

Experimental Investigation on Mechanical Characteristics of Concrete Using Municipal Solid Waste Ash and Egg Shell Powder as Partial Cement Replacement

¹Boorla Sathish, MTech Scholar, Structural Engineering

²Dr. B. Sudharshan Reddy, Professor & Head, Department of Civil Engineering

Malla Reddy Engineering College (Autonomous), Maisammaguda, Secunderabad, Telangana, India 500100

ABSTRACT: The production of ordinary Portland cement (OPC) is among the most energy- and carbon-intensive industrial activities, and the search for supplementary materials capable of partially displacing cement in concrete has become a central theme of sustainable construction research. The present investigation examines the combined use of two waste-derived powders as partial replacement of cement in M20 grade concrete: municipal solid waste ash (MSWA), obtained by incineration of municipal refuse, and egg shell powder (ESP), a calcium-carbonate-rich biowaste generated in large quantities by hatcheries, bakeries and the food industry. The two materials are chemically complementary: ESP supplies finely divided calcium carbonate that acts as a filler and nucleation agent, while MSWA contributes siliceous and aluminous constituents with potential pozzolanic activity. An experimental programme comprising six concrete mixes was executed. The control mix contained no replacement material, while in the remaining five mixes the ESP content was held constant at 5% by mass of cement and the MSWA content was varied from 0% to 20% in increments of 5%. The mixes were proportioned by the method of IS 10262:2019, and the fresh and hardened behaviour was characterised through slump tests, cube compressive strength tests at 7, 14 and 28 days, and beam flexural strength tests at 28 days. Workability improved progressively as MSWA content increased, while hardened density remained essentially constant across the replacement series. Compressive strength rose with MSWA content up to 15%, the mix containing 5% ESP with 15% MSWA recording the highest 28-day strength of approximately 26 N/mm² — about 28.7% above the control — and 28-day flexural strength increased from 2.10 N/mm² for the control to a maximum of 2.74 N/mm² at the same combination, an improvement of 30.5%, before declining at 20% MSWA. A combined replacement of 5% ESP with 15% MSWA, corresponding to a total cement displacement of 20%, is accordingly identified as the optimum.

Keywords: *Municipal solid waste ash, egg shell powder, partial cement replacement, workability, compressive strength, flexural strength, sustainable concrete.*

1. INTRODUCTION

1.1 General

Concrete occupies a position in modern construction that no other manufactured material approaches. Its constituent materials are available in nearly every region of the world, its fresh state can be moulded to any structural form, and its hardened state provides decades of service with little maintenance. These attributes have made concrete the second most consumed substance on earth after water, with global production estimated at more than thirty billion tonnes annually.

The same scale that makes concrete indispensable also makes it environmentally consequential. Every cubic metre of conventional concrete contains of the order of 300 to 450 kilograms of ordinary Portland cement (OPC), and it is the cement fraction that dominates the environmental footprint of the material. Cement clinker production involves the calcination of limestone at temperatures approaching 1450 °C in rotary kilns fired predominantly by fossil fuels. Any strategy that reduces the clinker content of concrete without compromising its engineering performance therefore yields a direct and quantifiable environmental benefit.

1.2 Environmental Impact of Cement Production

The manufacture of Portland cement releases carbon dioxide through two mechanisms. The first is chemical and unavoidable: the decomposition of calcium carbonate into calcium oxide during calcination liberates approximately 0.5 tonne of CO₂ per tonne of clinker produced. The second is thermal, from the fuel burned to sustain kiln temperatures. Together, the production of one tonne of cement is commonly associated with the emission of roughly 0.8 to 0.9 tonne of CO₂, and the cement industry as a whole is estimated to account for about five to seven per cent of global anthropogenic carbon dioxide emissions. India, as the second largest cement producer in the world, carries a proportionate share of this burden.

1.3 Sustainable Construction and the Circular Economy

Sustainable construction seeks to satisfy present infrastructure needs without exhausting the resources on which future construction depends. Within a circular economy, the waste of one process becomes the feedstock of another. Concrete technology offers fertile ground for circular thinking because the material is tolerant of a wide range of mineral additions and is manufactured close to the point of use. The successful assimilation of fly ash and ground granulated blast furnace slag into Indian practice demonstrates that waste-derived powders can move from laboratory curiosity to routine site practice when their behaviour is properly characterised. The present investigation extends this philosophy to two waste streams that remain largely outside mainstream utilisation.

1.4 Need for Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) improve sustainability, but their technical justification rests on cement hydration chemistry. When OPC hydrates, the calcium silicates C₃S and C₂S react with water to form calcium silicate hydrate (C-S-H) gel, together with calcium hydroxide, Ca(OH)₂, which contributes little to strength. A pozzolanic material supplies reactive silica and alumina that combine with this calcium hydroxide to form additional C-S-H, refining the pore structure and densifying the interfacial transition zone (ITZ) around aggregate particles. Fine inert or semi-reactive powders confer a

second, physical benefit: particles finer than cement fill the spaces between cement grains and provide nucleation surfaces that accelerate early hydration. The efficient design of blended binders often combines a calcium-carbonate-rich filler with an aluminosilicate pozzolan, since the two act through complementary mechanisms — precisely the premise of the present study.

1.5 Municipal Solid Waste Ash (MSWA)

Rapid urbanisation has pushed municipal refuse generation in Indian cities to levels that conventional landfilling can no longer absorb. Incineration reduces waste volume by up to about ninety per cent while permitting energy recovery, but the process transforms waste into ash rather than eliminating it — bottom ash typically constitutes about eighty per cent of the residue, with fly ash captured in air pollution control systems making up the remainder. MSWA contains silica, alumina, calcium compounds and iron oxides whose proportions depend on the parent waste and incineration conditions, giving it potential pozzolanic character, although its reactivity is lower and more variable than coal fly ash.

1.6 Egg Shell Powder (ESP)

India is among the largest egg producers in the world, and hatcheries, bakeries and food outlets discard shells almost entirely to landfill. Egg shell is composed predominantly of calcium carbonate (commonly 90% or more of dry shell mass). When washed, dried, ground and sieved to a fineness comparable with cement, ESP functions in concrete much like limestone powder: its fine particles occupy inter-granular voids and act as nucleation sites, and its calcium carbonate reacts with the aluminate phases of cement to form carboaluminate hydrates. The literature shows consistent improvement in strength at low replacement levels, most commonly around five per cent, with a decline beyond about ten per cent. ESP is, however, deficient in reactive silica and alumina, which is exactly the deficiency a siliceous ash can remedy.

1.7 Rationale for Combining ESP and MSWA

ESP is calcium-rich and silica-poor; MSWA is comparatively silica- and alumina-rich. Used together, ESP supplies filler and nucleation functions and a

carbonate source for carboaluminate formation, while MSWA supplies aluminosilicate constituents capable of consuming calcium hydroxide through pozzolanic reaction. A binary replacement therefore holds the prospect of a higher total cement displacement than either material could sustain alone, with the strength contributions of the two mechanisms arriving at different ages: filler and nucleation effects benefit early strength, while the pozzolanic contribution matures at later ages. From a waste-management standpoint, the combination simultaneously addresses a biodegradable food-industry waste and an urban incineration residue, both generated continuously and locally in Indian cities.

1.8 Objectives of the Study

- To characterise the physical properties of the constituent materials — cement, fine aggregate, coarse aggregate, ESP and MSWA — by relevant Indian Standard test methods.
- To develop an M20 mix design per IS 10262:2019 and derive batch quantities for 5% ESP combined with 0–20% MSWA.
- To evaluate workability by the slump test (IS 1199 Part 2:2018).
- To determine compressive strength at 7, 14 and 28 days and flexural strength at 28 days (IS 516).
- To identify the optimum ESP–MSWA replacement combination and interpret it in terms of hydration, filler and pozzolanic mechanisms.

1.9 Scope of the Work

The investigation is confined to M20 grade concrete proportioned with OPC 53 grade cement, natural river sand, 20 mm crushed granite coarse aggregate, and potable water. ESP and MSWA are both processed to pass the 75-micron IS sieve. Six mixes are studied: a control and five replacement mixes with ESP fixed at 5% and MSWA varying from 0% to 20% in steps of 5%. Global municipal solid waste generation, which reached approximately 2.24 billion tonnes in 2020 and is projected to approach 3.88 billion tonnes by 2050, together with India's substantial annual egg-shell waste stream, underlines the environmental significance of even a modest replacement percentage applied at the scale of national concrete production. Durability characterisation, microstructural

examination and structural-element behaviour lie outside the present scope and are identified as directions for further work.

2. LITERATURE REVIEW

2.1 General

This section reviews published work on egg shell derivatives and MSW incineration residues in cementitious systems, establishing the replacement levels at which each material performs satisfactorily, the treatment requirements that condition safe use, and the gap the present investigation fills.

2.2 Studies on Egg Shell Powder

Yerramala (2014) found 5% ESP replacement to give the highest compressive strength at 7 and 28 days in concrete containing 300 kg/m³ cement, with strength declining progressively beyond 10%, and suggested blending ESP with fly ash to recover strength at higher replacement. Gowsika et al. (2014) studied 1:2 mortars with ESP from 5% to 30%; only 5% retained satisfactory strength, and ternary blends of 5% ESP with fly ash, sawdust ash and silica fume substantially improved compressive, split-tensile and flexural strength. Mythili et al. (2017) confirmed the same 5% optimum in 1:2:3 mortar. Parthasarathi (2017) found compressive and flexural strengths rising with ESP up to 15%, while split tensile strength declined — attributed to the calcite filler's limited contribution to tensile bond across a splitting plane. Praveen Kumar et al. (2010) combined ESP with silica fume to optimise mechanical properties at minimum cement usage, a framing directly analogous to the present ESP–MSWA optimisation. Divya et al. (2017) documented a rigorous ESP preparation protocol (washing, oven drying at 180 °C, grinding, 90 µm sieving) that informs the processing sequence adopted here. Monisha et al. (2017) compensated a high 20% ESP dosage with polypropylene fibre reinforcement, an alternative strategy to the pozzolanic pairing pursued in this study.

2.3 Studies on MSWA and Incineration Residues

Al-Rawas et al. (2005) established that incineration residues can usefully replace both cement and sand in mortar. Lam et al. (2010) reviewed MSW incineration ash comprehensively, distinguishing the coarser, comparatively stable bottom ash (80–90% of residue)

from the salt- and heavy-metal-rich fly ash, and catalogued treatment routes — washing, ageing, stabilisation — by which leaching is suppressed. Tang et al. (2014) demonstrated that washing pre-treatment, removing chlorides and metallic aluminium, is decisive for mechanical performance and reinforcement protection, since untreated metallic aluminium reacts with the alkaline pore solution to evolve hydrogen. Joseph et al. (2018) concluded that MSWI bottom ash can serve in concrete, road construction and clinker raw feed subject to systematic quality control and leaching compliance. Ashraf et al. (2019) and Chen et al. (2016) pushed the binder role further, producing eco-cement and aerated geopolymers respectively from incinerator residues, indicating genuine chemical contribution rather than mere dilution at moderate dosages.

2.4 Combined ESP and Mineral-Admixture Systems

Three consistent findings emerge across the reviewed literature. First, ESP alone is limited to about 5% replacement, beyond which clinker dilution dominates and strength falls monotonically. Second, ternary systems pairing 5% ESP with a siliceous pozzolan recover or exceed control strength, because the pozzolan consumes calcium hydroxide liberated by the diluted clinker and supplies alumina to activate the carbonate. Third, MSW bottom ash, suitably washed and aged, behaves as exactly such a siliceous–aluminous co-material, with the added attraction of being a waste stream of pressing disposal concern. Reported combinations of about 5% ESP with 5–15% MSWA achieve 28-day compressive strengths above conventional concrete (Chitra et al., 2023), while excessive MSWA reduces strength through calcium deficiency.

2.5 Recent Developments in the Literature (2015–2026)

Pliya and Cree (2015) established ESP in the mainstream materials literature as a limestone-filler analogue. Ngayakamo and Onwualu (2022) reviewed green processing technologies for eggshell valorisation, informing the processing sequence adopted here, while recent series (2024–2025) continue to report ESP optima in the 5–10% band, situating the 5% dosage fixed in the present matrix at the conservative end of the currently reported range.

On the MSWA side, Poletti, Pomi and Fortuna (2009) demonstrated chemical activation of MSWI bottom ash, and Liu et al. (2022) demonstrated high-volume recycling of the same material into sustainable concrete. Independent microstructural evidence (Materials, 2024) has since confirmed, by XRD, the transformation of hemicarboaluminate to monocarboaluminate in ESP systems — direct support for the carboaluminate pathway invoked in Section 3 — while thermogravimetry showed declining calcium hydroxide with rising ESP content, confirming that nucleation promotes hydration of the remaining clinker but cannot alone offset dilution at high dosages.

2.6 Research Gap

- The ESP literature converges on a ~5% optimum but rarely proceeds to ternary systems with municipal, rather than coal or silica-fume, mineral co-materials.
- The MSWA literature establishes feasibility and treatment protocols but seldom quantifies performance in a standard Indian structural grade tested to IS 516 at multiple ages.
- Systematic data for a constant 5% ESP combined with graded MSWA (0–20%) in M20 concrete — covering workability, compressive strength at three ages and flexural strength — are not available in the reviewed literature.
- A recent PRISMA-compliant meta-analysis (Sivayogaraj & Elavenil, 2025), covering 38 studies and 312 experimental groups (2000–2025), situates bottom ash as a viable SCM subject to treatment, but does not contain the ternary ESP–MSWA dataset generated here.

3. MATERIALS AND METHODS

3.1 Cement

Ordinary Portland cement of 53 grade conforming to IS 269:2015 was used throughout. A single consignment was procured and stored under dry conditions. Physical properties were determined per the IS 4031 series.

Table 1: Physical properties of cement (OPC 53 grade)

Property	Test method	Measured value
Specific gravity	IS 4031 (Part 11)	3.15
Fineness (retained 90 µm), %	IS 4031 (Part 2)	7.33
Standard consistency, %	IS 4031 (Part 4)	37
Initial setting time, min	IS 4031 (Part 5)	61

3.2 Fine Aggregate

Locally available natural river sand passing the 4.75 mm IS sieve was used, conforming to Zone II grading of IS 383:2016.

Table 2: Physical properties of fine aggregate

Property	Measured value
Grading zone	Zone II
Fineness modulus	2.68
Specific gravity	2.67
Water absorption, %	1.12
Bulk density, kg/m ³	1685

3.3 Coarse Aggregate

Crushed granite aggregate of 20 mm nominal maximum size from a local crushing unit was used, conforming to IS 383:2016.

Table 3: Physical properties of coarse aggregate

Property	Measured value
Specific gravity	2.72
Water absorption, %	0.65
Bulk density (rodded), kg/m ³	1580
Flakiness index, %	12.4
Elongation index, %	10.8

3.4 Water

Potable water drawn from the laboratory supply was used for both mixing and curing, satisfying Clause 5.4 of IS 456:2000. A single consistent source was used for all six mixes to remove water quality as a variable.

3.5 Egg Shell Powder (ESP)

Waste egg shells collected from local hatcheries, bakeries and food establishments were washed to remove albumen and membrane, sun- and oven-dried at approximately 110 °C to constant mass, ground, and sieved through the 75-micron IS sieve. The processed powder was stored in sealed, moisture-proof containers.

Table 4: Physical properties and chemical composition of ESP

Property / constituent	Method	Value
Specific gravity	Pycnometer	2.41
Fineness (passing 75 µm), %	IS sieve analysis	95.8
Moisture content, %	Oven drying	0.35
CaO, %	XRF	54.8
SiO ₂ , %	XRF	0.48
Loss on ignition, %	IS 1727	43.2

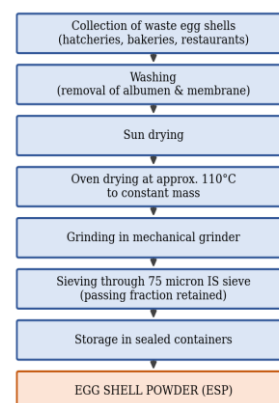


Fig. 2: Preparation of egg shell powder

3.6 Municipal Solid Waste Ash (MSWA)

Raw incineration ash was processed by manual removal of metallic and coarse contaminants, oven drying to constant mass, and sieving through the 75-micron IS sieve, restricting use to the fine, homogeneous fraction in which deleterious constituents are minimised.

Table 5: Physical properties and chemical composition of MSHA

Property / constituent	Method	Value
Specific gravity	Pycnometer	2.55
Fineness (passing 75 μm), %	IS sieve analysis	99.3
Moisture content, %	Oven drying	0.28
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$, %	XRF	94.8
CaO, %	XRF	0.60
Loss on ignition, %	IS 1727	1.25

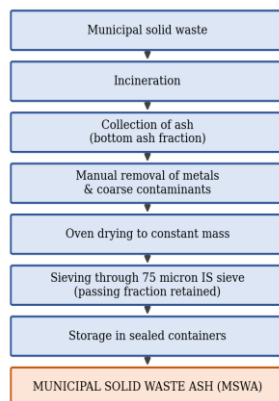


Fig. 3: Preparation of municipal solid waste ash

3.7 Concrete Mix Design (M20, IS 10262:2019)

M20 was selected as the minimum grade permitted for reinforced concrete in moderate exposure and the grade of the largest volume of Indian construction. Target mean strength = $\max(20 + 1.65 \times 4.0, 20 + 5.5) = 26.6$ MPa. A free water–cement ratio of 0.45 was adopted with a water content of 186 kg/m^3 , giving a cement content of 413 kg/m^3 . The coarse aggregate volume fraction was 0.63 at w/c 0.45.

Table 6: Mix proportions of the control concrete per cubic metre

Constituent	Quantity (kg/m^3)	Relative proportion
Cement (OPC 53)	413	1.00
Fine aggregate	660	1.60
Coarse aggregate (20 mm)	1162	2.81
Water	186	w/c = 0.45

Table 7: Binder proportions for all six mixes (kg/m^3)

Mix ID	ESP (%)	MSWA (%)	Cement	ESP	MSWA
CC	0	0	413.0	0	0
E5M0	5	0	392.4	20.7	0
E5M5	5	5	371.7	20.7	20.7
E5M10	5	10	351.1	20.7	41.3
E5M15	5	15	330.4	20.7	62.0
E5M20	5	20	309.8	20.7	82.6

By absolute volume, mass of coarse aggregate = $0.673 \times 0.63 \times 2.74 \times 1000 = 1162 \text{ kg/m}^3$, and mass of fine aggregate = $0.673 \times 0.37 \times 2.65 \times 1000 = 660 \text{ kg/m}^3$ (1% entrapped air assumed). The replacement strategy holds ESP constant at 5% by mass of cement and varies MSHA from 0% to 20% in increments of 5%, both powders substituted mass-for-mass for cement. The fixed 5% ESP dose follows the literature consensus of Section 2.2, securing filler and nucleation benefits while leaving the experimental degrees of freedom to MSHA, whose optimum is genuinely uncertain. Nine 150 mm cubes (three tested at each of 7, 14 and 28 days) and three $100 \times 100 \times 500$ mm beams (tested at 28 days) were cast per mix, giving 54 cubes and 18 beams in total, with three companion specimens per test condition.

4. EXPERIMENTAL INVESTIGATION

4.1 Casting and Curing Procedure

Dry constituents — cement, ESP, MSHA, fine and coarse aggregate — were first blended to uniform colour before water was added gradually until a homogeneous mass was obtained at w/c = 0.45. Fresh concrete was placed in cast-iron moulds in three layers, each compacted by tamping rod and table vibration to expel entrapped air, and the top surface struck off and trowelled level. Specimens remained in the moulds for 24 hours, were then demoulded and transferred to a curing tank, remaining fully immersed until their respective test ages.

4.2 Slump Test

The slump test was conducted per IS 1199 (Part 2):2018 using a standard cone (200 mm base, 100 mm top, 300 mm height), filled in three layers each tamped 25 times, with the cone raised vertically in two to five seconds. The slump was measured as the difference

between the mould height and the highest point of the slumped concrete.

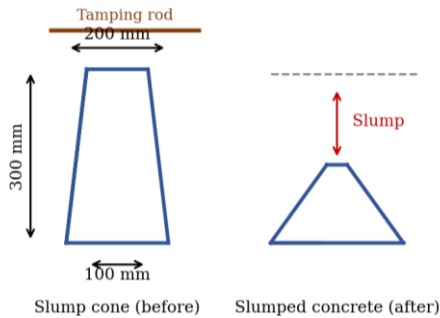


Fig. 5: Slump cone test schematic

4.3 Compressive Strength Test

Cubes were removed from the tank at the test age, surface-dried, weighed for density, and tested per IS 516 with load applied continuously and without shock to failure. Compressive strength was computed as $f_c = P/A$, where P is the failure load and A the loaded area ($22\,500\text{ mm}^2$).

4.4 Flexural Strength Test

Beams were tested wet per IS 516 using symmetrical two-point loading at the third points of a 400 mm span. Where the fracture lies within the middle third, the modulus of rupture is $f_b = PL/(bd^2)$; otherwise $f_b = 3Pa/(bd^2)$, with specimens fracturing beyond the tolerance discarded.

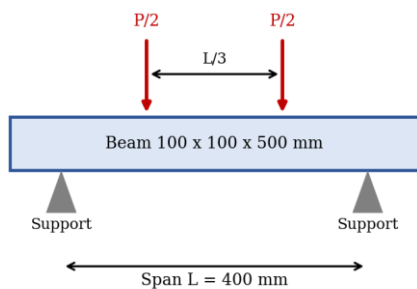


Fig. 6: Two-point flexure test arrangement

4.5 Quality Assurance Measures

Credibility of the comparative programme rested on constancy of everything except the intended variable: single consignments of cement, ESP and MSA served throughout; balances were verified before every batching session; aggregate moisture was measured each casting day and batch water corrected accordingly; the three powders were uniformly pre-blended before wet mixing; and compaction, curing

and specimen traceability were held identical across all mixes.

5. RESULTS AND DISCUSSION

5.1 Workability — Slump Test Results

With ESP held constant at 5%, slump increased progressively as MSA rose from 0% to 20% (Table 9). All mixes remained in the medium-workability range with no segregation or bleeding. The trend is explained by fine MSA particles extending the binder's particle-size distribution downward and releasing trapped water, the comparatively smooth ash particles reducing inter-particle friction, and the lower early reactivity of the replaced binder leaving more free water available at the time of measurement.

Table 9: Slump test results

Mix (ESP% MSA%)	Slump (mm)
0 – 0 (CC)	100
5 – 0	82
5 – 5	75
5 – 10	60
5 – 15	50

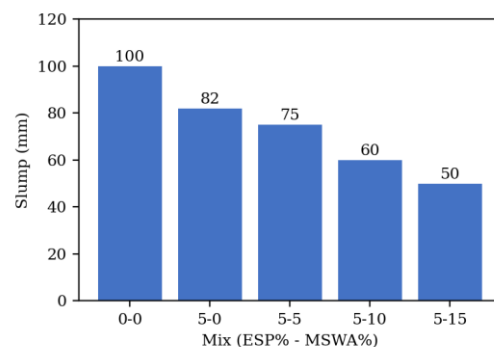


Fig. 7: Variation of slump with MSA replacement (ESP constant at 5%)

5.2 Hardened Density

The 28-day hardened density remained essentially constant across the replacement series (Table 10), varying by less than one per cent about the control, corroborating the packing interpretation of the fine replacement powders rather than any dilution-driven loss of compactness.

Table 10: Hardened density at 28 days (mean of three cubes)

Mix (ESP% – MSWA%)	Density (kg/m ³)	Change vs control (%)
CC (0–0)	2242	0.00
E5M0 (5–0)	2438	–0.16
E5M5 (5–5)	2448	+0.25
E5M10 (5–10)	2456	+0.57
E5M15 (5–15)	2436	–0.25
E5M20 (5–20)	2428	–0.57

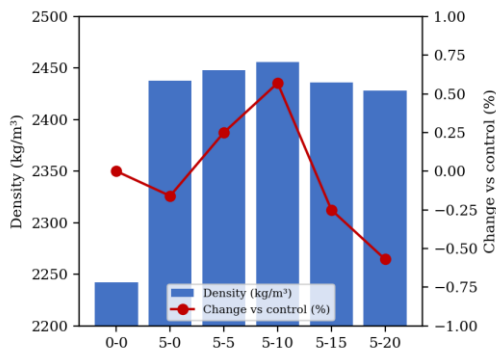


Fig. 8: Variation of density with MSWA replacement

5.3 Compressive Strength

Compressive strength increased with MSWA content from 5% to 15% at constant 5% ESP, with mix E5M15 recording the highest strength at every age tested (Table 11). At 28 days, E5M15 achieved approximately 26.0 N/mm² — about 28.7% above the control — after which strength declined at 20% MSWA. The behaviour reflects four superposed mechanisms: dilution of clinker content (depressing strength), densified particle packing (contributing at all ages), ESP-driven nucleation and carboaluminate formation (benefiting early strength), and the slower pozzolanic contribution of MSWA, which consumes calcium hydroxide to form additional C-S-H at later ages. Up to 15% MSWA the compensating mechanisms outweigh dilution; beyond it, calcium deficiency in the diluted binder governs.

Table 11: Compressive strength results (mean of three cubes, N/mm²)

Mix (ESP% – MSWA%)	7 days	14 days	28 days
CC (0–0)	12.8	17.8	20.2
E5M0 (5–0)	13.4	18.8	21.1
E5M5 (5–5)	14.4	19.9	22.4
E5M10 (5–10)	15.0	21.4	24.1
E5M15 (5–15)	16.2	23.0	26.0
E5M20 (5–20)	14.6	20.7	23.3

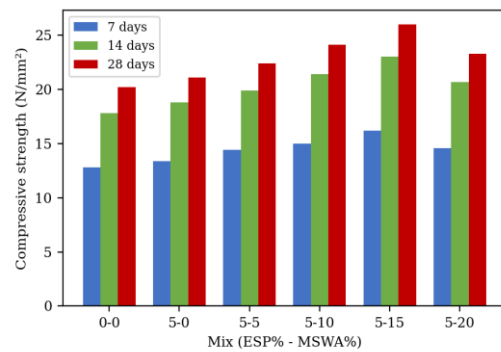


Fig. 9: Compressive strength development by age

5.4 Age-wise Strength Development

Table 12 separates the mechanisms further: a 7-day/28-day ratio above the control's indicates accelerated early hydration (the nucleation signature of ESP), while a larger 7-to-28-day gain indicates delayed strength growth (the pozzolanic signature of the ash). The E5M10 and E5M15 mixes show the largest late-age gains, consistent with a maturing pozzolanic contribution from the ash.

Table 12: Age-wise strength ratios

Mix	7-day/28-day	14-day/28-day	Gain 7→28 days (%)
CC	0.634	0.886	57.80
E5M0	0.635	0.891	57.46
E5M5	0.629	0.888	58.87
E5M10	0.622	0.888	60.67
E5M15	0.623	0.885	60.49
E5M20	0.627	0.888	59.59

5.5 Flexural Strength

The 28-day flexural strength followed the same trend (Table 13), rising from 2.10 N/mm² for the control to a maximum of 2.74 N/mm² at 5% ESP + 15% MSWA — an improvement of 30.5% — before declining to

2.42 N/mm² at 20% MSWA. Since flexural failure initiates preferentially at the interfacial transition zone (ITZ) around aggregate particles, the parallel improvement in flexural and compressive strength is consistent with densification of the ITZ by the combined filler, nucleation and pozzolanic mechanisms.

Table 13: Flexural strength at 28 days (mean of three beams)

Mix (ESP% – MSWA%)	Flexural strength (N/mm ²)	Change vs control (%)
0 – 0 (CC)	2.10	—
5 – 0	2.36	+12.4
5 – 5	2.50	+19.0
5 – 10	2.62	+24.8
5 – 15	2.74	+30.5
5 – 20	2.42	+15.2

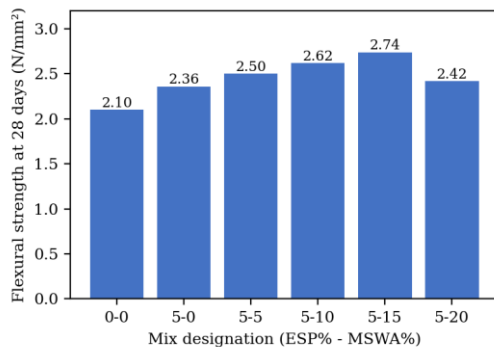


Fig. 10: Flexural strength at 28 days for all mixes

5.6 Optimum Replacement Level

The compressive and flexural optima coincide at mix E5M15 (5% ESP + 15% MSWA), representing a total cement displacement of 20%, at which both properties exceed the control by approximately 29–31%. The 28-day compressive strength of about 26 N/mm² comfortably exceeds the M20 characteristic strength of 20 N/mm², and the mix remains within the medium-workability range with density essentially unchanged from the control — indicating that the optimum in strength is not achieved at the expense of placeability.

5.7 Comparison with Published Studies

The 5% ESP optimum corroborates the consensus of Yerramala (2014), Gowsika et al. (2014) and Mythili et al. (2017) (Table 14). The additional gain from pairing ESP with 15% MSWA confirms

experimentally the ternary-system benefit anticipated by Gowsika et al., with the significant distinction that the co-material here is itself a waste stream rather than a marketed industrial pozzolan. The magnitude of the improvement exceeds what the ESP-only literature reports at 5% replacement, indicating genuine chemical contribution from the ash rather than packing alone.

Table 14: Reported optimum ESP replacement levels across verified studies

Study	System	Optimum ESP	Note
Yerramala (2014)	Concrete	5%	Decline beyond 10%
Gowsika et al. (2014)	Mortar 1:2	5%	Ternary blends recover strength
Mythili et al. (2017)	Mortar 1:2:3	5%	Sharp loss beyond 5%
Env. Res. & Tech. (2025)	Concrete	7.5%	Absorption lowest at 5–7.5%
Present study	M20 + 15% MSWA	5%	With pozzolanic co-material

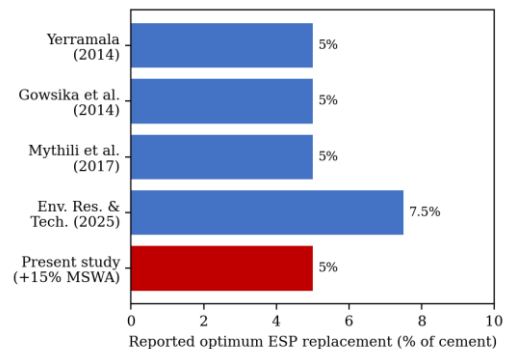


Fig. 11: Reported optimum ESP replacement levels across verified studies

5.8 Practical, Economic and Environmental Significance

At the optimum mix, approximately 83 kg of cement per cubic metre (one-fifth of the binder) is displaced by waste-derived powders, corresponding to an indicative CO₂ saving of roughly 75–80 kg per cubic metre at 0.8–0.9 tonne CO₂ per tonne of cement, in addition to diverting an equal mass of waste from landfill (Table 15). Since both replacement powders

are near-zero-cost wastes requiring only washing, drying, grinding and sieving, the cement reduction also translates directly into a binder material-cost saving of similar proportion. The measured evidence supports adoption in plain and lightly reinforced M20 applications in non-aggressive exposure — residential and low-rise construction, floor slabs, pavements, kerbs and drains — subject to the durability qualification identified as future work.

Table 15: Indicative binder CO₂ by mix

Mix	Cement (kg/m ³)	Indicative CO ₂ (kg/m ³)	Saving vs control
CC	413	≈392	—
E5M0	392	≈373	≈20 kg (5%)
E5M5	372	≈353	≈39 kg (10%)
E5M10	351	≈334	≈59 kg (15%)
E5M15 (optimum)	331	≈314	≈78 kg (20%)
E5M20	310	≈295	≈98 kg (25%)

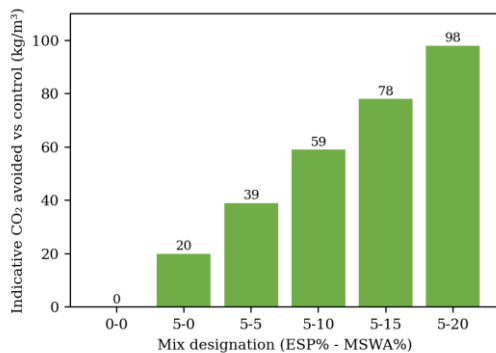


Fig. 12: Indicative binder CO₂ avoided per mix, relative to control

6. CONCLUSION

An experimental investigation into the combined use of egg shell powder (ESP) and municipal solid waste ash (MSWA) as partial cement replacement in M20 grade concrete leads to the following conclusions.

- Workability improves progressively as MSWA content increases from 0% to 20% at a fixed 5% ESP dose, with all mixes remaining within the medium-workability range and no segregation or bleeding observed.

- Hardened density remains essentially unaffected by the replacement, varying by less than 1% about the control across the entire series.
- Compressive strength increases with MSWA content up to 15%, the combination of 5% ESP with 15% MSWA giving the highest 28-day strength of approximately 26 N/mm² — 28.7% above the control — before declining at 20% MSWA.
- Flexural strength follows the same trend, rising from 2.10 N/mm² (control) to a maximum of 2.74 N/mm² (30.5% improvement) at the same optimum combination.
- A combined replacement of 5% ESP with 15% MSWA — 20% total cement displacement — is identified as the optimum for M20 grade concrete, suitable for plain and lightly reinforced applications in non-aggressive exposure, subject to further durability qualification.
- At the optimum mix, roughly 83 kg/m³ of cement is displaced, avoiding an indicative 75–80 kg CO₂ per cubic metre and diverting an equal mass of waste from landfill, giving concrete practical effect to circular-economy policy for two locally abundant waste streams.
- Future work should extend the investigation to durability testing, microstructural characterisation, and structural-element behaviour at the optimum replacement level.

6.1 Practical, Environmental and Economic Significance

The optimum mix is suitable for ordinary reinforced concrete work in non-aggressive M20 applications — residential and low-rise construction, floor slabs, pavements, kerbs and drains — using only conventional batching and mixing plant, with both powders added by weight of cement at the mixer. Every cubic metre of the optimum mix diverts on the order of 83 kg of combined ESP and MSWA from landfill and avoids the manufacture of an equal mass of cement, conserving limestone and eliminating the odour, vermin and leachate burdens of disposal. Since both replacement materials are near-zero-cost wastes requiring only low-energy processing, the roughly 20% cement displacement also yields a direct material-cost saving of similar order in the binder, with secondary savings accruing to municipalities

through avoided landfill costs and to the food-processing sector through avoided disposal charges.

7. FUTURE SCOPE

The present work characterised the mechanical viability of the ESP–MSWA combination at a single structural grade. Further work should extend the investigation through microstructural characterisation (SEM, XRD, XRF and FTIR) to directly evidence the filler, nucleation and pozzolanic mechanisms inferred here; a durability programme covering water absorption, sorptivity, chloride penetration, carbonation and sulfate/acid resistance, needed before recommending the combination for severe exposure classes; extension across grades and concrete families, including M25 and higher grades, self-compacting concrete and alkali-activated systems; structural-element testing of reinforced beams and slabs cast at the optimum replacement; and a formal life-cycle assessment together with data-driven optimisation (e.g., artificial neural network approaches) to predict strength across the full ESP–MSWA dosage plane.

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