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Recycled Aggregates from Concrete Waste: A Comprehensive Study on Material Properties, Environmental Sustainability, and Application Potential in Engineering

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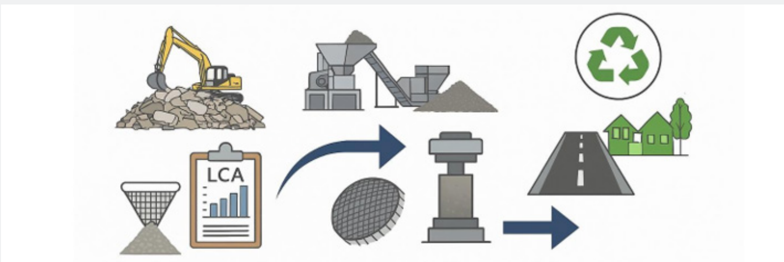
Abstract

This study evaluates the technical performance and environmental profile of recycled aggregates (RA) derived from waste concrete and considers their practical deployment in sustainable construction systems. Laboratory testing on locally sourced demolition concrete quantified particle-size distribution, specific gravity, water absorption, Los Angeles abrasion, alkali–silica reactivity, organic content, freeze–thaw resistance, methylene-blue index, and drying shrinkage. As expected, RA exhibited slightly lower density and higher water absorption than natural aggregates (NA), yet remained within ranges compatible with road bases, drainage layers, backfills, and select concrete applications when mix design and moisture conditioning are optimized. A cradle-to-gate life-cycle assessment (ISO 14040/44; 1-ton functional unit) compared RA with NA across CML categories and showed consistent reductions in global warming potential and abiotic resource depletion, with sensitivity dominated by transport radii and plant energy intensity. A Fine–Kinney operational review mapped key hazards in crushing-screening (unguarded drives, dust/noise exposure, falls, electrical risks, and mobile-equipment interactions) to engineering and administrative controls (fixed guarding, exclusion zones, dust suppression, health surveillance, competence-based training). Building on these findings, the paper outlines a deployment pathway: locating fixed or mobile recycling capacity near demolition clusters; using economic instruments that disincentivize disposal and reward recovery; linking laboratory results to clear end-use specifications for RA; and, where practicable, adopting minimum-use quotas supported by awareness programs. Project delivery hinges on site securing, plant selection, engineering design, and financing of CAPEX/OPEX, with RA sales underpinning viability. Treating waste concrete as a marketable material rather than a disposal burden can markedly reduce logistics costs while supplying local projects with lower-impact aggregates.

Graphical Abstract



Keywords: Recycled aggregates; Concrete waste; Material properties; Environmental sustainability; Demolition waste; Compressive strength reductions

Abbreviations: RA: Recycled Aggregates; NA: Natural Aggregates; CDW: Construction and Demolition Waste; P: Probability; S: Severity; F: Frequency; LOTO Lock-Out/Tag-Out; RPE: Respiratory Protective Equipment

Introduction

Construction and demolition waste (CDW) is a major challenge in rapidly urbanizing regions; concrete dominates this stream and, if unmanaged, imposes heavy environmental, logistical, and public-health burdens [1]. In Türkiye, the urgency became acute after the 2023 Kahramanmaraş earthquakes, which generated tens of millions of tons of debris, compressing local landfill capacity and foregrounding circular approaches such as on-site and near-site recycling to produce recycled aggregates (RA) from concrete waste [2].

International evidence indicates RA can displace a significant portion of natural aggregates (NA), particularly in road bases, drainage layers, backfills, and non-structural concretes, achieving lower life-cycle impacts than NA under typical logistic scenarios [3,4]. Yet, reservations persist regarding heterogeneity, adhered mortar, high water absorption, and consequent effects on concrete rheology and strength [5,6].

Literature Background

Meta-analyses and reviews consistently show that RA's specific gravity is lower and water absorption higher than NA due to adhered mortar; compressive strength reductions of ≈10– 20% are commonly reported at high replacement ratios unless mix designs are adapted [7,8]. Mechanical penalties can be mitigated through improved processing (multi-stage crushing, pre-soaking), surface treatments (e.g., carbonation, resins), and optimized binder systems [9,10].

Comparative LCAs report lower GWP, AP, and resource depletion for RA-based concretes/aggregates when transport and extra cement demand are controlled [11,4]. Recent syntheses emphasize allocation choices, transport radii, and cement content as the dominant drivers [12].

EU studies estimate high technical potential but heterogeneous circularity, with net environmental benefits of shifting concrete/brick fractions from landfill to advanced recycling pathways [13]. Japan's Construction Material Recycling Law institutionalizes selective demolition and mandatory sorting/recycling for specified scales, accelerating RA streams into higher-value uses (MoE Japan, 2001/2003; Sum ikura & Katsumi, 2022). Germany's long-standing CDW infrastructure and regulatory evolution toward closed-loop recycling for concrete are well documented [14].

Materials and Methods

This chapter details the materials, sampling and preprocessing workflow, and the standardized test methods used to characterize recycled aggregates (RA) produced from concrete waste and natural aggregates (NA). It also presents the data structures and acceptance criteria applied to evaluate usability in low-risk concrete, pavement, and geotechnical applications.

Sources and types of aggregates

i. Recycled aggregate (RA). Produced from processed concrete debris originating from urban renewal, demolition, post-earthquake debris, fire-damaged elements, defective concrete production, and discarded laboratory specimens. After primary selection, feedstock was crushed and screened to obtain defined size fractions.

ii. Natural aggregate (NA). Reference aggregates produced by conventional quarrying and crushing (fixed or mobile plants).

Sampling strategy

Representative bulk samples (≥ 30kg per size fraction) were collected at the plant discharge conveyors after steady-state operation was reached. Sampling followed a "multiple increments–one composite" approach to reduce bias from gradation fluctuations. Each composite sample was immediately sealed in moisture-tight containers and labeled with date, source, line, and fraction.

Preprocessing and fractionation

Incoming concrete waste was visually inspected to remove non-conformities (wood, plastics, metals, gypsum). The waste was then passed through:

i. Primary crushing (jaw/impact) to < 75mm.

ii. Secondary/tertiary crushing as required.

iii. Multi-deck screening to generate test fractions (e.g., 0–0.25, 0.25–0.5, 0.5–1, 1–2, 2–4, 4–8, 8–16mm).

All test portions were oven-dried at 105±5°C to constant mass unless the standard required a different moisture condition (e.g., pre-soaking prior to density/absorption).

Test methods and acceptance criteria

Each fraction was tested to confirm grading conformance and to quantify fines (≤ 0.075mm). Results informed suitability for specific end-uses and supported mix design envelopes.

Standards referenced in this program:

i. Particle size distribution: EN 933-1–series (sieve analysis)

ii. Specific gravity & water absorption: TS EN 1097-6

iii. Mechanical resistance (Los Angeles abrasion): TS EN 1097-2

iv. Alkali–silica reactivity (ASR) screening: ASTM C227

v. Organic impurities: TS EN 1744-1

vi. Freeze–thaw resistance: TS EN 1367-2

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vii. Drying shrinkage of aggregates: TS EN 1367-4

viii. Clay/fines indicator: Methylene blue test (laboratory procedure; threshold described below)

Apparent particle density and 24h water absorption was determined. RA was pre-soaked where relevant to reflect field batching practice. These parameters served as key inputs for mixture water correction and predicted permeability.

Table 1: Los Angeles Abrasion-Indicative Limits (TS EN 1097-2).

Application	Max LA (%)
Road base / sub-base	40
General concrete use	50

Mechanical resistance to impact/abrasion was measured using the standardized charge and drum rotations. Compliance thresholds are summarized in Table 1.

RA in the 5-12mm band generally satisfies these limits when produced under controlled crushing and screening.

Across studies, RA water absorption is consistently higher and LA resistance generally lower than NA, while densities remain within a usable range for many applications. Where fines (≤ 0.075mm) approach ~19%, the methylene blue test becomes critical for clay control prior to use in concrete.

Concrete waste collected from demolition/stockpile sites was processed through crushing– screening trains in Table 2. RA and NA were characterized via sieve analysis (EN 933-1 equivalent), specific gravity & water absorption (EN 1097-6), Los Angeles abrasion (EN1097-2), alkali–silica reactivity (ASTM C227), organic content (EN 1744-1), freeze–thaw (EN 1367-2), methylene blue, and drying-shrinkage.

Table 2: Representative Literature-Style Dataset for RA Properties.

Reference (as provided)	Size (mm)	Water Absorption (%)	Density (g/cm^3)	LA (%)	Flatness	Fineness	Unit Weight (kg/m^3)
[18]	0.4	10.64	2.69	31.72	–	–	–
	4–16	4.62	2.67	–	–	3.38	–
[29]	0–10	4.6	2.46	33	–	–	1338 /1427
	10–20	4.1	2.52	33	–	–	1432 /1568
Seara-Paz et al.	4–16	5.4	2.57	34.28	–	7.15	–
Mohamed Amer	4–16	5.05	–	51.5	–	–	–
Liu	0–25	4.8–5.2	2.4	–	16.8	–	1170
Ahmed Shaikh	0–19	4.9	–	–	–	–	–
[6]	0–10	4.57	2.65	33.3	11.5	–	1285
	10–20	4.66	2.66	41.2	12.2	–	1248
Malesev et al.	4–8	4.59	2.35	33.7	–	–	1275/1388
	8–16	2.87	2.48	–	–	–	1239/1323
[24]	–	5.5	2.34	–	–	–	–
	–	6.1	2.37	–	–	–	–
	–	4.9	2.3	–	–	–	–
[20]	10–20	–	–	35.63	9.97	–	1393/1553
Puthussery et al.	0–11	–	–	23.8	16.8	–	–
[25]	4–25	–	–	–	23.3	–	–

Measured specific gravity for RA ranged 2.18–2.59 g/cm^3 vs 2.45–2.68 g/cm^3 for NA; water absorption for RA rose from ≈2.5% (8–16 mm) to ≈19% (0–0.25 mm), while NA remained≈0.5–2.4%. Los Angeles abrasion values for RA lay ~31–51%, satisfying road-base criteria and some concrete uses. These ranges align with independent studies on RA classification and performance envelopes [7,15].

The study focused on aggregate properties; consistent with literature, strength losses at high RA contents are expected unless water demand is managed and mix rheology is tuned Evangelista & de Brito, 2007 [5].

It is implemented that, an ISO 14040/44-aligned cradle-to-gate LCA with the functional unit of 1ton of aggregate, comparing NA (quarry extraction + processing) and RA (collection + crushing/screening). Impact assessment followed CML 2001 categories with local inventories for fuel/electricity/water and site logistics; sensitivity to haul distances and electricity mix was examined. The approach and key drivers are consistent with recent LCA meta-studies [12,4].

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Figure 1: Fine-Kinney Risk Analysis for Recycling and Crushing Facility.

For NA production, blasting (ANFO/dynamite), loading/hauling, and crushing dominated energy/emissions; for RA, avoidance of blasting and shorter collection-to-plant distances moderated impacts but electricity for crushing/screening remained material.

Risk identification

The risk assessment aimed to systematically identify hazards within the aggregate recycling and crushing facility, evaluate the associated risks using the Fine–Kinney method, and eliminate or reduce them to acceptable, controlled levels through engineering, administrative, and PPE measures. Preventive and corrective actions were derived in line with applicable occupational health and safety regulations and good practice. The assessment covered four operating areas-waste concrete reception/loading, primary bunker and tipping zone, crushing–screening units, and stockpiles/vehicle circulation-based on the operating principles of a fixed crusher plant similar to the one at Çekmeköy-Ömerli quarry. The study is shown schematically in Figure 1.

Risk identification drew on-site inspections, records of past incidents, equipment/process reviews, and current legal requirements. A total of 36 hazards were evaluated via Fine–Kinney (Risk = Probability × Severity × Frequency), supported by field observations of material flows (loading–tipping–crushing–stockpiling), environmental aspects (dust, noise), and worker–equipment interactions.

Table 3: Simplified Fine–Kinney Risk Levels (typical bands): ≥400 Very High · 200–399 High · 70–199 Substantial · 20–69 Possible.

Area / Task	Hazard & Undesired Event	Initial (P–S–F → Risk)	Risk Level	Key Controls (Engineering / Admin / PPE)	Residual (P–S–F → Risk)	Residual Level
Bunker tipping	No physical barrier; truck tips into/over open edge → roll-over, crush injury/fatality	1–40–6 → 240	High	Install physical barriers/ stop logs and marked exclusion zone; marshal-guided reversing; audible– visual pre-start alarms; improved pavement/grade; spotters and cameras	0.5–40–6 → 120	Substantial

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Bunker & transfer points	Respirable dust from loading, tipping, screening → respiratory disease, eye/skin irritation	3–15–10 → 450	Very High	Water sprays, fogging or enclosure at sources; stockpile watering; closed cabs; dust monitoring; task rotation; RPE policy & fit-testing	0.5–15–10 → 75	Substantial
Crusher/ screen units	Unguarded moving parts (belts, pulleys, screens) → entanglement, amputation	3–15–10 → 450	Very High	Fixed guards, interlocked access, compliant walkways/handrails; LOTO; signage; permit-to-work	0.5–15–10 → 75	Substantial
Plant auto-start	Automatic start of belts/screens without full warning → struck/ caught-in	3–3–40 → 360	Very High	Time-delay audible– visual alarms; pre-start area sweep; access control to control room; operator training & supervision	0.5–3–40 → 60	Possible
Site traffic (stockpiles)	Vehicle overturn / collision (ramp grade/width, soft ground) → injury, property loss	3–2–15 → 90	Substantial	Engineered, ramps/ grades, one-way circuits, speed control, berms; visibility aids; traffic maps & driver induction	0.5–2–30 → 30	Possible
Work at height	Climbing on truck bodies / walking on belts → fall from height, serious injury	4–15–6 → 360	Very High	No-access policy to truck beds; fixed platforms where required; belt walkways with handrails; supervision & enforcement	0.5–15–6 → 45	Possible
Noise (bunker, crushers)	>85 dB(A) exposure → hearing loss, health effects	1–15–6 → 90	Substantial	Noise surveys, engineering damping/enclosures; task rotation; hearing protection, training, audiometry	0.5–15–6 → 45	Possible
Maintenance	Inadequate LOTO / unauthorized intervention → electrocution, entanglement	1–40–3 → 120	Substantial	LOTO procedure & locks; isolation points; permit-to-work; supervision; competency assurance	0.5–40–3 → **60**	Possible

Results

i. Very-high and high risks were concentrated in Table 3:

ii. Mobile equipment and tipping operations (truck roll-over, falling objects, unauthorized personnel near moving plant),

iii. Crushing–screening machinery (unguarded moving parts, auto-start of belts/screens, emergency stops),

iv. Airborne dust (respirable dust exposure during loading, tipping, transfer, and screening),

v. Noise (sustained >80–85 dB(A) exposures near bunker and crushers),

vi. Work at height/unsafe access (climbing on truck bodies, walking on belts),

vii. Electrical/grounding and maintenance controls (LOTO discipline, earthing integrity).

As immediate priorities, barriers and exclusion zones at the bunker front, machine guarding (fixed guards, walkways/ handrails), automated audible–visual pre-start alarms, LOTO for maintenance, segregated traffic routes, and dust/noise exposure

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controls were instituted. Dust suppression (fixed sprays and water trucks on stockpiles, enclosure/hooding of transfer points) was adopted as the most effective primary control, complemented by closed-cab equipment and fit-for-purpose RPE where required. Noise risk was mitigated via exposure measurements, task rotation, engineering damping/enclosures, and hearing protection with audiometric surveillance. Simplified Fine–Kinney Risk Register (Priority Items) resulted as Eq. 1.

Scale: Risk = P × S × F. (Eq. 1)

Residual risk reflects planned controls.

Targeted dust and noise controls results showed that:

i. **Dust:** Source-based control (sprays/fogging at hopper, crusher, transfer points), stockpile watering by fixed system or tanker, hooding/enclosure of high-emission points, housekeeping on haul roads, closed-cab mobile plant, and exposure monitoring linked to corrective actions.

ii. **Noise:** Exposure measurements (dB(A)), engineering controls (enclosures/damping, isolators), task rotation, and mandatory hearing protection with baseline and periodic audiometry.

iii. **PPE and supervision:** Fit-tested RPE for dusty tasks; hearing protection; enforcement by H&S team; induction and toolbox talk tailored to tipping, isolation, and access control.

iv. **Global Warming Potential (GWP):** The study found 304kg CO_2e/ton for NA vs 288kg CO_2e/ton for RA (≈5–8% reduction), contingent on transport radii and plant energy

v. **Intensity:** Comparative studies report similar directional outcomes, with parity thresholds governed by additional cement (in RAC) and increased transport for RA streams [11,4].

Abiotic depletion (fossil), acidification, ecotoxicity. It is reported lower ATPf/AP/ecotoxicity for RA, reflecting avoided blasting and moderated haulage; electricity usage remained the main lever. Meta-reviews corroborate transport and cement content as dominant levers [12].

Its cost allocation suggested broadly similar cost shares for RA vs NA (materials ~75%, electricity ~9%, transport ~10%), with RA advantaged where recycling plants are proximate to urban demolition zones and disposal fees are high. International experience shows RA is competitive in pavements/unbound layers and precast non-structural elements when quality control and logistics are optimized [15,16].

Conclusion

Locating recycling capacity next to demolition hot spots is pivotal; depending on demand volatility and site access, plants may be modular mobile units or compact fixed lines. A coherent policy mix should make disposal the expensive option (higher tipping/landfill fees) while rewarding recovery through municipal leadership and targeted incentives for contractors engaged in urban renewal. Clear specification pathways are needed so that laboratory results map directly to permitted end-uses of recycled aggregates, accompanied by outreach that helps client sectors adopt RA-ideally with minimum-use quotas where practicable [17-20]. Project delivery hinges on site securing, plant selection, engineering design, and financing for both CAPEX and OPEX; revenue from RA sales can underpin long-term viability. Crucially, marketing waste concrete into the local materials loop rather than hauling it to dumps can sharply reduce transport and disposal outlays, turning a recurring cost into a regional supply advantage [21-25].

The evidence confirms that recycled aggregates from concrete waste are technically adequate for numerous civil works and environmentally preferable to virgin aggregates per ton delivered when logistics and power intensity are controlled [26-33]. RA's broader climate benefit depends on where it is applied (unbound layers vs RAC), how it is processed, and how far it travels. Embedding selective demolition, quality protocols, and market instruments will accelerate uptake-especially salient for post-earthquake rebuilding [34-39]. Future work should couple process-level energy upgrades with mix-design optimization (e.g., low-clinker binders+ RA, carbonation treatments), and integrate social cost of carbon into public procurement to reflect RA's avoided burdens.

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