

# Multi-Criteria Performance Assessment of Innovative Coarse-Aggregate Substitutes in Concrete

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**Abstract**—Natural coarse aggregate is the dominant solid constituent of conventional concrete and its extraction creates cumulative land, energy, transport, and ecological burdens. This paper develops a literature-calibrated comparative framework for replacing natural coarse aggregate with recycled concrete aggregate (RCA), crushed brick aggregate, steel slag, processed e-waste plastic, crumb rubber, coconut shell, and sintered fly-ash aggregate (SFA). The contribution is not a claim of a new laboratory campaign; instead, peer-reviewed findings are harmonized into performance envelopes and coupled to a reproducible volumetric mix-design procedure, service-risk screening, life-cycle indicators, and a robust multi-criteria decision analysis (MCDA). Representative response curves show that mature, graded RCA can preserve structural performance at moderate replacement, aged steel slag can equal or exceed control strength in a favorable band, while low-stiffness polymeric and bio-derived particles primarily create lightweight, impact-tolerant, or non-structural opportunities. The proposed decision score combines strength retention, tensile response, density, absorption, durability risk, embodied impact, cost, supply reliability, and specification readiness. Under a balanced reinforced-concrete scenario, steel slag and RCA rank highest; under lightweight and impact-led scenarios, SFA, coconut shell, and rubber become competitive. The paper provides equations, a test matrix, acceptance gates, and a field specification pathway suitable for Indian practice. The results emphasize that replacement percentage alone is an inadequate design variable: source control, pre-treatment, moisture state, gradation, and application-specific weighting govern successful implementation.

**Index Terms**—circular concrete, coarse aggregate, recycled concrete aggregate, steel slag, waste plastic, crumb rubber, coconut shell, sintered fly ash, durability, MCDA.

## I. INTRODUCTION

Concrete consumes large volumes of quarried stone because coarse aggregate commonly occupies about one-third to nearly one-half of the concrete volume. Even where the cement fraction dominates cradle-to-gate greenhouse-gas emissions, aggregate extraction affects river systems, slopes, dust, haulage, and local material security. Simultaneously, demolition rubble, metallurgical slag, discarded polymers, end-of-life tyres, agricultural shells, and ash remain underutilized. The engineering opportunity is therefore circular, but it is not automatically safe: each substitute changes particle stiffness, shape, water demand, interfacial transition zone (ITZ), dimensional stability, and contaminant risk.

Existing studies usually optimize one waste stream in one binder system. Direct ranking is difficult because replacement may be reported by mass or volume, moisture states differ, control strengths vary, and many datasets omit transport or durability. This paper responds with an application-led comparison in which all candidate materials pass the same sequence of characterization, volume correction, performance normalization, risk gating, and decision scoring.

## A. Research Need and Contributions

A substitute may reduce quarry demand yet increase water absorption, chemical expansion, processing energy, or quality-control effort. Conversely, a modest strength reduction can be acceptable when lower density reduces structural dead load or when rubber improves impact and damping. A single “optimum percentage” is therefore misleading unless the objective, reference concrete, exposure class, and uncertainty are stated.

This manuscript makes five linked contributions. First, it organizes seven substitutes by origin and governing failure mechanism. Second, it provides a saturated-surface-dry (SSD), constant-volume replacement method that prevents the mass-versus-volume error. Third, it converts heterogeneous literature findings into transparent indices rather than presenting synthetic values as laboratory observations. Fourth, it integrates engineering, environmental, economic, and implementation criteria in an MCDA model. Fifth, it translates the comparison into acceptance gates and a validation program suitable for mix qualification.

Comparative decision architecture

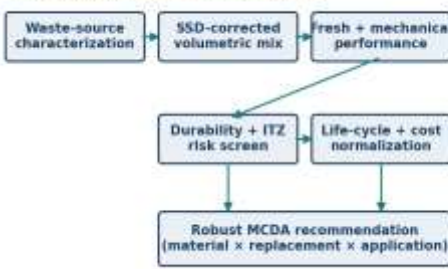


Fig. 1. Proposed literature-to-decision architecture.

Each candidate is screened before ranking.

$$R_v = 100 V_{alt} / (V_{alt} + V_{NA}) \quad (1)$$

Here,  $R_v$  is the replacement fraction by absolute aggregate volume. Volume is the preferred basis because steel slag can have substantially higher specific gravity than natural stone, whereas coconut shell, rubber, plastic, and SFA are much lighter. Equal-mass substitution would unintentionally change total aggregate volume and paste demand.

## B. Scope and Evidence Status

The paper addresses normal-vibrated and moderately high-performance concrete for buildings, pavements, precast units, and non-structural products. Alkali-activated binders, fibre dosage optimization, and reinforced-member design are discussed only where they clarify aggregate behavior. Numerical graphs are representative, literature-calibrated envelopes constructed from reported directional trends and practical ranges; they are explicitly not a pooled meta-analysis or author-generated laboratory dataset.

## II. CANDIDATE MATERIAL TAXONOMY

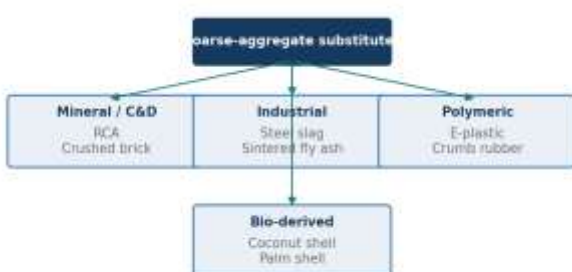


Fig. 2. Substitute families and representative materials included in the framework.

TABLE I — FUNCTIONAL TAXONOMY OF COARSE-AGGREGATE SUBSTITUTES

| Material      | Dominant benefit                | Primary risk                    |
|---------------|---------------------------------|---------------------------------|
| RCA           | C&D diversion;<br>local supply  | old mortar;<br>absorption       |
| Crushed brick | masonry-waste<br>recovery       | porosity; strength<br>loss      |
| Steel slag    | high hardness;<br>interlock     | free CaO/MgO<br>expansion       |
| E-plastic     | low density; waste<br>diversion | weak bond; fire<br>behavior     |
| Crumb rubber  | impact/damping                  | low stiffness;<br>entrained air |
| Coconut shell | bio-waste;<br>lightweight       | high absorption;<br>variability |
| SFA           | ash utilization;<br>low density | sintering energy;<br>porosity   |

## A. Recycled Concrete Aggregate

RCA consists of original mineral aggregate coated with residual mortar and, depending on demolition practice, small quantities of brick, plaster, asphalt, glass, or reinforcement fragments. The adhered mortar lowers specific gravity and increases absorption and crushing vulnerability. High-quality RCA produced from known structural concrete is fundamentally different from mixed demolition aggregate; source classification must therefore precede mix design.

The principal engineering controls are selective demolition, removal of steel and deleterious fines, multi-stage crushing, washing or air classification, density separation, and moisture conditioning. Two-stage mixing can first coat RCA with a portion of cement paste, reducing localized water theft and improving the new ITZ. Moderate replacement often preserves usable strength, but shrinkage, creep, chloride migration, and freeze–thaw response become controlling in severe exposure.

## B. Crushed Brick Aggregate

Crushed fired-clay brick is angular and rough but much more porous than dense stone. It can improve mechanical interlock while increasing effective water demand and lowering elastic modulus. Pre-soaking, narrow gradation, removal of gypsum/plaster, and limiting replacement are common controls. Brick-rich RCA is attractive for blocks, low-rise elements, internal concrete, and thermal-mass applications, but exposure-specific durability confirmation is essential.

### C. Steel Slag Aggregate

Air-cooled electric-arc-furnace or basic-oxygen-furnace slag can exhibit high density, angularity, abrasion resistance, and a rough surface that improves interlock. Mitwally et al. reported a favorable band near 30% coarse-aggregate replacement in their investigated system [10]. However, steel slag is not a single material: mineralogy depends on furnace, cooling, metal recovery, and ageing. Residual free CaO or MgO can hydrate expansively; weathering, steam ageing, stabilization, and expansion tests are non-negotiable before structural use.

Because slag specific gravity can exceed 4.0, mass replacement overfills the skeleton. Constant-volume batching preserves paste fraction and workability. Magnetic separation and leachability verification are required where metallic iron or regulated constituents may be present. When stabilized, slag can be preferred for high-abrasion floors, pavements, kerbs, and heavy concrete; its greater density is a disadvantage in weight-sensitive structures.

### D. Artificial and Sintered Fly-Ash Aggregate

Artificial aggregates pelletize fine wastes with cementitious, alkali-activated, or thermal binders. Cold-bonded particles harden below approximately 100 °C, whereas sintered particles are fired above approximately 1000 °C [24]. SFA is typically spherical, porous, and lightweight. Reported structural lightweight concretes occupy broad strength and density ranges; performance depends on pellet strength, shell vitrification, pore connectivity, and pre-wetting. The energy burden of sintering must be measured against avoided ash disposal and reduced structural mass.

**TABLE II — MATERIAL-SPECIFIC PRE-CONDITIONING CONTROLS**

| Control      | Reason                      | Acceptance evidence |
|--------------|-----------------------------|---------------------|
| Age slag     | consume/react free lime     | volume stability    |
| Pre-wet LWA  | limit slump loss            | moisture curve      |
| Grade RCA    | pack skeleton               | sieve compliance    |
| Remove fines | reduce demand/contamination | wash-loss test      |
| Trace source | manage variability          | batch certificate   |

$$\Delta V_{\text{exp}} = (V_t - V_0) / V_0 \times 100\% \quad (2)$$

Equation (2) expresses expansion during a prescribed stability test. Acceptance limits must be selected from the governing standard and intended exposure rather than copied across slag types.

### E. Plastic and E-Waste Aggregate

Processed high-density polyethylene, polypropylene, polyethylene terephthalate, and selected e-waste housings can be shredded, granulated, heat-formed, or pelletized into coarse particles. Their low density reduces unit weight and may improve thermal insulation and slump because hydrophobic surfaces absorb little water. The same smooth, low-energy surface weakens paste adhesion, while low elastic modulus concentrates strain in the matrix. Strength commonly declines as replacement grows [15]–[17].

Source separation is critical. Polyvinyl chloride, brominated flame-retardant plastics, batteries, printed circuit boards, and contaminated mixed residues require exclusion or specialized environmental assessment. Surface roughening, mineral coating, controlled particle aspect ratio, and low replacement can improve bond. Fire response, smoke, creep, thermal expansion mismatch, and long-term leaching deserve more attention than short-term cube strength alone.

### F. Crumb Rubber

Tyre-derived rubber is resilient, hydrophobic, and far less stiff than mineral aggregate. It generally reduces density, modulus, and compressive strength, yet improves impact resistance, energy absorption, damping, toughness, freeze–thaw accommodation, and sometimes acoustic behavior. Alkali treatment, cementitious coating, or silica-rich surface treatment can improve wetting and bond, but treatment effluent and process burden must be included in sustainability claims [18]–[21].

### G. Coconut Shell

Coconut shell is a hard lignocellulosic agricultural residue with low bulk density and high absorption. Crushed, graded shell can produce lightweight concrete and reduce dependence on quarried stone in tropical regions. Historical comparisons show that shell fraction, water correction, and mix richness dominate performance [22]. Biological cleanliness, salt contamination, oil or sugar residues, particle thickness, and seasonal source variability must be controlled. Full replacement is usually a specialty lightweight choice, whereas partial replacement offers a better strength–density balance.

**TABLE III — PRELIMINARY APPLICATION SCREEN**

| Family  | Best-fit role        | Avoid without validation |
|---------|----------------------|--------------------------|
| RCA     | general concrete     | severe chloride/frost    |
| Slag    | abrasion/heavy duty  | unstable slag            |
| Plastic | light non-structural | fire-critical members    |

| Family     | Best-fit role     | Avoid without validation |
|------------|-------------------|--------------------------|
| Rubber     | impact/barriers   | stiffness-led columns    |
| Shell/SF A | lightweight units | unconditioned absorption |

### III. RESEARCH METHODOLOGY

#### A. Evidence Harmonization

The comparative method uses a structured evidence matrix: material origin; particle size; specific gravity; absorption; replacement basis; binder type; water-to-binder ratio; admixture; curing; control strength; fresh response; mechanical response; durability indicators; and uncertainty. Findings are accepted only when a control mixture and replacement definition are explicit. Review articles inform mechanism and range selection, while primary experimental studies anchor direction and feasible bands.

Because the literature is heterogeneous, values are normalized to the control within each source before cross-material interpretation. If  $y_{ij}$  is a reported property of material  $j$  at replacement  $i$  and  $y_{0j}$  is the source-specific control, the normalized response is:

$$I_{ij} = 100 y_{ij} / y_{0j} \quad (3)$$

An index of 100 equals the source control. For burdens such as absorption or greenhouse-gas intensity, lower values may be preferred; desirability functions reverse the direction before aggregation. Studies using mass replacement are converted to estimated volume replacement only when particle specific gravities are reported. Otherwise, they are used qualitatively.

#### B. Quality and Bias Controls

TABLE IV — STUDY-QUALITY SCREEN USED FOR INTERPRETATION

| Check      | Low risk         | High risk            |
|------------|------------------|----------------------|
| Control    | same binder/cure | control altered      |
| Replicates | $n \geq 3$       | not stated           |
| Moisture   | SSD corrected    | dry porous aggregate |
| Source     | traceable/graded | mixed/unknown        |
| Statistics | dispersion shown | single values        |
| Durability | exposure linked  | strength only        |

No attempt is made to disguise uncertainty through excessive decimal precision. Representative graph values are rounded and labeled as literature-calibrated design data. They support sensitivity analysis, figure construction, and research planning; they must be replaced by project-specific test results before structural qualification.

#### C. Baseline and Candidate Scenarios

The conceptual baseline is an M35–M40 normal-weight concrete with crushed stone, 20 mm nominal maximum size, controlled workability, and a water–binder ratio near 0.40–0.45. Candidate scenarios retain binder content and effective water while replacing only the coarse fraction by absolute volume. This isolates the aggregate effect before optional paste optimization.

### IV. VOLUMETRIC MIX-DESIGN FRAMEWORK

For a candidate aggregate with oven-dry specific gravity  $G_{alt}$ , the mass needed to occupy a target absolute volume  $V_{alt}$  is obtained from Eq. (4). The same calculation is applied to the residual natural aggregate. This prevents dense slag from increasing aggregate volume or lightweight particles from leaving excess paste.

$$m_{alt,OD} = V_{alt} \rho_w G_{alt} \quad (4)$$

$$m_{alt,SSD} = m_{alt,OD} (1 + A_{24}/100) \quad (5)$$

$$W_{batch} = W_{eff} + \Sigma(m_{OD} A_{free}/100) \quad (6)$$

$A_{24}$  is 24-h absorption and  $A_{free}$  is the difference between absorption capacity and actual moisture content at batching. Equation (6) separates effective mixing water from water taken up by porous aggregate. For RCA, brick, coconut shell, and SFA, this correction can decide whether the mixture retains slump and intended water–binder ratio. Moisture is measured, not assumed.

TABLE V — PROPOSED SCREENING MIX MATRIX

| Mix     | Material      | $R_v$ (%) | Purpose           |
|---------|---------------|-----------|-------------------|
| C0      | Natural stone | 0         | reference         |
| R20/R40 | RCA           | 20/40     | structural band   |
| S15/S30 | Steel slag    | 15/30     | strength/abrasion |
| B10/B25 | Brick         | 10/25     | masonry recovery  |
| P5/P10  | E-plastic     | 5/10      | lightweight       |
| T5/T10  | Rubber        | 5/10      | impact            |
| C15/C25 | Coconut shell | 15/25     | lightweight       |
| F25/F50 | SFA           | 25/50     | low density       |

#### A. Packing and Paste Demand

Replacement should preserve combined grading rather than simply substituting a single size. Binary or ternary packing can blend natural aggregate with a candidate to minimize voids. Angular slag and RCA may increase inter-particle friction; rounded SFA may improve flow

but its pores consume water. Plastic flakes and elongated shell particles can bridge during placement. Therefore, particle-shape limits and a measured void-content test are included before admixture dosage is increased.

$$V_{\text{paste, req}} = V_{\text{void}} (1 + k_{\text{lub}}) \quad (7)$$

$V_{\text{void}}$  is compacted skeleton void volume and  $k_{\text{lub}}$  is a lubrication factor determined from workability trials. Increasing paste to mask poor grading is discouraged because it raises shrinkage and environmental burden.

## V. MATERIAL CHARACTERIZATION AND PRE-TREATMENT

TABLE VI — MINIMUM CHARACTERIZATION PLAN

| Property         | Method intent             | Design consequence   |
|------------------|---------------------------|----------------------|
| Gradation        | sieve distribution        | packing/segregation  |
| Specific gravity | SSD/OD density            | volume conversion    |
| Absorption       | 24-h uptake curve         | water correction     |
| Crushing/impact  | particle strength         | strength ceiling     |
| Abrasion         | wear resistance           | pavement suitability |
| Shape indices    | flaky/elongated content   | workability/ITZ      |
| Chemistry        | XRF/mineralogy/pH         | expansion/leaching   |
| Organics         | shell/plastic cleanliness | setting/bond         |

### A. RCA and Brick

RCA is washed to remove loose mortar dust and conditioned to a reproducible moisture state. Carbonation, chloride, sulfate, and gypsum contamination are checked when demolition history is uncertain. Brick aggregate is pre-wetted or internally cured to a specified moisture fraction, then surface dried to prevent free water from entering the mix. Strong acids are avoided because they may generate new waste streams and damage particle integrity.

### B. Steel Slag

Slag is processed for metal recovery, graded, aged, and tested for volumetric stability. Mineralogical screening distinguishes potentially expansive constituents. Stockpile age alone is not proof of stability; accelerated expansion, leachability, and source-specific factory production control provide stronger evidence. The higher density must be declared to designers because it affects dead load, lifting, and transport.

### C. Polymeric and Bio-Derived Particles

Plastic and rubber are washed, dried, and restricted by polymer class and contaminants. Surface treatment is evaluated with both bond improvement and environmental burden. Coconut shell is cleaned of pith, oil, soil, and salts; crushed to controlled thickness and aspect ratio; then moisture-conditioned. SFA pellets are screened for loose fines, crushing resistance, and water-uptake kinetics.

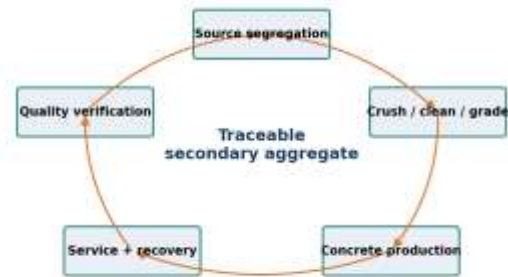


Fig. 3. Closed-loop production concept with traceability and verification at each transfer.

*Field rule: no substitute enters structural batching only on the basis of its waste identity; it must become a characterized construction product.*

## VI. PROPOSED EXPERIMENTAL VALIDATION PROGRAM

A project-level campaign should separate screening, optimization, and qualification. Screening uses the matrix in Table V with three independent batches where practical. Optimization adjusts grading, moisture conditioning, and admixture within a narrow replacement band. Qualification repeats the selected mix with production-scale materials and evaluates the governing exposure class.

TABLE VII — STAGED VALIDATION AND DECISION GATES

| Stage      | Tests                                 | Decision           |
|------------|---------------------------------------|--------------------|
| Screen     | slump, density, 7/28-d strength       | reject/retain band |
| Optimize   | packing, SSD, SP dosage               | freeze recipe      |
| Durability | sorptivity, chloride, sulfate/frost   | exposure gate      |
| Structural | E, shrinkage, bond/member test        | design factors     |
| Production | plant trial, pump/finish, variability | approve source     |

### A. Specimens and Replication

Compressive strength is measured at 7, 28, and 90 days; splitting tensile or flexural strength and modulus at 28 days; and density and absorption at specified ages. At least three specimens represent a batch and, where source variability is material, independent

batches are treated as the experimental unit. Reporting only specimen-level replication overstates confidence.

$$f_c = P_{\max} / A \quad (8)$$

$$f_{t,split} = 2P / (\pi LD) \quad (9)$$

$$f_r = PL / (bd^2) \quad (10)$$

Equations (8)–(10) express compressive, splitting tensile, and third-point flexural strength in their common idealized forms; specimen geometry and applicable standards govern the exact calculation. The program follows IS 10262 for proportioning, IS 383 for aggregate requirements, and relevant IS/ASTM test methods, with deviations declared rather than silently mixed.

## B. Statistical Model

$$y = \beta_0 + \beta_1 R + \beta_2 R^2 + \beta_3 M + \beta_4 (R \times M) + \varepsilon \quad (11)$$

R is replacement volume and M represents treatment or moisture condition. A quadratic term captures a favorable slag band or accelerating losses in low-stiffness aggregates. Confidence intervals, residual diagnostics, and practical effect sizes are reported with p-values.

## VII. FRESH CONCRETE PERFORMANCE

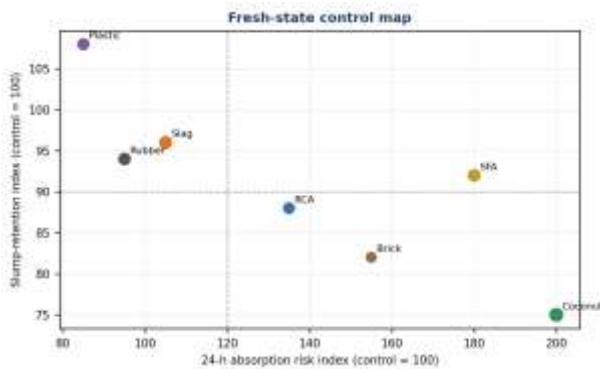


Fig. 4. Literature-calibrated fresh-state map. Indices are representative and control-normalized.

### A. Workability and Rheology

Fresh response is governed by the competition between surface absorption, angular friction, particle shape, and hydrophobicity. Dry RCA, brick, shell, and SFA remove water from the paste and can create rapid slump loss even when initial slump is acceptable. Steel slag may increase friction through angularity. Plastic can increase slump because it absorbs little water, but flat particles may segregate or trap air. Rubber frequently increases entrained air and apparent cohesion while lowering unit weight.

A single slump number is insufficient for pumpability. Slump retention at 30 and 60 min, visual stability, air content, density, and finishing response are recorded. Pre-wetting should not produce a surface water film; otherwise the local water–binder ratio rises around the particle and weakens the ITZ.

$$S_{60} = 100 \text{ Slump}_{60} / \text{Slump}_0 \quad (12)$$

## B. Practical Control Logic

If slump is low while effective water is correct, the first actions are to verify SSD state and combined grading, then adjust compatible superplasticizer. Adding unmeasured water is the last and normally unacceptable response. If plastic or rubber causes segregation, reduce particle size/aspect ratio, improve sand fraction, or use viscosity-modifying admixture only after confirming that air content remains controlled.

TABLE VIII — FRESH-CONCRETE TROUBLESHOOTING

| Symptom            | Likely cause             | Corrective action      |
|--------------------|--------------------------|------------------------|
| rapid slump loss   | dry porous particles     | SSD condition          |
| harsh mix          | angular/poor packing     | blend gradation        |
| floating particles | low density              | reduce size; viscosity |
| high air           | rubber/plastic interface | defoamer/sequence      |
| bleeding           | excess free water        | recheck moisture       |

Representative indices in Fig. 4 are scenario inputs, not measured values from a common laboratory series.

## VIII. DENSITY, ABSORPTION, AND DIMENSIONAL RESPONSE

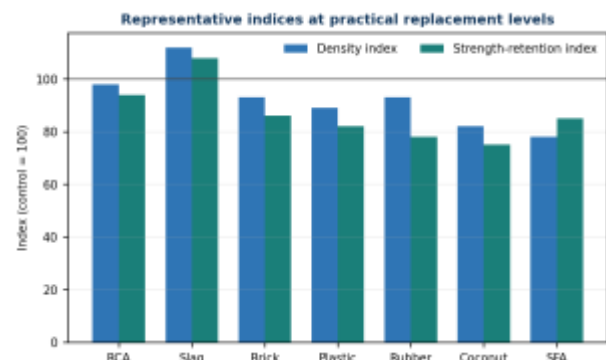


Fig. 5. Representative density and strength-retention indices at practical replacement levels.

### A. Density as a Design Variable

Steel slag increases density and can be useful where mass, abrasion resistance, or radiation attenuation is valued. Plastic, rubber, coconut shell, and SFA reduce unit weight; this can lower foundation demand, seismic mass, handling loads, and transport energy. RCA and brick produce intermediate reductions. Designers must use measured equilibrium or oven-dry density rather than nominal “lightweight” labels when calculating self-weight.

$$\rho_c = m_{\text{dry}} / V_{\text{specimen}} \quad (13)$$

## B. Water Absorption and Sorptivity

Particle absorption is not identical to concrete sorptivity, but porous aggregate often raises connected pore volume when paste quality or moisture control is inadequate. RCA contains old ITZs; brick and shell contain internal pores; SFA may possess a dense shell with a porous core. Pre-wetting can reduce fresh water demand and provide internal curing, yet excessive saturation may increase desorption near the new ITZ. Therefore, both aggregate uptake kinetics and hardened-concrete transport are measured.

$$I_s = \Delta m / (A \sqrt{t}) \quad (14)$$

## C. Shrinkage, Creep, and Modulus

Lower aggregate stiffness and higher paste-equivalent content increase deformation. RCA, brick, rubber, plastic, shell, and porous SFA generally reduce elastic restraint relative to dense natural stone. A mix may meet cube strength but still produce larger deflection, crack width, creep redistribution, or drying shrinkage. Structural qualification consequently requires modulus and shrinkage, especially at replacement levels above screening bands.

Rubber can distribute microcracking and improve post-peak behavior while markedly lowering secant modulus. Shell and SFA reduce dead load but may require member-level serviceability recalculation. Steel slag can increase stiffness if the ITZ remains sound, although its density penalty must be included in load combinations.

## IX. COMPRESSIVE-STRENGTH RESPONSE

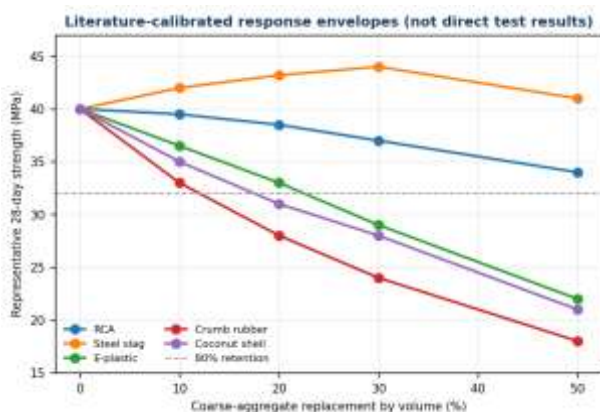


Fig. 6. Representative literature-calibrated strength envelopes for a common 40 MPa control; curves are not pooled experimental observations.

### A. Interpretation of Response Envelopes

The curves in Fig. 6 impose a common control only to visualize direction and sensitivity. RCA shows a gradual decline as old-mortar content and porosity increase. Properly aged steel slag displays a favorable moderate-replacement band due to hardness, angular interlock, and possible filler effects, followed by decline as workability and voids become controlling. Plastic, rubber, and coconut shell show steeper loss

because their stiffness and bond differ strongly from mineral aggregate.

The plot should not be used to specify a universal strength. Its purpose is to select experimental bands: 20–40% for quality RCA, 15–30% for stable slag, 10–25% for brick or shell, 5–10% for plastic or rubber, and 25–50% for SFA, with project-specific extension only after evidence. Replacement is stated by volume.

$$\eta_f = f_{c,alt} / f_{c,ctrl} \quad (15)$$

## B. Failure Mechanisms

In RCA concrete, cracks can traverse old mortar, old ITZ, new ITZ, or original aggregate depending on relative strengths. Brick particles may fracture internally. Slag may shift failure into paste when aggregate strength and bond are high. Plastic and rubber tend to debond or deform, creating stress concentrations under compression but sometimes bridging cracks after peak load. Coconut shell can split along its layered structure, whereas SFA performance depends on pellet shell strength and internal porosity.

## C. Strength Acceptance

A candidate passes screening when its characteristic strength, not merely mean strength, satisfies the target with production variability included. A preliminary retention gate of 0.85 may be used for comparison, but final acceptance follows the specified grade, statistical margin, exposure requirements, and structural design model. Strength enhancement does not waive chemical stability or durability checks.

## X. TENSILE, FLEXURAL, MODULUS, AND IMPACT PERFORMANCE

### A. Tensile and Flexural Strength

Tensile performance is particularly sensitive to ITZ quality. Stable slag and well-processed RCA can retain splitting and flexural strength at moderate replacement; excessive angularity or voids reverse the benefit. Plastic and rubber may reduce first-crack strength while improving deformation capacity, residual strength, or energy absorption. Shell and SFA lower stiffness and may reduce cracking load, but their lower density can be valuable in panels and precast products.

$$\eta_t = f_{t,alt} / f_{t,ctrl} ; \eta_E = E_{alt} / E_{ctrl} \quad (16)$$

### B. Impact and Energy Absorption

Crumb rubber is distinguished by strain capacity rather than compressive efficiency. Under impact, blast, vehicle barrier, or repeated contact, a lower static strength may be traded for reduced brittleness and greater energy dissipation. Plastic particles can also alter crack path but need fire and creep verification. An impact-led evaluation therefore weights absorbed energy and residual integrity more heavily than modulus.

$$U = \int_0^{\delta_u} \{ \delta_u \} P(\delta) d\delta \quad (17)$$

U is energy absorbed to a selected displacement or failure criterion. Comparison requires identical specimen geometry, support, impact mass, drop height, and failure definition. Counting blows without calibrating impact energy can obscure real differences.

**TABLE IX — QUALITATIVE MECHANICAL PROFILE**

| Material      | Static strength   | Modulus      | Toughness/impact |
|---------------|-------------------|--------------|------------------|
| RCA           | moderate–high     | moderate     | moderate         |
| Steel slag    | high potential    | high         | moderate         |
| Brick         | moderate          | low–moderate | moderate         |
| Plastic       | low–moderate      | low          | moderate         |
| Rubber        | lower             | low          | high             |
| Coconut shell | moderate at low R | low          | moderate         |
| SFA           | moderate          | low–moderate | moderate         |

### C. Structural Consequences

Design equations calibrated for normal-weight concrete may overpredict modulus, shear transfer, bond, or tension stiffening when low-stiffness aggregate is used. Member tests or conservative modification factors are required until a validated national provision covers the material. Lightweight benefits should be explicitly carried through self-weight, seismic mass, deflection, and connection design.

## XI. DURABILITY AND SERVICE-LIFE SCREENING

**TABLE X — DURABILITY RISK REGISTER**

| Threat           | Sensitive materials  | Required evidence       |
|------------------|----------------------|-------------------------|
| Carbonation      | RCA/brick/LWA        | depth vs control        |
| Chlorides        | porous RCA/brick     | migration/resistivity   |
| Freeze–thaw      | porous wet particles | mass/dynamic E          |
| Sulfate          | contaminated C&D     | expansion/strength      |
| ASR              | glass/slag/minerals  | petrography/expansion   |
| Volume stability | steel slag           | free lime + expansion   |
| Fire             | plastic/rubber       | residual strength/smoke |

| Threat   | Sensitive materials | Required evidence |
|----------|---------------------|-------------------|
| Leaching | slag/e-waste        | regulated eluate  |

### A. Transport-Controlled Deterioration

Durability is controlled by connected transport pathways, moisture state, binder chemistry, cracks, and exposure. RCA and brick can increase sorptivity or chloride ingress when added water, poor packing, or old mortar creates connectivity. Supplementary cementitious materials, lower effective water–binder ratio, controlled curing, and optimized packing can offset part of this risk. A strength-equivalent mix is not automatically transport-equivalent.

$$D_{app} = (0.0239 L^2) / t \quad (18)$$

Equation (18) is an illustrative migration-style relationship linking penetration length L and time t; the exact coefficient and units must follow the selected standard. The purpose is to show that exposure screening uses transport parameters, not only 28-day strength.

### B. Material-Specific Hazards

Steel slag requires volume-stability verification and, where relevant, leaching control. E-waste plastic requires polymer and additive identification; hazardous components are excluded. Rubber and plastic require assessment under elevated temperature and fire. Coconut shell requires resistance to biological contamination and stable moisture conditioning. Artificial aggregate made from ash or sludge requires feedstock traceability and environmental safety testing.

### C. Service-Life Gate

The candidate is accepted for an exposure only when the lower confidence bound of its durability indicator meets or improves the project limit, or when a validated service-life model demonstrates compliance. If evidence is incomplete, the application is restricted to protected or non-structural exposure rather than extrapolated from compressive strength.

## XII. MICROSTRUCTURE AND ITZ ENGINEERING

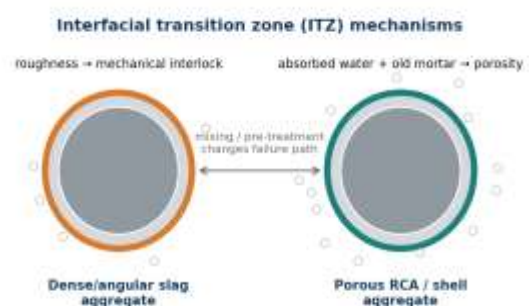


**Fig. 7. Simplified ITZ mechanisms for dense angular and porous secondary aggregates.**

### A. Multi-ITZ Nature of Recycled Aggregate

RCA introduces at least two generations of interface: original aggregate–old mortar and old mortar–new paste. Microcracks from demolition and crushing add a third weakness. Treatments that remove all adhered mortar can consume energy and damage particles; the more efficient objective is often to remove loose material, improve grading, and strengthen or seal the accessible surface.

### B. Roughness Versus Porosity

Surface roughness improves mechanical keying only if fresh paste can wet the surface and fill asperities. Slag provides angularity and hardness, but trapped air or instability cancels the benefit. Brick and shell offer rough surfaces yet may extract water and create a dry, porous ITZ. Plastic and rubber are hydrophobic; mineral or alkali treatments seek to raise surface energy, but their durability and environmental balance must be verified.

$$\phi_{ITZ} = V_{void,ITZ} / V_{ITZ} \quad (19)$$

### C. Diagnostic Methods

Optical microscopy identifies particle distribution and visible debonding. Scanning electron microscopy with elemental mapping examines hydration and contaminant zones, while X-ray computed tomography quantifies entrapped air and connected pores without sectioning. Mercury intrusion results require cautious interpretation because ink-bottle pores distort connectivity. Image analysis should report field selection, thresholding, and replicate regions.

**TABLE XI — MICROSTRUCTURE-TO-MIX FEEDBACK**

| Observation        | Interpretation   | Design response         |
|--------------------|------------------|-------------------------|
| paste gap          | poor wetting/air | surface/sequence        |
| cracked old mortar | weak RCA         | source/crushing         |
| dense slag ITZ     | good interlock   | retain moderate R       |
| porous shell ITZ   | water theft      | SSD correction          |
| pellet fracture    | weak SFA shell   | reduce R/improve pellet |

Microstructure is used to explain measured performance, not to replace it. A “dense-looking” selected image cannot establish bulk durability without transport and variability data.

## XIII. ENVIRONMENTAL ASSESSMENT

### A. Functional Unit and System Boundary

Environmental comparison uses a declared functional unit, preferably 1 m<sup>3</sup> of concrete meeting specified strength, exposure, workability, and service life. A

mass-only functional unit favors lightweight materials without ensuring equivalent function. The boundary includes collection, sorting, crushing or pelletization, washing, treatment, transport, rejected fraction, and avoided disposal only when allocation rules are transparent.

$$GWP_{m^3} = \sum m_k EF_k + \sum E_q EF_q + T \cdot d \cdot EF_{tr} - C_{avoided} \quad (20)$$

m<sub>k</sub> and E<sub>q</sub> are material and process energy quantities, EF are emission factors, T·d represents freight work, and C<sub>avoided</sub> is a separately disclosed credit. Cement should remain visible because aggregate substitution may indirectly alter paste or admixture demand. A longer haul or energy-intensive sintering process can erase aggregate-stage savings.

### B. Circularity and Burden Shifting

RCA directly substitutes quarry material and diverts demolition waste. Slag and ash aggregates valorize industrial residues but require stability and leaching control. Plastic and rubber diversion is meaningful when the material is unsuitable for higher-value closed-loop recycling. Coconut shell can be low impact near agro-processing sources; transport over long distances weakens the case. SFA may save structural mass but incurs thermal processing energy.

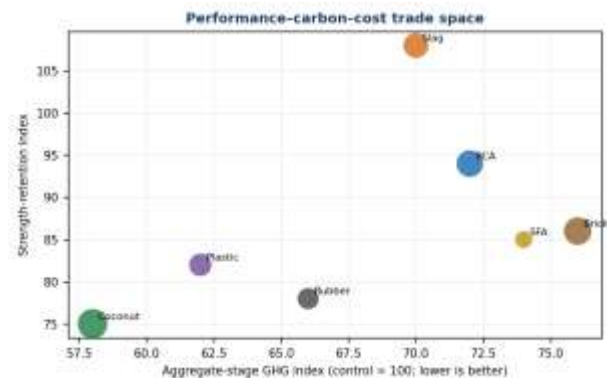


Fig. 8. Illustrative performance–carbon–cost trade space; bubble area increases as relative cost improves.

Environmental indices are scenario data used to demonstrate the method. A project EPD/LCA must replace them for procurement.

### C. Service-Life Adjustment

$$GWP_{yr} = GWP_{m^3} / L_{service} \quad (21)$$

Dividing by service life is a simplified screening metric, not a full consequential LCA. It prevents a low-production-impact mixture with premature repair from appearing unconditionally superior. Maintenance and end-of-life scenarios should be added for high-consequence decisions.

#### XIV. COST, SUPPLY, AND CONSTRUCTABILITY

##### A. Delivered Cost

Waste does not mean free aggregate. Delivered cost includes gate fee or purchase price, segregation, contamination removal, crushing, grading, washing, ageing or treatment, moisture management, testing, yield loss, transport, storage, and production disruption. Dense slag raises transported mass; lightweight particles may reduce mass but occupy greater volume and require larger storage. Local RCA can be economical when demolition and concrete production are spatially coordinated.

$$C_{del} = C_{src} + C_{proc} + C_{QA} + C_{tr} + C_{risk} - C_{credit} \quad (22)$$

##### B. Supply Reliability

Structural production needs a declared product, not intermittent waste. Supply reliability is scored from annual volume, source consistency, stockpile segregation, processing capacity, moisture control, test frequency, and contingency source. A technically superior material with unstable availability can rank below a slightly lower-performing but traceable alternative.

TABLE XII — SUPPLY-CHAIN QUALIFICATION

| Criterion       | Evidence              | Minimum gate             |
|-----------------|-----------------------|--------------------------|
| Source identity | supplier declaration  | known process/feed       |
| Consistency     | monthly property data | bounded variation        |
| Capacity        | tonnes/month          | project demand + reserve |
| Storage         | segregated stockpiles | no cross-contamination   |
| QA response     | hold/release plan     | traceable batch          |
| Contingency     | approved alternate    | no silent blending       |

##### C. Plant and Site Constructability

The plant trial verifies charging sequence, mixer power, actual moisture, admixture timing, discharge uniformity, pump pressure, finishing, bleed, washout, and returned-concrete handling. Porous aggregates may require dedicated bins or moisture probes. Lightweight particles can segregate during transport; slag can increase equipment wear. Plastic and rubber may affect pumpability and finishing at low density.

Construction acceptance combines fresh concrete data, batch tickets, aggregate certificates, and early-age strength trends. A change in demolition source, furnace, polymer stream, shell processor, or pellet recipe triggers requalification proportional to risk.

#### XV. MULTI-CRITERIA DECISION ANALYSIS

##### A. Criteria and Normalization

The MCDA ranks a material–replacement–application option after mandatory safety gates. Nine criteria are used: compressive retention, tensile/flexural retention, modulus or density fit, absorption/durability risk, environmental burden, delivered cost, source reliability, constructability, and specification readiness. A failing expansion, hazardous-contaminant, or exposure gate cannot be compensated by a high weighted score.

$$u_{ij} = (x_{ij} - x_{i,min}) / (x_{i,max} - x_{i,min}) \quad (23)$$

$$S_j = 100 \sum_i w_i u_{ij}, \quad \sum_i w_i = 1 \quad (24)$$

For cost or burden criteria the normalized direction is reversed. Missing data receive an uncertainty penalty rather than a neutral midpoint. The base-case balanced weights are: mechanical 0.30, durability 0.20, environmental 0.15, cost 0.10, density/application fit 0.10, supply 0.075, and implementation readiness 0.075.

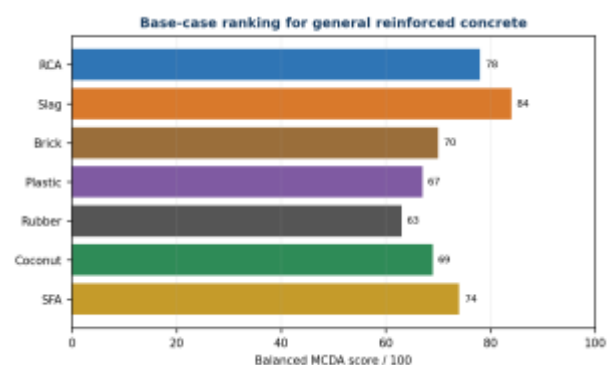


Fig. 9. Base-case illustrative ranking for general reinforced concrete after mandatory gates.

##### B. Base-Case Interpretation

Stable steel slag ranks highest because of strength and abrasion potential, followed by quality RCA because it combines circularity with comparatively mature practice. SFA benefits from lightweight performance but carries porosity and processing-energy uncertainty. Brick, coconut shell, plastic, and rubber are valuable in targeted roles rather than as universal replacements. Score differences smaller than the uncertainty interval should be treated as ties.

$$S^*_j = S_j - \lambda \sigma_j \quad (25)$$

$S^*_j$  is the risk-adjusted score,  $\sigma_j$  represents evidence uncertainty, and  $\lambda$  reflects decision conservatism. This prevents a poorly documented option from outranking a mature option on optimistic point estimates.

## XVI. SENSITIVITY, ROBUSTNESS, AND PARETO SELECTION

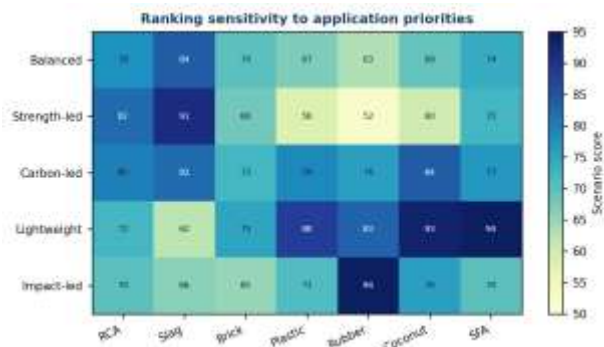


Fig. 10. Illustrative MCDA sensitivity: the preferred material changes with the engineering objective.

### A. Scenario Sensitivity

The balanced ranking is not universal. Strength-led weighting favors slag; carbon-led weighting improves locally available shell, plastic, rubber, and RCA; lightweight weighting strongly favors SFA and shell; impact-led weighting elevates rubber. The correct output is therefore a short list conditional on application, not a permanent league table of waste materials.

$$\Delta S_j = \max_s(S_{js}) - \min_s(S_{js}) \quad (26)$$

A large  $\Delta S_j$  indicates that the option is preference-sensitive. Robust options remain near the top across plausible weights and data perturbations. Monte Carlo sampling can vary normalized data, transport distance, treatment energy, and weights to estimate rank probability.

$$P_{j,top} = N(S_j = \max_k S_k) / N_{total} \quad (27)$$

### B. Pareto Logic

An option is Pareto-dominated when another option is no worse in every selected criterion and better in at least one. Removing dominated options before weighting makes the final decision easier to explain. Figure 8 illustrates why RCA and slag are strong balanced candidates, while shell and SFA occupy a lower-density frontier and rubber occupies an impact-response frontier.

### C. Decision Rules

TABLE XIII — APPLICATION-SPECIFIC SHORT LIST

| Application    | Primary weights       | Short list          |
|----------------|-----------------------|---------------------|
| General RCC    | strength + durability | RCA, aged slag      |
| Pavement/kerb  | abrasion + durability | slag, RCA           |
| Light precast  | density + handling    | SFA, shell, plastic |
| Barrier/impact | energy + residual     | rubber hybrid       |

| Application | Primary weights | Short list |
|-------------|-----------------|------------|
| ct          |                 |            |

Blocks/non-structural cost + diversion brick, plastic, shell

A final selection requires local source data and trial results. MCDA documents trade-offs; it does not replace engineering judgment, statutory compliance, or exposure-specific testing.

## XVII. IMPLEMENTATION SPECIFICATION AND CONCLUSIONS

### A. Model Project Specification

The specification should state permitted source and process, excluded contaminants, nominal maximum size, grading envelope, specific-gravity and absorption range, moisture-control method, volume-based replacement, treatment/ageing, expansion or leaching limits, batch traceability, fresh limits, characteristic strength, modulus where relevant, durability acceptance, plant-trial requirements, and change-control triggers. Naming only a percentage and a waste type is insufficient.

TABLE XIV — SIX-GATE ACCEPTANCE PROTOCOL

| Gate          | Requirement                | Action if failed  |
|---------------|----------------------------|-------------------|
| G1 Safety     | no hazardous contamination | reject/segregate  |
| G2 Stability  | expansion within limit     | age/treat/reject  |
| G3 Fresh      | slump/air/density window   | correct process   |
| G4 Strength   | $f_{ck} + \text{margin}$   | reduce R/redesign |
| G5 Durability | exposure indicator         | restrict exposure |
| G6 Production | stable plant trial         | requalify         |

### B. Principal Conclusions

- 1) Replacement must be defined by absolute volume and corrected for actual moisture; otherwise material density and absorption confound the comparison.
- 2) Quality RCA and stabilized steel slag are the strongest balanced candidates for general reinforced concrete at moderate replacement, subject to source and exposure qualification.
- 3) Crushed brick, coconut shell, plastic, rubber, and SFA are not inferior in every sense; each occupies a distinct lightweight, thermal, impact, diversion, or local-economy design space.
- 4) Strength-only optimization is unsafe. Modulus, shrinkage, transport properties, volume stability, fire,

leaching, and source variability can govern service performance.

5) The MCDA must follow mandatory safety gates and include uncertainty. Application-specific sensitivity is a design feature, not a weakness.

6) The numerical envelopes and scores in this paper are transparent literature-calibrated scenarios. Project use requires source-specific experiments and production trials.

### C. Future Research

Priority work includes shared open datasets with volume-based replacement, independent-batch replication, long-term creep and shrinkage, chloride-carbonation interaction, fire response of polymeric aggregates, stabilized-slag expansion under field moisture, life-cycle inventories for Indian processing routes, and structural-member reliability models. Hybrid aggregate skeletons may be more productive than full replacement: dense slag or natural stone can supply stiffness while RCA, SFA, shell, or rubber supplies circularity or functional performance.

### REFERENCES

- [1] Bureau of Indian Standards, IS 383:2016, Coarse and Fine Aggregate for Concrete—Specification, 3rd rev., New Delhi, India, 2016 (reviewed 2025).
- [2] Bureau of Indian Standards, IS 10262:2019, Concrete Mix Proportioning—Guidelines, New Delhi, India, 2019.
- [3] Bureau of Indian Standards, IS 456:2000, Plain and Reinforced Concrete—Code of Practice, New Delhi, India, 2000.
- [4] Bureau of Indian Standards, IS 9142 (Part 2):2018, Artificial Lightweight Aggregates for Concrete—Sintered Fly Ash Coarse Aggregate, New Delhi, India, 2018.
- [5] ASTM International, ASTM C33/C33M, Standard Specification for Concrete Aggregates, West Conshohocken, PA, USA.
- [6] ASTM International, ASTM C127, Standard Test Method for Relative Density and Absorption of Coarse Aggregate, West Conshohocken, PA, USA.
- [7] ASTM International, ASTM C39/C39M, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, West Conshohocken, PA, USA.
- [8] ASTM International, ASTM C496/C496M, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, West Conshohocken, PA, USA.
- [9] ASTM International, ASTM C78/C78M-22, Standard Test Method for Flexural Strength of Concrete, 2022, doi: 10.1520/C0078\_C0078M-22.
- [10] M. E. Mitwally, A. Elnemr, A. Shash, et al., “Utilization of steel slag as partial replacement for coarse aggregate in concrete,” *Innovative Infrastructure Solutions*, vol. 9, art. 175, 2024, doi: 10.1007/s41062-024-01464-y.

- [11] Y. K. Sabapathy, V. B. Balasubramanian, N. Shiva Shankari, A. Yeshwant Kumar, and D. Ravichandar, “Experimental investigation of surface-modified EOF steel slag as coarse aggregate in concrete,” *Journal of King Saud University—Engineering Sciences*, vol. 29, no. 4, pp. 388–393, 2017, doi: 10.1016/j.jksues.2016.07.002.
- [12] Q. Wang, P. Yan, J. Yang, and B. Zhang, “Influence of steel slag on mechanical properties and durability of concrete,” *Construction and Building Materials*, vol. 47, pp. 1414–1420, 2013, doi: 10.1016/j.conbuildmat.2013.06.044.
- [13] M. H. Lai, Z. H. Chen, Y. H. Wang, and J. C. M. Ho, “Effect of fillers on the mechanical properties and durability of steel slag concrete,” *Construction and Building Materials*, vol. 335, art. 127495, 2022, doi: 10.1016/j.conbuildmat.2022.127495.
- [14] H. Qasrawi, “The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment,” *Construction and Building Materials*, vol. 54, pp. 298–304, 2014, doi: 10.1016/j.conbuildmat.2013.12.063.
- [15] F. Ahmad, A. Jamal, K. M. Mazher, W. Umer, and M. Iqbal, “Performance evaluation of plastic concrete modified with e-waste plastic as a partial replacement of coarse aggregate,” *Materials*, vol. 15, no. 1, art. 175, 2022, doi: 10.3390/ma15010175.
- [16] K. Ali, M. I. Qureshi, S. Saleem, and S. U. Khan, “Influence of recycled plastic incorporation as coarse aggregates on concrete properties,” *Sustainability*, vol. 15, no. 7, art. 5937, 2023, doi: 10.3390/su15075937.
- [17] M. A. Mohamedsalih et al., “The use of plastic waste as replacement of coarse aggregate in concrete,” *Sustainability*, vol. 16, no. 23, art. 10522, 2024, doi: 10.3390/su162310522.
- [18] H. H. Awan, M. F. Javed, A. Yousaf, F. Aslam, H. Alabduljabbar, and A. Mosavi, “Experimental evaluation of untreated and pretreated crumb rubber used in concrete,” *Crystals*, vol. 11, no. 5, art. 558, 2021, doi: 10.3390/cryst11050558.
- [19] R. B. Ataria and Y. C. Wang, “Mechanical properties and durability performance of recycled aggregate concrete containing crumb rubber,” *Materials*, vol. 15, no. 5, art. 1776, 2022, doi: 10.3390/ma15051776.
- [20] Y. Han, Z. Lv, Y. Bai, G. Han, and D. Li, “Experimental study on the mechanical properties of crumb rubber concrete after elevated temperature,” *Polymers*, vol. 15, no. 14, art. 3102, 2023, doi: 10.3390/polym15143102.
- [21] O. Youssf, J. E. Mills, and R. Hassanli, “Assessment of the mechanical performance of crumb rubber concrete,” *Construction and Building Materials*, vol. 125, pp. 175–183, 2016, doi: 10.1016/j.conbuildmat.2016.08.040.
- [22] E. A. Olanipekun, K. O. Olusola, and O. Ata, “A comparative study of concrete properties using coconut shell and palm kernel shell as coarse

aggregates,” *Building and Environment*, vol. 41, no. 3, pp. 297–301, 2006, doi: 10.1016/j.buildenv.2005.01.029.

[23] K. Rahal, “Mechanical properties of concrete with recycled coarse aggregate,” *Building and Environment*, vol. 42, no. 1, pp. 407–415, 2007, doi: 10.1016/j.buildenv.2005.07.033.

[24] G. B. Bekkeri et al., “Synthesis of artificial aggregates and their impact on performance of concrete: a review,” *Journal of Material Cycles and Waste Management*, 2023, doi: 10.1007/s10163-023-01713-9.

[25] L. Domagała, “Durability of structural lightweight concrete with sintered fly ash aggregate,” *Materials*, vol. 13, no. 20, art. 4565, 2020, doi: 10.3390/ma13204565.

[26] H. P. Nguyen, A. Mueller, V. T. Nguyen, and C. T. Nguyen, “Development and characterization of lightweight aggregate recycled from construction and demolition waste mixed with industrial by-products,” *Construction and Building Materials*, vol. 313, art. 125472, 2021, doi: 10.1016/j.conbuildmat.2021.125472.

[27] N. U. Kockal and T. Ozturan, “Effects of lightweight fly ash aggregate properties on the behavior of lightweight concretes,” *Journal of Hazardous Materials*, vol. 179, nos. 1–3, pp. 954–965, 2010, doi: 10.1016/j.jhazmat.2010.03.098.

[28] C. L. Hwang, L. A. T. Bui, K. L. Lin, and C. T. Lo, “Manufacture and performance of lightweight aggregate from MSWI fly ash and reservoir sediment,” *Cement and Concrete Composites*, vol. 34, no. 10, pp. 1159–1166, 2012, doi: 10.1016/j.cemconcomp.2012.07.004.

[29] S. Narendra and V. Vasugi, “Development of sintered artificial coarse aggregate by employing the Taguchi optimization technique,” *Case Studies in Construction Materials*, vol. 22, art. e04724, 2025, doi: 10.1016/j.cscm.2025.e04724.

[30] S. B. Park, Y. I. Jang, J. Lee, and B. J. Lee, “Hazard assessment and mechanical properties of porous concrete utilizing coal bottom ash coarse aggregate,” *Journal of Hazardous Materials*, vol. 166, no. 1, pp. 348–355, 2009, doi: 10.1016/j.jhazmat.2008.11.054.

[31] C. Thomas, J. Setién, J. A. Polanco, P. Alaejos, and M. Sánchez de Juan, “Durability of recycled aggregate concrete,” *Construction and Building Materials*, vol. 40, pp. 1054–1065, 2013.

[32] V. W. Y. Tam, C. M. Tam, and Y. Wang, “Optimization on proportion for recycled aggregate in concrete using two-stage mixing approach,” *Construction and Building Materials*, vol. 21, no. 10, pp. 1928–1939, 2007, doi: 10.1016/j.conbuildmat.2006.05.040.

[33] C. S. Poon and D. Chan, “The use of recycled aggregate in concrete in Hong Kong,” *Resources, Conservation and Recycling*, vol. 50, no. 3, pp. 293–305, 2007, doi: 10.1016/j.resconrec.2006.06.005.

[34] I. B. Topçu and N. F. Günçan, “Using waste concrete as aggregate,” *Cement and Concrete*

*Research*, vol. 25, no. 7, pp. 1385–1390, 1995, doi: 10.1016/0008-8846(95)00131-U.

[35] I. B. Topçu and S. Şengel, “Properties of concretes produced with waste concrete aggregate,” *Cement and Concrete Research*, vol. 34, pp. 1307–1312, 2004, doi: 10.1016/j.cemconres.2003.12.019.

[36] A. A. Sharba, “The efficiency of steel slag and recycled concrete aggregate on the strength properties of concrete,” *KSCE Journal of Civil Engineering*, vol. 23, pp. 4846–4851, 2019, doi: 10.1007/s12205-019-0700-3.

[37] J. Zhang et al., “Experimental study on preparation and characteristics of modified recycled aggregate,” *Applied Sciences*, vol. 14, no. 5, art. 1974, 2024, doi: 10.3390/app14051974.

[38] D. C. Gámez-García et al., “Sustainable concrete with recycled aggregate from plastic waste,” *Applied Sciences*, vol. 15, no. 7, art. 3468, 2025, doi: 10.3390/app15073468.

[39] International Organization for Standardization, ISO 14040:2006, *Environmental Management—Life Cycle Assessment—Principles and Framework*, Geneva, Switzerland, 2006.

[40] International Organization for Standardization, ISO 14044:2006, *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*, Geneva, Switzerland, 2006.

[41] ACI Committee 213, ACI 213R, *Guide for Structural Lightweight-Aggregate Concrete*, American Concrete Institute, Farmington Hills, MI, USA.

[42] ACI Committee 555, ACI 555R, *Removal and Reuse of Hardened Concrete*, American Concrete Institute, Farmington Hills, MI, USA.

[43] British Standards Institution, BS EN 206, *Concrete—Specification, Performance, Production and Conformity*, London, U.K.

[44] M. Dwarampudi et al., “Performance of lightweight concrete with different aggregates—a comprehensive review,” *Discover Civil Engineering*, 2024, doi: 10.1007/s44290-024-00015-9.

## DATA AND ETHICS STATEMENT

No human or animal subjects were involved. No new laboratory measurements are claimed. Numerical curves and MCDA scores are literature-calibrated representative scenarios created for transparent comparison and experimental planning; they should not be treated as certified material properties. All project decisions require source-specific testing and compliance with applicable codes.