	734	1468
3	Coarse Aggregate	0.87	Kg	1175	1022.25	1175	1022.25
4	Egg Shell Powder	1.24	Kg	0	0	29.18	36.1832
Material Cost for 1 cum of concrete					6185.75		5853.2

The cost comparison focused solely on raw material prices, excluding factors like labor and transportation. The results showed that replacing 7.5% of cement with egg shell powder led to a reduction in material costs, offering a more cost-effective and environmentally sustainable alternative for concrete production in the region.

The incorporation of 7.5% egg shell powder (ESP) as a partial replacement for cement in the concrete mix resulted in a 5.3% cost reduction compared to the traditional mix. This reduction was primarily due to the lower cost of egg shell powder compared to cement. By reducing the amount of cement used, the modified mix not only lowered the material costs but also provided an economically viable alternative, making the production of concrete more cost-effective while maintaining optimal strength and performance.

VII. CONCLUSION

The investigation into the effects of Egg Shell Powder (ESP) as a partial replacement for cement in concrete mixes reveals several important trends that contribute to the understanding of ESP's influence on concrete's properties.

1) The slump test results indicate a decrease in workability as the percentage of ESP increases. This reduction can be attributed to the denser nature of the mix due to the pozzolanic properties of ESP, which absorb moisture and reduce available free water. These findings are consistent with previous studies and suggest that higher ESP content leads to a stiffer mix, which may pose challenges during placement and finishing.
2) The results show a notable increase in compressive strength up to a 7.5% ESP replacement level, with a maximum strength of 40.39 MPa at 7.5% ESP. This improvement is attributed to the pozzolanic reaction of ESP, which promotes the formation of additional calcium silicate hydrate (C-S-H) gel, resulting in a denser and stronger concrete matrix. However, at higher ESP levels (10%), a slight reduction in strength was observed, indicating that excessive ESP content may have diminishing returns.
3) The split tensile strength also improved with ESP replacement, peaking at 7.5% ESP (4.95 MPa), reinforcing the positive impact of ESP on tensile properties at moderate replacement levels. At higher percentages, the tensile strength decreased, suggesting that excessive ESP could negatively affect the concrete's tensile properties.
4) Water absorption decreased up to 7.5% ESP replacement, indicating improved durability and reduced permeability due to the enhanced microstructure from the pozzolanic reaction. However, at 10% ESP replacement and beyond, the water absorption increased, likely due to the non-hydraulic nature of ESP at higher levels, which contributes to increased porosity and water absorption.
5) Incorporating 7.5% egg shell powder (ESP) as a partial replacement for cement in the concrete mix led to a 5.3% cost reduction, offering a more cost-effective and economically viable alternative while maintaining optimal strength and performance.
6) This modification not only improves the cost-effectiveness of concrete production but also contributes to environmental sustainability by reducing cement consumption, a major contributor to CO_2 emissions. Thus, using ESP in concrete mixes offers a promising, sustainable solution for the construction industry.

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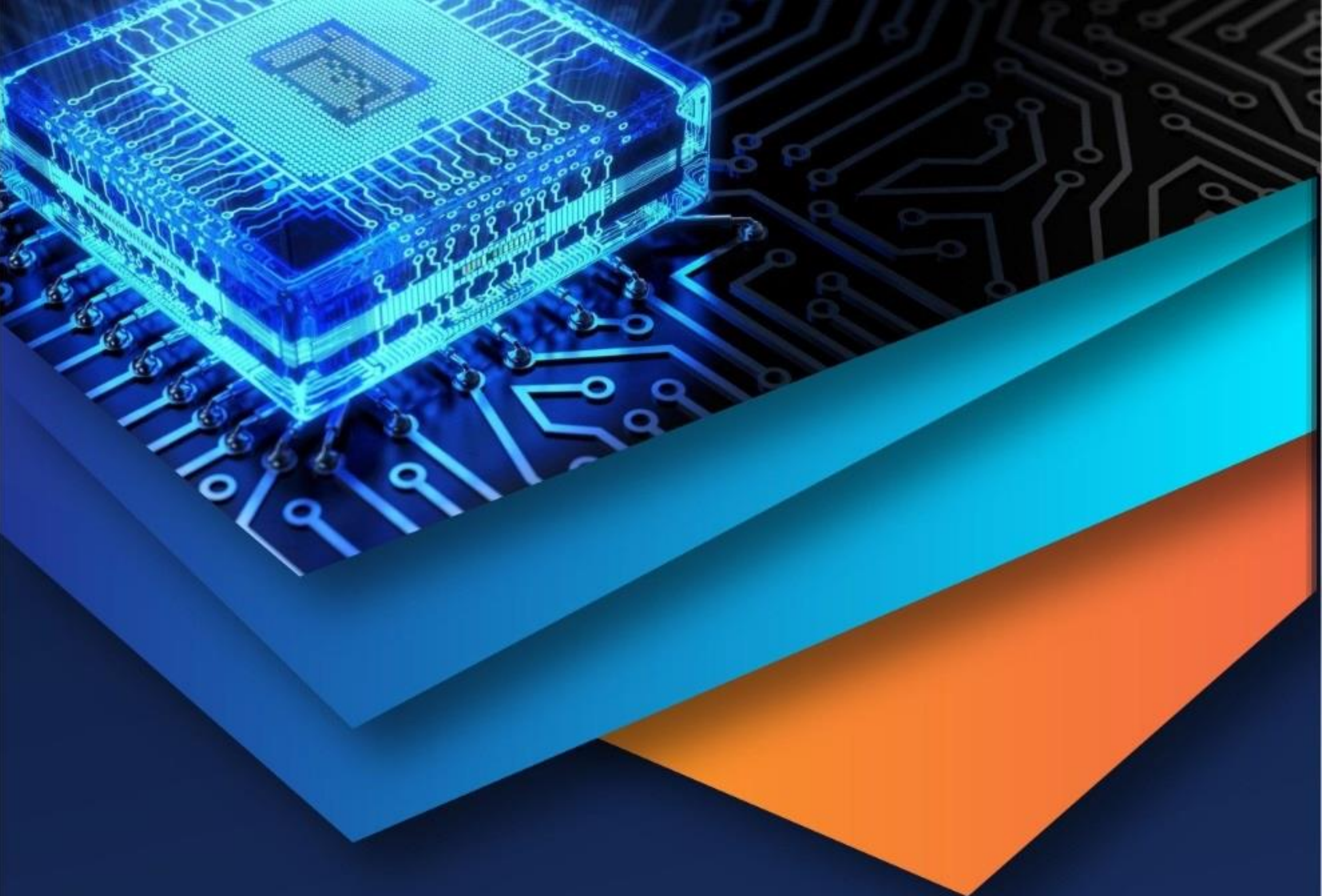

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