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Original Research Paper

Experimental Investigation on Waste-Derived Sustainable Concrete Mixes Incorporating Fly Ash, Red Mud, Eggshell Powder, and Construction & Demolition Waste

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Abstract. The growing global demand for concrete has intensified concerns regarding the environmental impact of Portland cement production, which contributes significantly to greenhouse gas emissions and the depletion of natural resources. This study presents a systematic experimental evaluation of waste-derived sustainable concrete in which four industrial and agro-industrial by-products — fly ash, red mud, eggshell powder, and construction and demolition waste (C&DW) — were individually incorporated as supplementary cementitious materials (SCMs) in M25-grade concrete at cement replacement levels of 0–20%. Mechanical performance was characterised through compressive, split-tensile, and flexural strength tests at 7, 14, and 28 days, together with workability assessment of all mixes. The comparative evaluation identified optimum replacement levels of 20% for fly ash, 10% for eggshell powder, 10% for red mud, and 15% for C&DW. At these optima, the 28-day compressive strength improved by 12.2%, 8.85%, 6.05%, and 13.83%, respectively, over the control mix, with corresponding gains in split-tensile (up to 12.64%) and flexural strength (up to 11.85%); all mixes retained slump values within IS 456:2000 workability limits. A cost-effectiveness appraisal indicated that C&DW at 15% and fly ash at 20% offer the most economical strength enhancement, as both materials carry negligible acquisition cost. The results demonstrate that single-stream valorisation of locally available wastes can reduce cement consumption, lower CO_2 emissions, and divert substantial waste volumes from landfills without compromising — and in most cases improving — the structural performance of normal-strength concrete.

Introduction

The depletion of natural resources and the emission of greenhouse gases place enormous strain on the environment, and the building industry is among the most resource-intensive sectors worldwide. The manufacture of Ordinary Portland Cement (OPC), a principal constituent of concrete, accounts for approximately 8% of all anthropogenic carbon dioxide emissions globally [1, 2]. With the rapid pace of urbanisation and industrialisation, the demand for concrete continues to escalate, prompting an urgent need for sustainable and eco-efficient alternatives that can mitigate the environmental impact of conventional construction materials. One promising approach is the valorisation of industrial by-products — transforming waste materials into valuable resources for construction applications — which reduces dependence on virgin raw materials while advancing waste management and circular-economy principles [3, 4]. India, as a rapidly developing nation, generates substantial quantities of industrial waste that remain underutilised; if effectively harnessed, these by-products could serve as low-cost and sustainable inputs for concrete manufacturing.

A considerable body of research supports the use of supplementary cementitious materials (SCMs) in concrete [5]. Agro-industrial ashes such as sugarcane bagasse ash and rice husk ash enhance compressive strength, durability, and resistance to environmental degradation through pozzolanic and filler actions [6]. Fly ash, a by-product of coal combustion in thermal power plants, is the most established SCM: its pozzolanic reactivity improves long-term strength and durability, lowers the heat of hydration, and reduces clinker demand, with replacements of 10–30% generally reported to optimise strength and workability; a recent study found that 20% fly ash replacement improved compressive, split-tensile, and flexural strengths by 8.1%, 5.9%, and 7.8%, respectively [7]. Red mud, the alkaline residue of the Bayer process for alumina production, is generated at more than 70 million tonnes annually worldwide and poses serious storage and contamination hazards owing to its high pH; its incorporation into cementitious systems offers a route for safe reuse, with red mud–fly ash blends showing improved early-age hydration, densified interfacial transition zones, and, in geopolymer formulations, compressive strengths exceeding 60 MPa [8, 9]. The fineness fractions of coal ashes further influence the density and strength of blended cements [10]. Eggshell powder, composed of about 95% calcium carbonate, enriches

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the calcium content of the binder and promotes secondary hydration; substitutions of 5–10% have been reported to significantly enhance compressive and flexural strength, particularly under water curing. Construction and demolition waste (C&DW) constitutes one of the largest solid-waste streams globally; its recycling into aggregates and fine powders reduces landfill pressure and conserves natural resources, with recycled-aggregate concretes retaining satisfactory workability and strength at replacements up to about 30%, and successful applications now demonstrated in masonry blocks and other building products [11–15].

Despite these advancements, barriers to widespread adoption of sustainable construction remain. The World Green Building Trends SmartMarket Report identified that nearly 40% of construction firms in the United Kingdom cited cost as the primary obstacle to implementing sustainable practices, while 50% perceived green construction as requiring higher initial investment [16]; systematic reviews similarly identify cost perception, inconsistent material availability, and the absence of standardised performance data as recurring impediments [17]. A further gap in the technical literature is that most studies examine a single waste stream in isolation, under differing grades, mix designs, and curing regimes, which prevents a like-for-like comparison; comparative data on multiple locally available wastes evaluated under identical mix proportions, materials, and testing conditions are scarce. The present study addresses this gap by evaluating four waste streams — fly ash, red mud, eggshell powder, and C&DW — as individual cement replacements in the same M25-grade concrete under identical laboratory conditions, thereby providing a directly comparable basis for material selection. It should be noted that this work deliberately adopts a comparative single-waste design; the study of combined (binary or ternary) waste blends is identified as a subsequent research stage.

The societal relevance of this investigation is considerable. Cement production in India exceeds 400 million tonnes annually, so every 1% of cement replaced by waste-derived SCMs avoids substantial CO_2 emissions and conserves limestone reserves. Simultaneously, the utilisation pathways demonstrated here divert fly ash from ash ponds, red mud from hazardous storage lagoons, eggshell waste from municipal streams, and C&DW from landfills, converting disposal liabilities into construction resources. For small and medium concrete producers, the identified optimum replacement levels offer immediate, low-cost routes to greener M25 concrete — the grade most widely used in Indian residential and light commercial construction — without specialised equipment or admixture technology.

The specific objectives of the study are: (i) to characterise the physical and chemical properties of the selected waste materials; (ii) to determine the optimal individual replacement levels of fly ash, eggshell powder, red mud, and C&DW in M25-grade concrete through compressive, split-tensile, and flexural strength testing at 7, 14, and 28 days; and (iii) to evaluate the workability and cost-effectiveness of the resulting mixes so as to identify the most economical strength-enhancing option.

2 Materials and methods

2.1 Materials

Cement: Ordinary Portland Cement of 43 grade, conforming to IS 8112:2013, was used as the primary binder. The cement had a specific gravity of 3.15, normal consistency of 31%, and a specific surface area of 320 m²/kg. Initial and final setting times were 34 minutes and 290 minutes, respectively. These properties satisfied the standard requirements for producing M25-grade concrete.

Fly ash: Class F fly ash, collected from a nearby thermal power station, served as a supplementary cementitious material. The fly ash contained a combined $SiO_2 + Al_2O_3 + Fe_2O_3$ content exceeding 75%, consistent with ASTM C618, and its high pozzolanic reactivity contributed to secondary hydration and improved workability.

Red mud: Red mud was obtained from an aluminium refinery in Visakhapatnam, India. It was oven-dried at 110°C, ground to a fine powder, and sieved through a 90 µm IS sieve before use. Its high alkalinity (pH ≈ 11.8) and significant iron oxide content (Fe_2O_3 ≈ 32%) made it a suitable reactive filler; prior to blending, the red mud was neutralised with dilute acetic acid to minimise adverse reactions.

Eggshell powder: Eggshell waste was collected from food-processing outlets, cleaned, dried, and calcined at 900°C for 2 hours to eliminate organic residues. The calcined shells were ground and sieved to below 75 µm; chemical analysis indicated a $CaCO_3$ content of about 95%, confirming its suitability as a calcium-rich SCM.

Construction and demolition waste: C&DW, consisting primarily of crushed concrete and masonry debris, was collected from a demolition site, washed, oven-dried, and crushed to fine powder passing the 90 µm sieve for use as a cement replacement at 5–20% levels.

Aggregates, water, and admixture: Natural river sand (Zone II as per IS 383:2016) and crushed granite of 20 mm nominal size were used as fine and coarse aggregates, with specific gravities of 2.63 and 2.70 and water absorption within 1.5–2.0%, tested per IS 2386 (Parts I–IV):1963. Potable tap water free from deleterious materials was used for mixing and curing, and a polycarboxylate ether-based superplasticizer conforming to IS 9103:2019 was dosed at 1% by weight of cementitious material.

2.2 Mix proportioning

Concrete mixes were designed for M25 grade as per IS 10262:2019 with a total binder content of 377 kg/m³, water content of 158 kg/m³, and coarse aggregate content of 1,159 kg/m³, giving a water–binder ratio of 0.42. Cement was partially replaced, one waste material at a time, at 0%, 5%, 10%, 15%, and 20% by mass of binder, keeping the total binder, water, and aggregate contents constant so that the influence of each SCM could be isolated. Table 1 presents the resulting constituent quantities, and Table 2 lists the specimen designations for the three strength tests. A control mix (0% replacement) was cast for baseline comparison.

Table 1. Mix proportions per m³ of M25 concrete (w/b = 0.42).

Replacement (%)	Cement (kg)	SCM (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
0	377.00	0	158	1159
5	358.15	18.85	158	1159
10	339.30	37.70	158	1159
15	320.45	56.55	158	1159
20	301.60	75.40	158	1159

Table 2. Specimen designations for each waste–cement combination.

S. No.	Combination (%)	CS	STS	FS
1	0FA + 100C	FAC-1	FAC-6	FAC-11
2	5FA + 95C	FAC-2	FAC-7	FAC-12
3	10FA + 90C	FAC-3	FAC-8	FAC-13
4	15FA + 85C	FAC-4	FAC-9	FAC-14
5	20FA + 80C	FAC-5	FAC-10	FAC-15
6	0ESP + 100C	ESWC-1	ESWC-6	ESWC-11
7	5ESP + 95C	ESWC-2	ESWC-7	ESWC-12
8	10ESP + 90C	ESWC-3	ESWC-8	ESWC-13
9	15ESP + 85C	ESWC-4	ESWC-9	ESWC-14
10	20ESP + 80C	ESWC-5	ESWC-10	ESWC-15
11	0RM + 100C	RMC-1	RMC-6	RMC-11
12	5RM + 95C	RMC-2	RMC-7	RMC-12
13	10RM + 90C	RMC-3	RMC-8	RMC-13
14	15RM + 85C	RMC-4	RMC-9	RMC-14
15	20RM + 80C	RMC-5	RMC-10	RMC-15
16	0CDW + 100C	CDWC-1	CDWC-6	CDWC-11
17	5CDW + 95C	CDWC-2	CDWC-7	CDWC-12
18	10CDW + 90C	CDWC-3	CDWC-8	CDWC-13
19	15CDW + 85C	CDWC-4	CDWC-9	CDWC-14
20	20CDW + 80C	CDWC-5	CDWC-10	CDWC-15

2.3 Casting and curing

A laboratory pan mixer was used to ensure uniform distribution of all constituents. Specimens comprised 150 mm × 150 mm × 150 mm cubes for compressive strength, 150 mm × 300 mm cylinders for split-tensile strength, and 100 mm × 100 mm × 500 mm beams for flexural strength. The freshly mixed concrete was compacted on a table vibrator to eliminate entrapped air. Specimens were demoulded after 24 hours and water-cured for 7, 14, and 28 days under identical laboratory conditions at 27 ± 2°C and 90 ± 5% relative humidity. Three specimens were cast and tested for each mix, test, and age, and mean values are reported.

2.4 Testing procedures

Workability of each fresh mix was measured by the slump cone test per IS 1199:1959. Compressive strength was determined per IS 516 (Part 1/Sec 1):2021 on a 2,000 kN compression testing machine; split-tensile strength was determined on cylinders under diametral compression per IS 5816:1999; and flexural strength was obtained by two-point loading of beams per IS 516:1959, with load–deflection behaviour observed to assess ductility. All hardened tests were conducted at 7, 14, and 28 days after water curing.

3 Results and discussion

3.1 Workability

The slump of the M25-grade mixes decreased with increasing dosages of red mud, C&DW, and fly ash beyond low replacement levels, because the higher fineness and water absorption of these powders reduced the free water available and stiffened the mix. In contrast, eggshell powder marginally increased slump owing to its fine, low-absorption particles. All mixes, including those at

20% replacement, retained slump values in the range of 60–100 mm, satisfying the workability requirements of IS 456:2000 with the adopted superplasticizer dosage. The incorporation of the waste materials therefore did not impair the handling and placing characteristics of the concrete.

3.2 Compressive strength

Table 3 presents the compressive strength of all twenty combinations at 7, 14, and 28 days, and Figures 3–6 show the strength development for each waste stream. Each reported value is the mean of three specimens; the coefficient of variation of replicate cubes remained within acceptable limits for laboratory concrete.

Table 3. Compressive strength of all combinations (MPa; mean of three specimens).

Combination (%)	7 days	14 days	28 days	Combination (%)	7 days	14 days	28 days
0FA+100C	25	33	35	0RM+100C	23	28	33
5FA+95C	26	35	36	5RM+95C	24	29	34
10FA+90C	26	36	38	10RM+90C	25	30	35
15FA+85C	28	37	40	15RM+85C	23	27	32
20FA+80C	28	39	40	20RM+80C	19	26	28
0ESP+100C	23	26	31	0CDW+100C	25	25	31
5ESP+95C	24	29	32	5CDW+95C	24	28	32
10ESP+90C	26	32	34	10CDW+90C	24	32	35
15ESP+85C	22	26	29	15CDW+85C	25	33	36
20ESP+80C	21	24	28	20CDW+80C	23	32	34

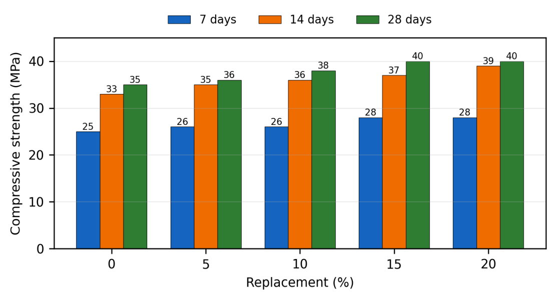

Fig. 1. Variation of compressive strength for the FA + cement combination.

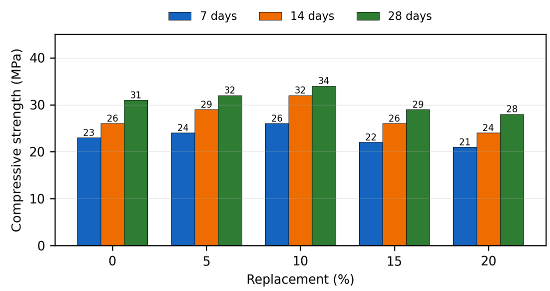

Fig. 2. Variation of compressive strength for the ESP + cement combination.

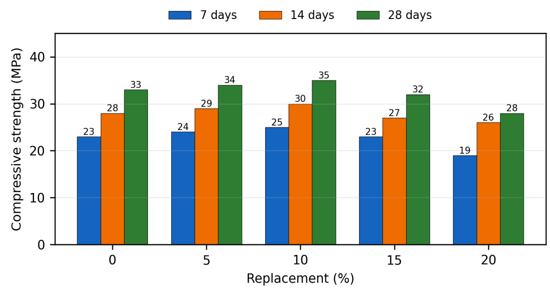

Fig. 3. Variation of compressive strength for the RM + cement combination.

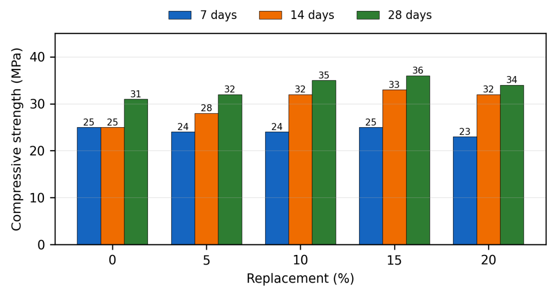

Fig. 4. Variation of compressive strength for the CDW + cement combination.

The strength of all waste-modified concretes improved consistently with curing age. Relative to the corresponding control mixes at 28 days, compressive strength increased by up to 6.05% for red mud (optimum 10%), 8.85% for eggshell powder (optimum 10%), 12.2% for fly ash (optimum 15–20%), and 13.83% for C&DW (optimum 15%). Beyond the optima, strength declined — most sharply for red mud and eggshell powder at 20% — as the diluted cement content and unreacted filler fractions limited hydration.

3.3 Split-tensile and flexural strength

Split-tensile strength followed the same pattern as compressive strength, improving over the control value of 3.12 MPa by 1.75–5.05% for red mud, 1.99–5.65% for eggshell powder, 2.5–10.2% for fly ash, and 3.9–12.64% for C&DW across the beneficial replacement ranges. Flexural strength likewise improved by 2.65–6.32% for red mud, 2.01–6.58% for eggshell powder, 3.65–11.35% for fly ash, and 4.32–11.85% for C&DW, with load–deflection observations indicating no loss of ductility in the modified beams.

3.4 Discussion of strength mechanisms

The observed improvements are consistent with mechanisms established in the literature, although it is emphasised that the interpretations below are literature-supported inferences: microstructural confirmation by SEM, XRD, or FTIR was outside the scope of the present experimental programme and is recommended as future work. The gains in the fly ash mixes align with the well-documented pozzolanic reaction of Class F ash with calcium hydroxide and the packing effect of its fine spherical particles, which refine the pore structure and improve the interfacial transition zone [5, 7]; the 20% optimum agrees closely with the 20% optimum and 8.1% compressive gain reported for the same replacement in recent comparable work [7]. The behaviour of red mud is consistent with reports that its reactive silica, alumina, and lime fractions contribute to additional C–S–H gel formation and matrix densification at moderate dosages, while its high alkalinity and fineness penalise workability and hydration at higher contents [8, 9]. The eggshell powder optimum of 10% reflects the calcium-enrichment and filler effects reported for 5–10% substitutions, beyond which the inert carbonate fraction dilutes the binder. The strong performance of C&DW powder corresponds to the combined filler action and residual cementitious activity of finely ground old mortar reported in recycled-material studies [11, 12]. The consistency of the present percentage gains with these independent findings lends confidence to the experimental results.

3.5 Cost-effectiveness and practical significance

For a producer, the relevant criterion is strength gain per unit material cost. Among the four wastes, C&DW and fly ash are the most economical: both are available at negligible or even negative cost (tipping-fee offsets), require only crushing/sieving or direct use, and delivered the two largest 28-day compressive strength improvements (13.83% at 15% C&DW and 12.2% at 20% fly ash). Fly ash at 20% additionally replaces the largest share of cement, maximising the CO_2 and cost savings per cubic metre. Eggshell powder, although technically effective at 10%, requires calcination at 900°C, which adds processing energy and cost and restricts it to locations with concentrated food-industry waste streams. Red mud requires neutralisation and careful proportioning, and delivered the smallest gain (6.05%), so its use is best justified where disposal pressure from alumina refineries dominates the economics. On a combined strength–cost–availability basis, C&DW at 15% replacement is identified as the most cost-effective option for general practice, with fly ash at 20% the preferred choice wherever a thermal power station is nearby; both allow M25 concrete to be produced with roughly one-sixth to one-fifth less cement at equal or better strength.

4 Conclusions

Based on the experimental evaluation of fly ash, red mud, eggshell powder, and C&DW as individual cement replacements in M25-grade concrete, the following conclusions are drawn:

- All four waste materials can partially replace cement in M25 concrete without impairing workability; slump values of all mixes (60–100 mm) satisfied IS 456:2000 requirements, with eggshell powder marginally improving and the other wastes marginally reducing flowability.
- The optimum individual replacement levels were 20% for fly ash, 10% for eggshell powder, 10% for red mud, and 15% for C&DW; strength declined beyond these levels owing to binder dilution and incomplete pozzolanic reaction.
- At the optima, 28-day compressive strength improved by 12.2% (fly ash), 8.85% (eggshell powder), 6.05% (red mud), and 13.83% (C&DW) relative to the control mix.
- Split-tensile strength improved by up to 10.2% (fly ash) and 12.64% (C&DW), and flexural strength by up to 11.35% (fly ash) and 11.85% (C&DW), confirming that the waste-modified concretes match or exceed conventional concrete across all three strength measures.
- C&DW at 15% replacement offers the best balance of strength gain, cost, and availability, followed by fly ash at 20%; both enable significant cement, cost, and CO_2 savings in routine M25 production.
- The strength-enhancement mechanisms inferred here (pozzolanic C–S–H formation, particle packing, and filler effects) should be confirmed through microstructural studies (SEM, XRD, FTIR) in future work, and multi-waste (binary/ternary) combinations, long-term durability under aggressive exposure, and data-driven mix-optimisation approaches [18–21] represent natural extensions of this research.

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