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Compressive Strength of Cement Mortar Blended With Eggshell Powder Ash

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Abstract

The poultry eggshell waste disposal and the environmental burden of Portland cement production motivate the use of calcium-rich waste materials in cementitious composites. This study evaluated eggshell powder ash (ESPA) as a partial cement replacement in mortar. Cement was replaced by 0, 2, 4, 6, 8 and 10% ESPA by mass in 1:2, 1:3 and 1:4 cement-to-sand proportions, and water-cured cubes were tested after 3, 7 and 28 days. All reported observations were retained without alteration and assessed using descriptive linear trend analysis. In the 1:3 series, 28-day strength decreased systematically with ESPA content at approximately 1.06 MPa per percentage point ($R^2 = 0.90$). The 1:2 and 1:4 series showed negligible linear associations ($R^2 < 0.01$) because their apparent gains occurred at isolated replacement levels. The maximum observed 28-day values were 40.87 MPa at 8% ESPA for 1:2 mortar and 21.28 MPa at 10% ESPA for 1:4 mortar, but the available summarized data do not establish either dosage as a statistically verified optimum. Low ESPA contents are therefore the most defensible starting point for strength-sensitive mixtures, while the isolated higher-strength combinations require independent replication, controlled ash characterization, workability assessment and durability verification.

Keywords: eggshell powder ash; cement replacement; mortar; compressive strength; waste valorization; sustainable construction

1 Introduction

Cement mortar is used extensively in masonry, plastering, pointing and flooring. Its large-scale use consumes limestone and energy and contributes to greenhouse-gas emissions. At the same time, eggshell waste from households, bakeries, food industries and poultry operations is commonly landfilled. Eggshell consists predominantly of calcium carbonate, with smaller quantities of calcium phosphate, magnesium carbonate and organic matter. After cleaning, drying, grinding and controlled processing, it can potentially function as a mineral filler or reactive calcium-bearing constituent in cement-based materials.

Earlier studies reported mixed strength responses at low and moderate replacement levels [1-6]. Potential benefits are commonly associated with particle packing, nucleation and carbonate-bearing hydration products, whereas excessive replacement can dilute clinker and introduce unreactive or agglomerated particles. More recent research has clarified the importance of processing and mixture design. Ngayakamo and Onwualu reviewed green processing routes for converting eggshell waste into construction materials [7]. Das et al. reported peak concrete strength near 10% eggshell-powder replacement [8], while Islam and Mohr compared eggshell-powder blended binders with ASTM Type IL cement systems [9]. A 2025 mortar investigation found improved strength up to 10% calcined eggshell powder but increased water absorption at higher contents [10]. Recent mortar research has also expanded the assessment from mechanical behavior to thermal performance [11]. Collectively, these studies show that optimum content depends on fineness, calcination, chemical composition, binder system, water-to-binder ratio, mortar proportion and curing age; values obtained for ESP or calcined ESP should therefore not be transferred directly to ESPA mixtures without validation.

This study investigated ESPA replacement from 0 to 10% in three mortar proportions. The objectives were to quantify strength development at 3, 7 and 28 days, compare the response of rich and lean mortar matrices, and identify replacement levels worthy of further study.

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2 Materials and Methods

2.1 Materials

Locally procured 53-grade ordinary Portland cement, natural sand and tap water were used. Eggshell waste was collected in Solapur and processed into eggshell powder ash. The cement had a fineness of 3.5%, standard consistency of 34%, initial and final setting times of 175 and 320 min, and soundness of 4 mm. The fine aggregate had a fineness modulus of 3.2, specific gravity of 2.72 and water absorption of 2.19%. Table 2.1 shows physical properties of cement and fine aggregates

Table 2.1 Physical properties of cement and fine aggregate

Material	Property	Value
Cement	Fineness	3.5%
Cement	Standard consistency	34%
Cement	Initial and final setting time	175 and 320 min
Cement	Soundness	4 mm
Fine aggregate	Fineness modulus	3.2
Fine aggregate	Specific gravity	2.72
Fine aggregate	Water absorption	2.19%

2.2 Mixture design and specimen preparation

Three cement-to-sand proportions, 1:2, 1:3 and 1:4, were prepared. In each series, cement was replaced by ESPA at 0, 2, 4, 6, 8 and 10% by mass. Sand and mixing-water quantities were held constant within each proportion as reported in the project. Twelve cubes were produced for every mixture. Dry constituents were blended, water was added, and the mortar was mixed to a homogeneous consistency. Specimens were compacted in moulds, demoulded after the initial curing period and submerged in water until testing. Table 2.2 shows experimental schedule for laboratory work.

Table 2.2 Experimental schedule

Factor	Levels
Mortar proportion	1:2, 1:3 and 1:4
ESPA replacement	0, 2, 4, 6, 8 and 10% of cement mass
Replicates reported	12 cubes per mixture
Curing ages	3, 7 and 28 days
Primary response	Compressive strength

2.3 Compressive strength and analysis

Compressive strength was determined at 3, 7 and 28 days. The reported strength values were transcribed from the project result tables. For the present manuscript, 28-day percentage change was calculated relative to the corresponding control mortar. The reported observations were not altered to impose a smoother or predetermined trend. Ordinary least-squares linear fits were added only as descriptive aids; R^2 values indicate how consistently each series follows an overall direction and do not convert fitted values into

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test results. The source report provides one summarized strength value for each age and mixture, so standard deviation, confidence intervals, outlier testing and inferential significance could not be calculated.

3 Results and Discussion

3.1 Strength development

Figure 3.1.1 shows variation in the compressive strength of mortar for different mix proportions.

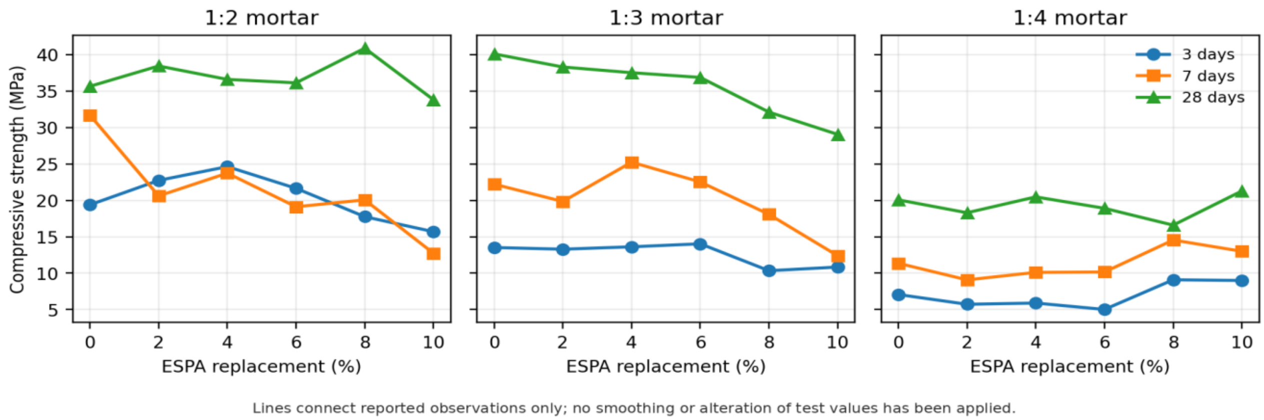

Figure 3.1.1 Compressive Strength Variation for Different Proportions

Strength generally increased with curing age, but the response to ESPA dosage was non-monotonic in several mixtures. In the 1:2 series, 4% ESPA gave the highest reported 3-day strength (24.62 MPa), whereas 8% gave the highest reported 28-day strength (40.87 MPa). In the 1:3 series, 6% was slightly above the control at 3 days and 4% exceeded the control at 7 days, but no ESPA mixture exceeded the control at 28 days. In the 1:4 series, 8 and 10% improved early-age observations relative to the control, and 10% was highest at 28 days. Because specimen-level dispersion is unavailable, these isolated peaks must be treated as candidates for repeat testing rather than confirmed improvements.

3.2 Effect of ESPA on 28-day strength

Table 3.1 shows twenty-eight days compressive strength and change with respect to control value.

Table 3.1 Twenty-eight-day compressive strength and change relative to control

ESPA replacement	1:2 MPa	Change	1:3 MPa	Change	1:4 MPa	Change
0%	35.64	+0.0%	40.09	+0.0%	20.06	+0.0%
2%	38.43	+7.8%	38.29	-4.5%	18.29	-8.8%
4%	36.59	+2.7%	37.51	-6.4%	20.47	+2.0%
6%	36.12	+1.3%	36.86	-8.1%	18.90	-5.8%
8%	40.87	+14.7%	32.10	-19.9%	16.59	-17.3%
10%	33.80	-5.2%	29.04	-27.6%	21.28	+6.1%

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Figure 3.2 shows observed 28 compressive strengths with descriptive trend lines.

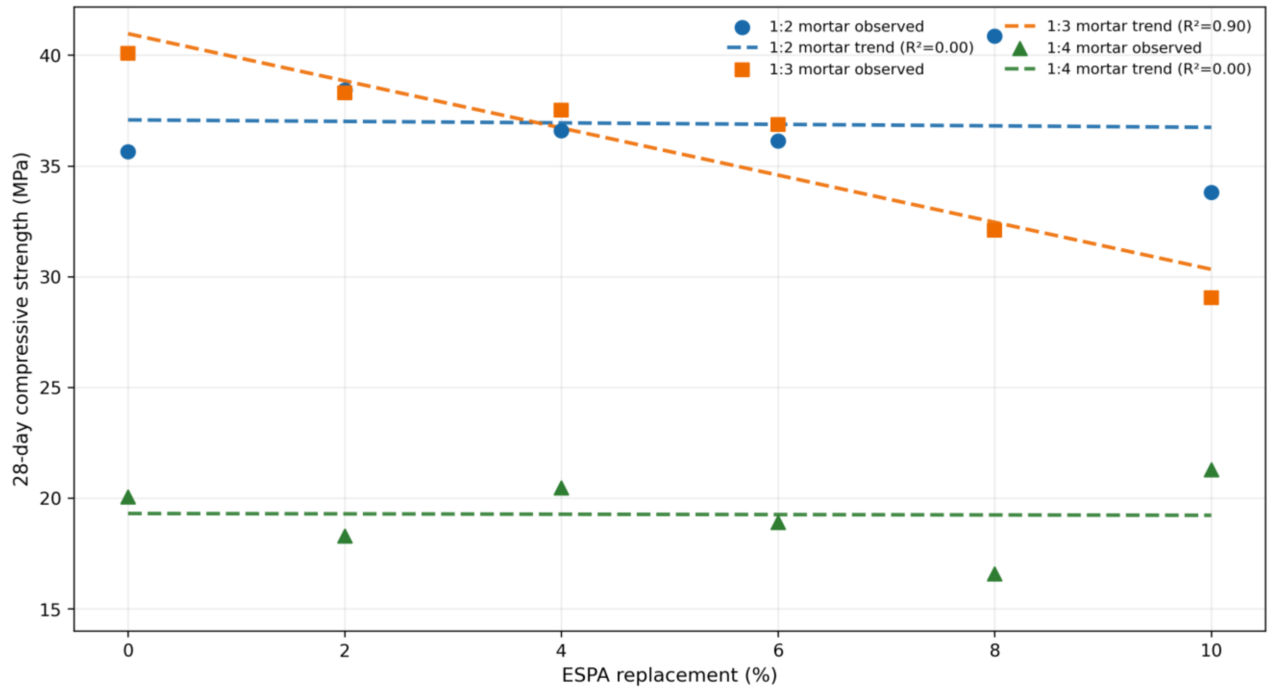

Figure 3.2 Observed 28-day compressive strengths with descriptive linear trend lines; R^2 values indicate goodness of fit

The fitted trends show that one replacement rule cannot be applied across all mortar proportions. The 1:3 series exhibited a strong overall decline of approximately 1.06 MPa per percentage point of ESPA ($R^2 = 0.90$), supporting the conclusion that increasing replacement progressively reduced its 28-day strength. By contrast, the 1:2 and 1:4 series had near-zero linear slopes and R^2 values below 0.01, meaning that dosage alone did not explain their variation. The observed 14.7% gain at 8% in the 1:2 series and the 6.1% gain at 10% in the 1:4 series may reflect packing, nucleation, processing or experimental variability, but they cannot be declared statistically significant from summarized values alone. The matrix-dependent response is consistent with literature emphasizing interactions among eggshell processing, binder chemistry, water demand and mixture proportion [7,9-11].

The project report states that 6% ESPA gave the maximum strength in the 1:3 mortar, but its own tabulated 28-day data show 40.09 MPa for the control and 38.29 MPa at 2% ESPA, compared with 36.86 MPa at 6%. The manuscript therefore follows the numerical result table and identifies 2% as the least strength-reducing ESPA-modified 1:3 mixture at 28 days. This discrepancy, together with the isolated peaks in the other series, should be checked against original specimen and laboratory records before journal submission.

3.3 Engineering and sustainability implications

Replacing part of the cement with processed eggshell waste can reduce clinker demand and divert a calcium-rich residue from disposal. For preliminary screening, 8% ESPA in 1:2 mortar and 10% ESPA in 1:4 mortar merit repeat testing because they produced the highest observed 28-day strengths in their respective series. They should not yet be described as optimum dosages. For the 1:3 mix, the strong downward trend supports using a low replacement level when strength retention is important. Practical adoption requires verification of ash consistency, mortar flow, water retention, adhesion, density, shrinkage, permeability and long-term durability. A life-cycle assessment should compare avoided cement and disposal impacts with energy and emissions from washing, drying, grinding and calcining eggshells.

4 Conclusions

This study demonstrates that eggshell powder ash (ESPA) can serve as a technically viable and environmentally beneficial partial cement replacement in mortar, although its effectiveness is strongly governed by mortar proportion, replacement level and

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curing age. The most significant performance was obtained in the 1:2 mortar containing 8% ESPA, which achieved a 28-day compressive strength of 40.87 MPa—14.7% higher than the control—indicating that favourable particle packing, nucleation and hydration effects can outweigh cement-dilution effects at an appropriate dosage. Conversely, the 1:3 mortar was sensitive to ESPA incorporation, with all modified mixtures remaining below the 40.09 MPa control and 2% emerging as the least detrimental replacement, while the 1:4 mortar achieved its highest strength of 21.28 MPa at 10% ESPA, representing a 6.1% improvement. These contrasting responses confirm that a universal optimum ESPA content cannot be prescribed and that replacement must be tailored to the binder–aggregate proportion and intended application. Overall, 8% ESPA in 1:2 mortar is identified as the leading candidate for sustainable masonry and non-structural applications, subject to validation through independently batched replicates, standardized ash characterization, controlled workability, durability testing and life-cycle assessment. The findings establish a credible pathway for simultaneously valorizing eggshell waste, reducing cement consumption and advancing resource-efficient construction materials.

5 Future Scope

Future research should evaluate all mixtures using at least three independent batches, retain individual specimen results, and report the mean, standard deviation, coefficient of variation and 95% confidence interval, supported by factorial ANOVA to quantify the effects of eggshell powder/ash (ESPA) content, mortar proportion and curing age. Dosage intervals should be refined around the observed response regions—6–10% for 1:2 mortar, 0–4% for strength-sensitive 1:3 mortar and 8–12% for 1:4 mortar—and optimized using response-surface and multi-objective methods. Eggshell sourcing and processing should be standardized, while uncalcined powder and ash produced under controlled calcination conditions should be characterized using XRF, XRD, TGA, laser diffraction and SEM-EDS. With a controlled water-to-binder ratio and flow-based admixture adjustment, fresh properties, mechanical performance, hardened density, porosity, transport characteristics, microstructure, dimensional stability and long-term durability should be assessed. Promising mixtures should subsequently be validated in plaster panels, masonry prisms and non-load-bearing blocks for adhesion, thermal, acoustic, moisture-buffering and fire performance, followed by embodied-carbon, energy, cost and life-cycle assessments considering local transport, processing, calcination fuel, avoided cement consumption, eggshell disposal, leaching and hygiene requirements.

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