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Research Article

Upcycling C&D Waste via Mechanical Abrasion: Balancing Aggregate Quality Enhancement against Process-Induced Damage

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Abstract

The construction industry is a significant consumer of natural aggregates and a major contributor to carbon emissions. Recycled Concrete Aggregates (RCA) derived from Construction and Demolition (C&D) waste offer a promising sustainable alternative. This study examines how mechanical abrasion affects RCA processed in a Los Angeles (LA) abrasion drum with revolutions ranging from 100 to 1000 to find an optimal treatment window that maximizes quality without causing aggregate damage. The results indicate that coarse RCA processed at 500–600 revolutions significantly improved specific gravity (~2.55 from ~2.3) and reduced water absorption (~2.0% from ~4-5%), meeting the standards for natural aggregates. This treatment effectively removed fine mortar particles and improved durability (soundness loss ~15%), surpassing untreated RCA, which exhibited soundness losses >30%. However, excessive abrasion beyond ~700 revolutions led to an increase in fines and micro-cracking, resulting in a soundness loss exceeding 23%, failing durability criteria. The optimal abrasion range (~500 revolutions) resulted in a coarse aggregate yield of about 50%, compared to only 27% at 1000 revolutions. The study shows that on-site processing of C&D waste at this optimal level produces high-value aggregates for structural concrete, supporting the circular economy by reducing dependence on virgin aggregates and diverting waste from landfills. Cost analysis indicates that moderate abrasion (~500 revolutions) maximizes net material value while minimizing energy use and dust production. These results emphasize the viability of mechanical abrasion as a sustainable upcycling method for RCA, balancing quality improvement with process-related damage.

Keywords: Circular Economy; Cost Analysis; Environmental Impact; Recycled Concrete Aggregates (RCA); Sustainable Construction.

1. INTRODUCTION

The rapid growth of urbanization and infrastructure development in recent decades has driven a substantial increase in the generation of construction and demolition (C&D) waste worldwide [1]. This trend poses a dual challenge: addressing the environmental and logistical burdens associated with vast volumes of waste, while simultaneously leveraging opportunities for resource recovery and circular economy implementation [2]–[4]. The global construction sector consumes enormous quantities of raw materials, with aggregates comprising sand, gravel, and crushed stone accounting for the largest share by mass [5], [6]. Quarrying of natural aggregates (NA) depletes finite geological resources, disrupts ecosystems, generates dust and noise pollution, and contributes significantly to greenhouse gas (GHG) emissions [7].

In parallel, the magnitude of C&D waste generation is staggering. Estimates indicate that industrialized regions produce more than 0.9 billion tons of C&D waste annually [8], while the United States alone generated approximately 600 million tons in 2018 [9]. In rapidly urbanizing economies, such as China and India, the annual production of C&D waste has been reported to exceed 2 billion tons and 150 million tons, respectively [10]–[12]. This waste stream, if unmanaged, results in massive landfill disposal, land occupation, and potential contamination of soil and groundwater [13]. Hence, diverting C&D waste into recycled materials is critical for sustainable construction practices and achieving global sustainability targets [14], [15].

Among the various constituents of C&D waste, recycled concrete aggregate (RCA) obtained by crushing and processing waste concrete has gained substantial attention due to its potential as a substitute for NA in concrete production. RCA utilization can contribute to closing the material loop in the construction sector, conserving virgin resources, lowering embodied energy, and reducing the carbon footprint of concrete [16]–[18]. However, despite these environmental advantages, RCA adoption in structural applications remains limited, primarily due to its inherent quality limitations.

The primary factor affecting RCA quality is the presence of residual adhered mortar, which remains attached to the aggregate surface after crushing [19], [20]. This adhered mortar is more porous, less dense, and weaker than the parent NA, resulting in typical RCA densities of 2.2–2.5 g/cm³ and water absorption rates of 3–8%, compared to 2.6–2.7 g/cm³ and <2% for NA [21], [22]. The porous nature of adhered mortar negatively affects the interfacial transition zone (ITZ) between the aggregate and the cement paste in new concrete, increasing permeability, shrinkage, and susceptibility to freeze-thaw damage [23], [24]. Consequently, recycled aggregate concrete (RAC) typically exhibits 10–30% lower compressive strength compared to conventional concrete when NA is entirely replaced by untreated RCA [25], [26].

Despite these drawbacks, numerous studies have demonstrated that appropriate treatment and mix design optimization can significantly enhance RCA performance. Incorporating supplementary cementitious materials (SCMs), such as fly ash, ground granulated blast furnace slag (GGBFS), and silica fume, can improve RAC strength and durability by refining the pore structure and mitigating ITZ weaknesses [25], [27], [28]. Furthermore, high-quality RCA, when properly processed, has been used successfully at 100% coarse aggregate replacement levels without compromising structural performance [19], [29], [30].

Various upgrading techniques have been developed to address the issue of adhered mortar on recycled concrete aggregate (RCA), broadly classified into four categories. Mechanical treatments, such as additional crushing, grinding, and abrasion, physically remove the residual mortar from the aggregate surface and are widely adopted due to their simplicity, scalability, and compatibility with existing processing equipment [31]. Thermal treatments exploit the thermal incompatibility between mortar and natural aggregate by heating RCA to induce interfacial microcracking, enabling mortar detachment without significant aggregate damage when controlled appropriately [32], [33]. Chemical treatments involve immersing RCA in acidic or alkaline solutions to dissolve or weaken the mortar, yielding significant quality improvements but raising concerns over cost, environmental impact, and safe handling [33], [34]. More recently, biological treatments using microbial-induced calcium carbonate precipitation (MICP) have emerged as a sustainable alternative, in which bacteria precipitate calcium carbonate to fill pores and strengthen aggregate surfaces, offering an innovative and low-energy approach to RCA enhancement [35], [36].

Among these, mechanical removal of adhered mortar is considered the most feasible for large-scale industrial applications due to its simplicity, relatively low cost, and compatibility with existing aggregate processing infrastructure [24], [37]. Methods such as Los Angeles (LA) abrasion drum processing—initially designed for testing aggregate hardness—have been successfully adapted to remove adhered mortar while preserving aggregate integrity. Tam et al. [38] found that mechanical abrasion substantially reduced residual mortar content, improving aggregate density and lowering water absorption. Similarly, Purushothaman et al. [31] demonstrated that RCA subjected to LA abrasion achieved higher compressive strength in RAC than untreated RCA.

However, a critical knowledge gap remains: most previous studies have examined only one or a few abrasion levels, limiting insight into the trade-off between mortar removal efficiency and potential aggregate damage. Overly aggressive abrasion can lead to particle size reduction, excessive fines generation, and microcracking of aggregates, which may offset the benefits of mortar removal [39]–[41]. Conversely, insufficient abrasion may fail to adequately improve RCA properties, leaving it unsuitable for structural applications. Therefore, the relationship between abrasion duration (or revolutions) and RCA quality is expected to be non-linear, with an optimal processing range that maximizes performance improvements while minimizing material loss.

The present study addresses this gap by systematically evaluating the effects of mechanical abrasion durations ranging from 100 to 1000 revolutions in an LA abrasion drum. The research objectives are to: (1) quantify the influence of abrasion intensity on the physical and mechanical properties of fine and coarse RCA, (2) determine the optimal abrasion level that produces aggregates meeting relevant standards for gradation, specific gravity, water absorption, and durability, and (3) assess the potential environmental and economic benefits of implementing the optimized RCA processing method at scale. By benchmarking the upgraded RCA against typical natural aggregate properties, the study aims to provide a practical and scientifically grounded approach to enhancing RCA quality, enabling its broader application in structural concrete and contributing to the circular economy in construction.

2. MATERIAL AND METHODS

2.1. Research Design

This flowchart provides a clear overview of the systematic stages of processing construction and demolition (C&D) waste concrete into recycled aggregate that meets quality standards. The process involves several critical stages, from material collection and preparation, primary processing, abrasion treatment, and aggregate quality testing. Each step aims to ensure that the recycled material meets the necessary technical and environmental standards for reuse in construction projects. Emphasis on quality testing, including sieve analysis and mechanical properties, ensures that the produced aggregate is safe for use and durable for long-term applications.

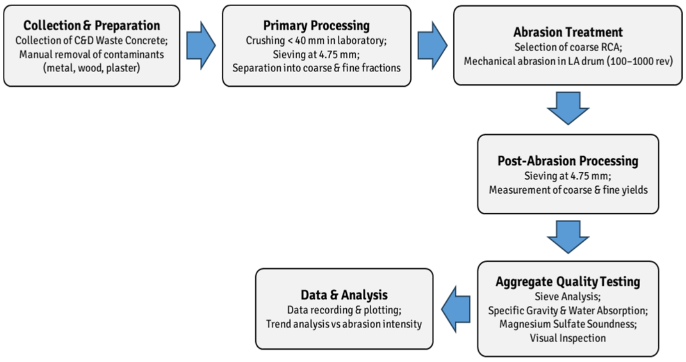

Figure 1. Flowchart Processing of C&D Waste Concrete

This flowchart illustrates converting C&D waste concrete into recycled aggregate through structured and interconnected stages. The process begins with material collection and preparation, which involves manually removing contaminants such as metal, wood, and plaster. The material is then crushed and sieved to separate coarse and fine fractions. The next stage is abrasion treatment, aimed at testing the aggregate's resistance to friction, followed by post-abrasion processing, which includes further sieving to optimize the material.

Quality testing of the aggregate is performed at the final stage to ensure that its physical and mechanical properties meet the required standards. The tests include specific gravity, water absorption, sulfate, and soundness resistance. Additionally, data analysis is conducted to identify trends in abrasion intensity and the quality of the aggregate produced, ensuring that each step is carried out accurately and efficiently to achieve the best results.

2.2. Source of Recycled Aggregate

The C&D concrete waste used in this study was sourced from demolished building components of mixed structural concrete rubble of unknown exact mix design. Large chunks of waste concrete were manually broken and then mechanically crushed in the laboratory to produce raw recycled concrete aggregate (RCA) up to 40 mm in size. Non-concrete contaminants such as metals, wood, and plaster were manually removed to ensure that the RCA consisted predominantly of clean concrete particles, as recommended by previous RCA quality control guidelines [17], [42]. The crushed RCA was sieved to separate the coarse fraction (>4.75 mm) from the fines (<4.75 mm). Only the coarse RCA was selected for abrasion experiments, as this fraction generally contains the majority of adhered mortar on particle surfaces and is most influential in determining recycled aggregate concrete performance [19], [43].

Initial characterization of the coarse RCA revealed an oven-dry specific gravity of approximately 2.30 and a 24 h water absorption of 4.5%, values consistent with literature reports for untreated RCA, which typically range from 2.2–2.5 in specific gravity and 3–8% in water absorption [21], [22]. These values are notably inferior to those of typical parent natural aggregate (gravel), which generally exhibits specific gravities of 2.6–2.7 and water absorption below 2% [17]. Although the magnesium sulfate soundness of the untreated RCA was not measured in this study, previous research indicates that RCA with high adhered mortar content often exhibits >30% weight loss in the test, reflecting its lower resistance to weathering [34], [44].

2.3. Mechanical Abrasion Treatment

A Los Angeles (LA) abrasion machine was employed to mill the coarse RCA mechanically, removing adhered mortar through impact and attrition forces. The LA abrasion apparatus, widely used for aggregate toughness and soundness testing, consists of a horizontal rotating steel drum with internal dimensions of Ø711 mm × 508 mm (ASTM C131/C131M-20 [45]; IS 2386 Part IV [46]). For each test, approximately 5 kg of oven-dry coarse RCA was placed in the drum with 12 cast iron spheres (total mass ≈ 5000 g), constituting the standard Gradation An abrasive charge for the LA test. The drum was rotated at a speed of 30–33 rpm, in line with the standard operating range for abrasion testing [47], [48].

Instead of the conventional 500 revolutions specified in ASTM/AASHTO for abrasion resistance evaluation, the present study varied the revolution count to control processing intensity. Target abrasion levels were set at 100, 200, 400, 500, 600, 800, and 1000 revolutions, ranging from mild to aggressive abrasion. At 33 rpm, the maximum duration (1000 revolutions) corresponded to approximately 30 minutes of tumbling. After processing, the drum was stopped and the material was discharged. The treated aggregate was sieved on a 4.75 mm sieve to separate the retained coarse RCA from the generated fines (<4.75 mm), primarily consisting of abraded mortar fragments and small broken aggregate particles. The coarse and fine fractions were weighed to calculate the coarse aggregate yield at each abrasion level, following approaches used in prior RCA processing optimization studies [31]. Lower abrasion levels predominantly remove attached mortar, while higher levels risk damaging the aggregate core, reducing particle size, and increasing fines generation [49], [50].

2.4. Aggregate Testing

The processed coarse RCA from each abrasion level was subjected to standard aggregate quality tests to assess improvements relative to untreated RCA and compliance with relevant specifications.

2.4.1. Sieve Analysis

- Coarse and fine fractions were analyzed for particle size distribution using the methods in IS 2386 (Part I) [51] and IS 383:2016 [52], similar to ASTM C136/C136M-19 [53].
- Fine aggregates were graded down to 150 μm to determine their fine aggregate zone classification (Zone I–IV). Coarse aggregates were sieved on 40 mm, 20 mm, 10 mm, and 4.75 mm sieves to check compliance with

grading limits for 20 mm nominal size aggregates (BS EN 12620:2013 [54]).

2.4.2. Specific Gravity (SG) and Water Absorption (WA)

- For each abrasion level, representative coarse RCA samples (retained on a 10 mm sieve) were tested per IS 2386 (Part III) [55], equivalent to ASTM C127-15 [56].
- Fine RCA (<4.75 mm) was tested per the delicate aggregate procedure in ASTM C128-15 [57].
- Higher SG and lower WA indicate reduced adhered mortar and a denser aggregate matrix [17].

2.4.3. Magnesium Sulfate Soundness Test

- Durability was assessed using the magnesium sulfate soundness test (IS 2386 Part V [58]; ASTM C88/C88M-18 [59]), which simulates weathering by salt crystallization.
- Coarse RCA samples in the 10 mm size range from each abrasion level were immersed in $MgSO_4$ solution for five cycles, with oven drying between cycles, and the percentage mass loss was recorded.
- Lower mass loss indicates higher durability, with ≤18% generally required for structural concrete aggregates in many standards (BS EN 12620:2013 [54]; ASTM C33/C33M-18 [60]).

2.4.4. Visual Examination

- Before-and-after samples from each abrasion level were photographed and visually inspected.
- Surface characteristics, such as the presence or absence of the whitish cementitious coating, were qualitatively assessed as indicators of mortar removal effectiveness [31].

All tests were conducted at ambient laboratory conditions. Each parameter value (e.g., SG, WA, soundness) represents the mean of at least two independent measurements on sub-samples. Test equipment, including balances and sieves, was calibrated before use following standard procedures. The results were recorded, tabulated, and plotted to evaluate trends in RCA quality as a function of abrasion intensity.

3. RESULTS AND DISCUSSIONS

3.1. Aggregate Yield and Particle Size Distribution

Mechanical abrasion caused the RCA to break down into varying proportions of coarse and fine material depending on the number of drum revolutions. Most material remained coarse at low abrasion levels (e.g., 100–200 rev), with only a small fraction of fines generated (mostly detached mortar particles). With increasing abrasion, a larger portion of the RCA mass was converted into penalties. Figure 1 illustrates the coarse vs. fine mass distribution from 100 to 1000 revolutions. At 100 rev, about 86% of the input remained coarse aggregate and ~14% became fines. By 500 rev, the coarse fraction dropped to ~66% (34% fines). At 600 rev, the coarse yield sharply fell to only ~36%, with ~64% of the mass as fines. Finally, at 1000 rev, only ~27% remained coarse while ~73% had been pulverized into penalties. This trend shows that excessive abrasion can significantly diminish the yield of usable coarse aggregate. Initially, the loss of coarse mass is primarily due to weak attached mortar being ground off. Still, beyond a certain point, even the natural aggregate begins to abrade and fracture.

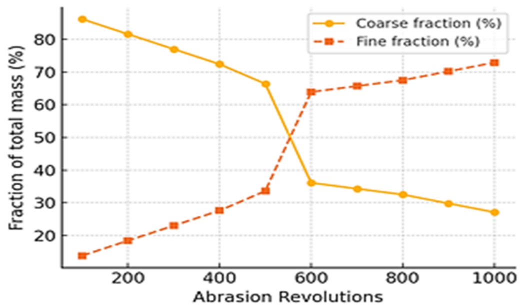

Figure 2. Coarse vs. fine fraction yield as a function of abrasion revolutions. (Coarse yield maximizes at low revolutions and drops drastically after ~500–600 revolutions, where aggregate breakage accelerates.)

Notably, there is a sharp transition around 600 revolutions. Between 500 and 600 rev, the coarse fraction plummeted from ~66% to ~36% (a drop of nearly half the mass). This indicates that once most of the easily-removable mortar was stripped (~500 rev), the bare aggregate particles collided more aggressively, causing significant aggregate breakage and generating excess ultrafine debris (stone dust). In effect, the dominant wear mechanism shifted: at lower revolutions (up to ~500), mortar is preferentially abraded off in sand-sized particles, while the parent stones remain mostly intact. Around 600 rev, a surge of fine dust (<0.15 mm) appeared, consistent with pulverization of the remaining mortar and onset of aggregate fragmenting. At even higher counts (>700), the aggregate itself starts cracking – larger pieces of the original stone break off, which paradoxically results in the fines gradation becoming coarser again (more sand-sized fragments rather than pure dust). The gradation analysis of the penalties supports these observations.

The particle size distributions of the <4.75 mm portion were classified into IS 383 fine aggregate zones (Zone I = coarsest sand, Zone IV = finest). For 100 rev, the resulting fines were Zone II (medium sand). Interestingly, 200–500 rev fines were all Zone I (relatively coarse sand). This suggests that initial abrasion produces fines that are granulated mortar and small stone chips spanning a broad size range, but generally on the coarser side (since the weakest mortar comes off in chunks rather than powder). However, at 600 rev, the fine aggregate was “Non-Conforming (NC)”, meaning the gradation fell outside the Zone I–IV envelopes due to an excess of excellent particles (dust). This confirms the inflection point: the 600-rev sample contained a peak of ultrafine material, likely pulverized mortar paste that dramatically increased the sub-150 µm fraction. Beyond 600, the fines gradation shifted back – fines from 700–1000 rev again met Zone I criteria (coarse sand). The anomaly at 600 revolutions thus appears to be a short-lived spike in production of filler-like dust, after which additional abrasion mainly created more sand-sized rock fragments as the aggregate fractured. Practically, this means operators should avoid the regime that produces excessive dust (around 600 rev) if fine powder is undesirable or if it would require costly dust mitigation. An optimal stopping point would be just before this occurs (near 500 rev in our case) to maximize mortar removal and minimize ultra-fines. Re-examining the complete particle size data at 600 rev confirmed the fine fraction had a distinct deficit of mid-sized sand and surplus of <150 µm particles, consistent with this interpretation.

In summary, moderate abrasion cleans the RCA by preferentially removing mortar as fine sand, but over-abrasion leads to diminishing coarse yield and a surge in wasteful dust. This underlines a key trade-off between cleaning efficiency and aggregate preservation. For our material, the transition occurred sharply at ~600 revolutions. Thus, from a yield perspective, the optimal processing intensity is slightly below the 600-rev threshold – aggressive enough to remove most mortar, but not so aggressive as to significantly grind the aggregate itself.

3.2. Specific Gravity and Water Absorption of RCA

The removal of adhered mortar dramatically affected aggregate density and porosity. Table 1 summarizes the specific gravity (SG) and water absorption (WA) of the processed aggregates at various abrasion levels, for both the coarse and fine portions. The untreated RCA initially had SG in the mid-2.3s and WA around 4–5%. After abrasion, the coarse RCA's SG increased and WA decreased progressively with more intense processing – up to a point. By around 400–500 rev, most of the improvement had been realized: the coarse aggregate achieved SSD specific gravity ~2.55 (oven-dry SG ~2.50–2.53) and water absorption ~1.5–2.0%, within the range of typical natural aggregates. Further abrasion beyond 500–600 rev gave only marginal gains in SG (e.g., 1000 rev coarse SG ~2.60) and WA did not improve further (oscillating around 1.3–2.2% within 500–1000 rev, with a minimum ~1.3%).

This plateauing corresponds to the point where most removable mortar was already gone by ~500 rev. Any additional reduction in water absorption at very high revolutions likely comes from eliminating a few remaining mortar islands but is counteracted by new micro-cracks introduced in the aggregate (discussed later). The fine RCA (abraded mortar) also showed an increase in SG (from ~2.15 at 100 rev to ~2.5 at 600 rev, then fluctuating) and a decrease in WA (from ~8.8% at 100 rev down to ~7.2% at 400 rev). The fine fraction, largely mortar particles, remained more porous than the coarse fraction, but still saw quality improvement with processing. By 600 rev, even the fines had SG ~2.5 (indicating many fines were small stone pieces by then), although their absorption rose temporarily due to the high dust content at that stage.

Table 1. Effect of abrasion processing on aggregate quality indicators

Abrasion Level	Coarse RCA – SG (OD)	Coarse RCA – WA (%)	Fine RCA – SG (OD)	Fine RCA – WA (%)
0 (Unprocessed)	2.30–2.35 (est.)	~4.5 (4–5% typical)	2.1–2.2 (est.)	~8% (typical)
500 revs (Optimum)	~2.53–2.56	~1.5–2.0	~2.4–2.5	~2.5–3.0
600 revs	2.53	2.20	2.50	8.0
1000 rev	2.60	1.30	2.52	7.8
Natural Agg.	~2.6–2.7	< 2.0	~2.6	< 2.0

(OD = oven-dry basis; WA = 24 h water absorption; Natural aggregate values for reference)

Abrasion-treated RCA (around 500 rev) achieved specific gravities >2.5 and water absorption ~2% or below, meeting typical criteria for structural concrete aggregates. In contrast, the unprocessed RCA's high absorption (~5%) would usually be unsuitable for high-quality concrete. The ~70% reduction in water absorption (from ~5% to ~1.5%) is especially noteworthy. This improvement indicates the removal of the old porous mortar and the relative densification of the aggregate. Our findings are consistent with other studies that employed mechanical mortar removal. For instance, Alqarni et al. [61] observed that LA abrasion treatment of RCA could reduce water absorption by up to ≈76% (relative to untreated RCA), significantly enhancing aggregate quality. The treated RCA in their study showed absorption well below 2%, similar to what we achieved. Verma et al. [62] also obtained RCA with properties approaching natural aggregate after a combination of abrasion and mild acid soak. They reported that concrete with treated RCA had only ~5–10% lower compressive strength than natural aggregate concrete. The convergence of our RCA's specific gravity and absorption to the natural aggregate range explains why: by 500–600 rev, the RCA was essentially converted into "like-new" aggregate in terms of bulk density and porosity. Minor further gains at 800–1000 rev (e.g., SG to 2.60) were offset by the disproportionate material loss and potential damage, as discussed later.

Notably, the fine aggregate produced (essentially ground mortar and small stones) also moved toward natural sand properties, but to a lesser degree than the coarse aggregate. By optimal processing, the fine RCA's absorption dropped from ~8% to ~2.5–3%, which, while higher than river sand (<1%), still represents a significant improvement. Some residual higher absorption in fines is expected because tiny mortar particles are harder to eliminate without washing or further treatment. Nonetheless, the overall trend confirms that mechanical abrasion substantially upgrades RCA quality, especially for the coarse fraction critical for structural concrete. These quantitative results demonstrate that a moderately treated RCA can match NA performance in density and absorption, which bodes well for the strength and durability of RAC made with it. Finally, synthesize the key property changes in comparing Untreated vs. Treated vs. Over-Processed RCA, alongside typical natural aggregate (NA) benchmarks (Table 2). This highlights the trade-offs encountered:

Table 2. Performance Comparison of RAC vs NAC and Improvements with Treatments

Property	Untreated RCA (Literature)	Optimally Treated RCA (≈500 rev)	Over-processed RCA (1000 rev)	Natural Aggregate (typical)
Bulk Specific Gravity (SSD)	2.2–2.5	~2.53–2.56	~2.60	2.6–2.7
Water Absorption (%)	4.0–8.0%	~1.5–2.2%	~1.3%	< 2.0%
Soundness Loss ($MgSO_4$ %)	>30% (estimated)	15–16% (passes 18% limit)	>23% (fails limit)	< 18%
Coarse Aggregate Yield (% of original)	100% (by definition)	~36–66% (at 500–600 rev)	~27% (at 1000 rev)	(Virgin material)

Untreated RCA values based on initial tests and Refs. "Optimally treated" refers to the 500–600 revolution range identified in this study. Soundness limit from IS 2386 / ASTM C88 requirements for concrete aggregates.

This comparison emphasizes that moderate abrasion (500±100 rev) strikes a balance: it brought the RCA's specific gravity and absorption to within natural aggregate ranges (SG >2.5, WA ~2% or below) and ensured durability (soundness loss ~15%, comfortably passing the ≤18% criterion), while still retaining roughly 50% of the material as coarse aggregate. Pushing the process too far (1000 rev) did yield a slightly denser product (SG ~2.6) with extremely low absorption (~1.3%), but at the cost of much lower yield (~27%) and, critically, a durability drop (soundness loss exceeding 23%, failing specifications). On the other hand, without any treatment, the RCA's high absorption and likely poor soundness would render it unsuitable for high-quality concrete. Our optimal window of ~500 revolutions maximize quality improvement with acceptable yield loss – a conclusion supported by the data and in line with observations by other researchers. For instance, a study found that treated RCA achieving absorption <2% can serve as a cost-effective substitute for NA in concrete [63], [64]. Likewise, Purushothaman et al. [31] noted that beyond a specific abrasion duration, benefits plateau and aggregate breakage increases, mirroring our findings.

In concrete production, the significance of these quality improvements is clear: higher specific gravity and lower absorption mean the aggregates contribute more strength and consume less mix water, thus improving the resulting concrete's compressive strength and workability. Prior research has shown that using such improved RCA can eliminate most of the strength penalty of recycled aggregate concrete. Our results corroborate those findings by demonstrating that mechanical processing can restore the RCA's fundamental properties close to NA levels.

3.3. Durability Performance and Aggregate Damage

A key finding of this study is that over-processing the aggregate can negatively impact durability even as density/absorption improve. The magnesium sulfate soundness test results revealed a non-linear trend. Coarse RCA treated at moderate levels showed dramatically improved soundness compared to untreated material, but extreme abrasion caused durability to decline. Specifically, the untreated RCA (0 rev) was not directly tested. Still, based on its high mortar content, one can infer it would suffer very high weight loss (>30%) under soundness cycling – far exceeding typical limits (this aligns with literature reports for unprocessed RCA). At 500 rev, the soundness loss was ~15%, efficiently meeting the 18% maximum requirement. This indicates that removing the weak mortar makes the remaining aggregate much more resilient to sulfate attack and freeze-thaw cycles. However, at 1000 rev, the soundness loss increased to >23%, meaning the sample failed the durability criterion. In other words, excessive abrasion had damaged the aggregate's integrity, making it more vulnerable in the soundness test. We observed this uptick beginning once abrasion exceeded ~600–700 rev: e.g., the sample at 800 rev showed soundness loss in the low 20s% (marginal), and by 1000 rev it failed. Thus, there exists a critical upper limit to beneficial abrasion treatment – beyond that, each additional revolution is doing more harm (micro-cracking the aggregate) than good (mortar removal). Notably, the optimal window (~500 rev) was well below this threshold, which is fortunate because it means the process can be stopped at an optimal point without approaching the severe damage regime.

To visualize durability performance across conditions: untreated RCA would likely fail soundness (soft mortar triggers disintegration), RCA treated ~500 rev passed soundness comfortably (15% loss), but RCA overtreated to 1000 rev failed soundness (23% loss) despite having little mortar. This seemingly paradoxical result (cleaner aggregate performing worse in durability after extreme abrasion) is explained by process-induced micro-cracks in the aggregate.

3.4. The Duality of Mechanical Abrasion

While mechanical abrasion effectively removes deleterious mortar, it can also impart damage to the aggregate particles themselves at high intensity. The LA abrasion process subjects the aggregate to repetitive high-energy collisions with steel balls and other aggregates. Once the outer mortar layers are gone, the hard stone-on-steel impacts can create micro-fractures inside the aggregate. These micro-cracks are often invisible to the naked eye but have a pronounced effect on durability – they increase the aggregate's porosity and create pathways for water and aggressive chemicals. In our study, the evidence of micro-cracking was the worsening soundness beyond 700 rev. LA abrasion is essentially a high-energy impact and grinding process, and such mechanical stresses are known to induce micro-cracks in brittle materials like rock and concrete.

Excessive mechanical crushing/grinding of aggregates led to internal micro-crack formation and lower strength, even as external shape improved [65]. Similarly, our heavily abraded RCA (1000 rev) had almost no mortar (hence very low absorption) but likely contained micro-cracks within the aggregate – making it less durable when subjected to salt crystallization pressure in the soundness test. The micro-cracked aggregate allows sulfate solution to penetrate and attack more readily, causing pieces to scale off during the cycling. Thus, beyond an optimal point, process-induced damage outweighs mortar-removal benefits [66], [67]. Additionally, several studies have shown that excessive grinding significantly reduces the mechanical strength and durability of aggregates due to the formation of micro-cracks and the reduction of mortar content [68]. As the grinding process increases, it exposes more of the aggregate's internal structure, which, in turn, can lead to a faster degradation of the material when subjected to external stresses such as salt crystallization [69], [70].

This dual effect highlights why the soundness loss dropped then rose with increasing revolutions: initial mortar removal (up to ~500–600 rev) eliminated the most porous, weak parts of RCA, significantly improving durability (from >30 % loss down to ~15%). But continued impact past ~700 rev started to crack the aggregate, reducing durability (loss climbing above 23%). We observed a “U-shaped” durability curve with a sweet spot in the middle. Practically, this finding is a caution for recycling operators – more abrasion is not always better, and there is a critical upper limit for processing intensity. Exceeding that can produce an RCA that, while geometrically clean, has compromised internal integrity.

Micro-cracking from over-processing is an essential consideration for the long-term performance of RCA concrete. Micro-cracked aggregates can reduce freeze-thaw resistance and lower strength over time, as cracks propagate under load or environmental stress. Future work should directly verify micro-crack presence (e.g., via microscopic or ultrasonic methods). Nevertheless, our results demonstrate via the soundness test that such damage occurs at high abrasion levels. In summary, mechanical abrasion has a dual nature: it beneficially removes weak mortar (enhancing quality), but excessive abrasion can detrimentally damage the aggregate (undermining durability). The goal is to find the optimal window where net benefit is maximized. For our RCA, that window was roughly 400–600 revolutions. Stopping in this range ensured the aggregate was upgraded (density up, absorption down, soundness good) without incurring significant mechanical damage.

3.5. Environmental and Economic Impact Analysis

Beyond technical performance, it is vital to consider the sustainability implications of the mechanical RCA processing. Re-using C&D waste as aggregates has clear environmental benefits: each ton of RCA produced is one less ton of natural aggregate that must be quarried, and one less ton of rubble sent to landfill. This directly conserves natural resources (stone, sand) and avoids the environmental footprint of quarrying (habitat disruption, dust, noise, and carbon emissions from heavy machinery). Moreover, on-site recycling of concrete can significantly reduce transportation impacts. In our case, the abrasion process can be done with a mobile setup at the demolition site or recycling facility, meaning less hauling of heavy materials. Tam et al. [54] noted that processing RCA at or near the source reduces transport fuel use and emissions. The energy consumption of the LA abrasion machine for ~10–20 minutes (e.g., 500 rev) is relatively modest – comparable to operating a large concrete mixer for a short time – and importantly, no heat or chemicals are required, so the process itself has a minimal environmental footprint (aside from electricity for the motor). The steel abrasive balls are reusable virtually indefinitely, generating no ongoing waste. Overall, the carbon footprint of producing recycled aggregate is generally lower than that of virgin aggregate, since primary aggregate production involves drilling, blasting, crushing, and long-distance transport. Studies have quantified this: for example, Alibeigibeni et al. [71] found that life-cycle assessments show reductions in energy use and CO_2 emissions when RCA is appropriately processed and used locally instead of NA. One analysis calculated that a 50% replacement of NA with RCA can lower the carbon emissions of concrete by ~20%, mainly due to avoided aggregate mining and shorter transport distances.

Another benefit is waste reduction. Every ton of demolished concrete reused as aggregate is diverted from landfills, helping municipalities meet waste recycling targets and saving landfill space. Many regions are moving toward mandates for minimum recycled content in construction (a policy trend supporting the circular economy) – having viable processes like this makes meeting those mandates feasible. Reduced hauling of waste and virgin materials also means less traffic, less road wear, and lower air pollution in urban areas. From a dust and air quality perspective, one environmental concern with mechanical abrasion is the generation of fine cement dust during processing. Adequate measures (e.g., dust extraction systems or misting to suppress dust) should be employed to prevent local air pollution and protect workers. The fine powder by-product collected can be recycled too (for instance, as a mineral filler in concrete or asphalt, or cement clinker production), moving toward zero-waste processing.

From an economic standpoint, the viability of on-site RCA processing depends on balancing the processing costs with the savings from avoided disposal and replaced natural aggregates. Our simplified analysis suggests the balance is favorable in the optimal range. Consider that untreated demolished concrete might otherwise incur disposal costs (landfill tipping fees) and one would still need to purchase new natural aggregates for construction. Two cost savings occur by processing the waste into RCA: avoided disposal fee and avoided virgin aggregate purchase. For example, if landfill costs are on the order of $50/ton and aggregate costs ~$20–30/ton, there is roughly $70–80/ton incentive to recycle (not including processing cost). The processing cost primarily comes from equipment, energy, and labor. The LA abrasion machine used in this study is standard lab equipment – in practice, larger capacity mobile crushers/abrasion mills are available. Energy-wise, a rough estimate for our process: a 2 HP motor running for 15 minutes (500 rev) consumes about 0.37 kWh; even at $0.10/kWh, that is just a few cents per batch (5 kg processed). Scaled up, per ton, the electricity might be on the order of $1–2. Equipment wear (steel drum and balls) is minor per ton, as these are durable components. Thus, processing costs are relatively low, especially when amortized over large volumes.

Importantly, the value of the output aggregate can be substantially higher than that of unprocessed waste. Untreated RCA is often down-cycled as fill or road base at ~$5–10 per ton (low-end value). In contrast, processed RCA that meets concrete specifications can command a price closer to natural aggregate (e.g., $20–30 per ton). This "value uplift" by improving quality essentially pays for the processing. To illustrate with our experimental yields and nominal market prices, suppose coarse aggregate sells at $25/ton and fine aggregate at $15/ton. Processing 10 kg of waste at 500 rev yielded about 6.6 kg coarse (~0.0066 ton) and 3.4 kg fine (~0.0034 ton). The coarse portion's value is ~$0.0066×25 = $0.165, and the fine portion, totaling $0.176. So, over-processing reduced the recoverable value by ~$0.04 (≈20%) per 10 kg in this simple model. More importantly, if the excess ultra-fines at 1000 rev are unusable and must be landfilled (incurring cost), the net value drops further – potentially erasing any profit. In our example, ~4 kg more fines were produced at 1000 rev vs 500 rev (7.3 kg vs 3.4 kg). If that extra 3.9 kg is below usable size and incurs a ~$50/ton disposal fee, that's an additional $0.195 cost, making the 1000 rev scenario possibly net-negative. Moderate processing maximizes the economic return by yielding more valuable coarse aggregate and avoiding unnecessary waste. Even the fine sand produced at optimal processing can be used in concrete or masonry mortar, so nearly all output is saleable.

On-site processing also eliminates transport costs for removing debris and bringing virgin aggregate. Hauling heavy debris to the landfill can be a significant expense (fuel, driver time, disposal tipping fee). Using the recycled aggregate on the same site (or nearby) means those transport and disposal costs are avoided, which often outweighs the direct processing cost by a large margin. Contractors also benefit from reduced dependency on purchased raw materials and can avoid potential waste-handling penalties or compliance issues. Using recycled materials may also earn project credits or incentives (e.g., under green building certification programs), adding further economic motivation.

In summary, the cost-benefit analysis strongly favors the described RCA recycling method, especially in regions with high landfill tipping fees and aggregate prices. At the optimal processing level identified (around 500 rev), the process yields a high-quality product that can replace expensive natural aggregate for a relatively low processing expenditure. Case studies in some markets have reported up to ~20% total project cost savings when recycled aggregates are used extensively. While exact economics will vary, the combination of environmental benefits (lower CO_2 footprint, conservation of resources, waste reduction) and economic advantages (material cost savings, avoidance of disposal, potential regulatory incentives) makes a compelling argument for adopting mechanical RCA processing in practice.

4. IMPLICATIONS

The optimized mechanical abrasion process produces structural-grade recycled aggregates, thereby supporting a circular economy in construction. Using these processed RCAs in new concrete can significantly reduce the need for quarried natural aggregate and reduce C&D waste sent to landfills. The process is relatively low-energy (no thermal or chemical input) and can be executed on-site, reducing transport emissions. Life-cycle assessments indicate notable reductions in embodied energy and CO_2 emissions when RCA replaces NA in concrete. Economically, moderate processing maximizes value recovery – it yields a high proportion of coarse aggregate that can be sold or used at near virgin-aggregate prices, with minimal residual waste. A simple cost analysis showed that intermediate abrasion (~500 rev) provided the best net material value per unit input, whereas over-processing led to more waste fines and lower net value. On-site recycling also avoids landfill fees and supply costs, often making the project more economical. In summary, the mechanical processing of RCA (when optimized) is both environmentally beneficial and cost-effective, converting would-be waste into a resource and reducing the carbon footprint of concrete production. The only caution is dust control during processing – appropriate measures should be in place to capture or suppress fine particulate to prevent air pollution.

5. FUTURE RESEARCH

This work focused on lab-scale processing and fundamental aggregate properties. Building on these findings, future studies should: (a) employ microstructural analysis (e.g. SEM, X-ray CT) on RCA processed at different intensities to directly observe micro-crack development and quantify mortar removal at the interface – this would visually confirm the damage mechanisms inferred here; (b) evaluate the performance of concrete made with optimally processed RCA – including long-term durability tests like freeze-thaw, shrinkage, and creep, as well as structural behavior, to ensure that the improved aggregate properties translate into improved concrete performance (initial evidence and literature suggest they do); (c) investigate scaling up the abrasion process – for instance, integrating this method into mobile recycling units or commercial crushing operations, and assessing throughput, energy consumption, and cost at scale; and (d) explore hybrid treatment combinations (mechanical plus mild chemical or thermal) to see if the optimal window can be further improved (e.g. even shorter processing time or enhanced outcomes without crossing the damage threshold). Such studies will help refine the technique and facilitate its implementation in real-world recycling and concrete production.

6. DISCUSSIONS

This study demonstrated an effective method to upcycle concrete waste into high-quality aggregates using a mechanical abrasion process. Mechanical abrasion substantially enhances RCA quality (increasing specific gravity and reducing water absorption), but at the cost of some mass loss. An optimal range of roughly 500–600 revolutions in the LA abrasion drum was identified. Within this window, the coarse RCA attained SSD specific gravity > 2.53 and water absorption < 2.2%, approaching natural aggregate standards, while retaining about 36–66% of the original material as coarse aggregate. This balance maximizes quality improvement with acceptable yield – a clear improvement over untreated RCA (SG ~2.3, WA ~5%) without the excessive breakdown seen at higher revolutions.

Over-abrasion beyond ~700 revolutions proved detrimental. Although it further cleaned the aggregate, it deteriorated aggregate durability. Soundness (Mg SO_4 loss) improved to ~15% at moderate processing (pass), but worsened to >23% at 1000 rev (fail). This is attributed to micro-cracking induced in the aggregate at high impact energy. Thus, there is a critical upper limit to processing intensity – crossing this threshold (around 600–700 rev in our case) causes aggregate damage that outweighs the benefits of additional mortar removal. Excessive abrasion should be avoided, as it yields diminishing returns and can compromise the structural integrity of the RCA.

The abrasion process results in two products – upgraded coarse aggregate and fine residuals. The fines were predominantly sand-sized at low–moderate abrasion (Zone I/II material suitable as fine aggregate). A sharp anomaly was observed at ~600 rev where excessive ultra fine (<150 µm dust) were generated, causing the fine output to become "non-conforming." At higher revolutions (800+), fines again became coarser (as parent rock started shattering). This indicates an intermediate stage where mortar is pulverized to dust, after which aggregate fracture produces more sand-sized pieces. Practically, the fines from 100–500 rev were usable as concrete sand (coarse Zone I/II), and even at 800–1000 rev the fines mostly met Zone I (though accompanied by higher waste dust). The optimal processing avoids the excessive dust generation stage (around 600 rev), yielding both coarse and fine recycled aggregates that can be utilized.

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References

[1] H. Yuan and L. Shen, "Trend of the research on construction and demolition waste management," *Waste Manag.*, vol. 31, no. 4, pp. 670–679, 2011, doi: 10.1016/j.wasman.2010.10.030.

[2] Z. Duan, S. Hou, J. Xiao, and B. Li, "Study on the essential properties of recycled powders from construction and demolition waste," *J. Clean. Prod.*, vol. 253, p. 119865, 2020, doi: 10.1016/j.jclepro.2019.119865.

[3] F. Pacheco-Torgal, "Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020," *Constr. Build. Mater.*, vol. 51, pp. 151–162, 2014, doi: 10.1016/j.conbuildmat.2013.10.058.

[4] M. Menegaki and D. Damigos, "A review on current situation and challenges of construction and demolition waste management," *Curr. Opin. Green Sustain. Chem.*, vol. 13, pp. 8–15, 2018, doi: 10.1016/j.cogsc.2018.02.010.

[5] R. Přikryl, "Geomaterials as construction aggregates: a state-of-the-art," *Bull. Eng. Geol. Environ.*, vol. 80, no. 12, pp. 8831–8845, 2021, doi: 10.1007/s10064-021-02488-9.

[6] D. Vijerathne, S. Wahala, and C. Illankoon, "Impact of Crushed Natural Aggregate on Environmental Footprint of the Construction Industry: Enhancing Sustainability in Aggregate Production," *Buildings*, vol. 14, no. 9, p. 2770, 2024, doi: 10.3390/buildings14092770.

[7] Z. Agioutantis, K. Komnitsas, and A. Athousaki, "Aggregate transport and utilization: ecological footprint and environmental impacts," *Bull. Geol. Soc. Greece*, vol. 47, no. 4, p. 1960, 2016, doi: 10.12681/bgsg.11005.

[8] S. K. Ghosh, *Waste Management as Economic Industry Towards Circular Economy*. Springer, 2020.

[9] United States Environmental Protection Agency (US-EPA)., "Advancing sustainable materials management: Facts and figures report," *Environ. Prot. Agency*, 2020.

[10] L. Zheng *et al.*, "Characterizing the generation and flows of construction and demolition waste in China," *Constr. Build. Mater.*, vol. 136, pp. 405–413, 2017, doi: 10.1016/j.conbuildmat.2017.01.055.

[11] S. H. Hassan, H. A. Aziz, I. Johari, and Y.-T. Hung, "Construction and demolition (C&D) waste management and disposal," in *Solid Waste Engineering and Management: Volume 2*, Springer, 2022, pp. 165–216.

[12] S. Jain, S. Singhal, and N. K. Jain, "Construction and demolition waste (C&DW) in India: generation rate and implications of C&DW recycling," *Int. J. Constr. Manag.*, vol. 21, no. 3, pp. 261–270, 2021, doi: 10.1080/15623599.2018.1523300.

[13] A. Akhtar and A. K. Sarmah, "Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective," *J. Clean. Prod.*, vol. 186, pp. 262–281, 2018, doi: 10.1016/j.jclepro.2018.03.085.

[14] C. P. Ginga, J. M. C. Ongpeng, and M. K. M. Daly, "Circular economy on construction and demolition waste: A literature review on material recovery and production," *Materials (Basel).*, vol. 13, no. 13, pp. 1–18, 2020, doi: 10.3390/ma13132970.

[15] N. Kisku, H. Joshi, M. Ansari, S. K. Panda, S. Nayak, and S. C. Dutta, "A critical review and assessment for usage of recycled aggregate as sustainable construction material," *Constr. Build. Mater.*, vol. 131, pp. 721–740, 2017, doi: 10.1016/j.conbuildmat.2016.11.029.

[16] N. Makul, *Recycled Aggregate Concrete: Technology and Properties*. CRC Press, 2023.

[17] R. V. Silva, J. De Brito, and R. K. Dhir, "Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production," *Constr. Build. Mater.*, vol. 65, pp. 201–217, 2014, doi: 10.1016/

j.conbuildmat.2014.04.117.
[18] Y. Zhang, W. Luo, J. Wang, Y. Wang, Y. Xu, and J. Xiao, "A review of life cycle assessment of recycled aggregate concrete," *Constr. Build. Mater.*, vol. 209, pp. 115–125, 2019, doi: 10.1016/j.conbuildmat.2019.03.078.
[19] S. C. Kou and C. S. Poon, "Enhancing the durability properties of concrete prepared with coarse recycled aggregate," *Constr. Build. Mater.*, vol. 35, pp. 69–76, 2012, doi: 10.1016/j.conbuildmat.2012.02.032.
[20] M. C. Limbachiya, E. Marrocchino, and A. Koulouris, "Chemical-mineralogical characterisation of coarse recycled concrete aggregate," *Waste Manag.*, vol. 27, no. 2, pp. 201–208, 2007, doi: 10.1016/j.wasman.2006.01.005.
[21] L. Evangelista and J. De Brito, "Concrete with fine recycled aggregates: A review," *Eur. J. Environ. Civ. Eng.*, vol. 18, no. 2, pp. 129–172, 2014, doi: 10.1080/19648189.2013.851038.
[22] J. Xiao, L. Li, V. W. Y. Tam, and H. Li, "The state of the art regarding the long-term properties of recycled aggregate concrete," *Struct. Concr.*, vol. 15, no. 1, pp. 3–12, 2014, doi: 10.1002/suco.201300024.
[23] D. Pedro, J. de Brito, and L. Evangelista, "Mechanical characterization of high performance concrete prepared with recycled aggregates and silica fume from precast industry," *J. Clean. Prod.*, vol. 164, pp. 939–949, 2017, doi: 10.1016/j.jclepro.2017.06.249.
[24] J. De Brito, J. Ferreira, J. Pacheco, D. Soares, and M. Guerreiro, "Structural, material, mechanical and durability properties and behaviour of recycled aggregates concrete," *J. Build. Eng.*, vol. 6, pp. 1–16, 2016, doi: 10.1016/j.jobe.2016.02.003.
[25] B. S. Thomas, R. C. Gupta, P. Kalla, and L. Cseteneyi, "Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates," *Constr. Build. Mater.*, vol. 59, pp. 204–212, 2014, doi: 10.1016/j.conbuildmat.2014.01.074.
[26] L. Butler, J. S. West, and S. L. Tighe, "Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength," *Constr. Build. Mater.*, vol. 47, pp. 1292–1301, 2013.
[27] J. M. Khatib, "Properties of concrete incorporating fine recycled aggregate," *Cem. Concr. Res.*, vol. 35, no. 4, pp. 763–769, 2005, doi: 10.1016/j.cemconres.2004.06.017.
[28] S.-C. Kou and C.-S. Poon, "Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates," *Constr. Build. Mater.*, vol. 23, no. 8, pp. 2877–2886, 2009, doi: 10.1016/j.conbuildmat.2009.02.009.
[29] B. González-Fonteboa and F. Martínez-Abella, "Concretes with aggregates from demolition waste and silica fume. Materials and mechanical properties," *Build. Environ.*, vol. 43, no. 4, pp. 429–437, 2008, doi: 10.1016/j.buildenv.2007.01.008.
[30] M. Etxeberria, E. Vázquez, A. Marí, and M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete," *Cem. Concr. Res.*, vol. 37, no. 5, pp. 735–742, 2007, doi: 10.1016/j.cemconres.2007.02.002.
[31] R. Purushothaman, R. R. Amirthavalli, and L. Karan, "Influence of treatment methods on the strength and performance characteristics of recycled aggregate concrete," *J. Mater. Civ. Eng.*, vol. 27, no. 5, p. 4014168, 2015, doi: 10.1061/(ASCE)MT.1943-5533.0001128.
[32] H. Zhang, W. Wei, Z. Shao, and R. Qiao, "The investigation of concrete damage and recycled aggregate properties under microwave and conventional heating," *Constr. Build. Mater.*, vol. 341, p. 127859, 2022, doi: 10.1016/j.conbuildmat.2022.127859.
[33] Y. Li, S. Zhang, R. Wang, Y. Zhao, and C. Men, "Effects of carbonation treatment on the crushing characteristics of recycled coarse aggregates," *Constr. Build. Mater.*, vol. 201, pp. 408–420, 2019, doi: 10.1016/j.conbuildmat.2018.12.158.
[34] A. Katz, "Treatments for the improvement of recycled aggregate," *J. Mater. Civ. Eng.*, vol. 16, no. 6, pp. 597–603, 2004, doi: 10.1061/(ASCE)0899-1561(2004)16:6(597).
[35] V. Achal, A. Mukherjee, and M. S. Reddy, "Microbial concrete: A way to enhance durability of building structures," *2nd Int. Conf. Sustain. Constr. Mater. Technol.*, vol. 23, no. 6, pp. 23–28, 2010, doi: 10.1061/(asce)mt.1943-5533.0000159.
[36] L. Chaurasia, V. Bisht, L. P. Singh, and S. Gupta, "A novel approach of biomineralization for improving micro and macro-properties of concrete," *Constr. Build. Mater.*, vol. 195, pp. 340–351, 2019, doi: 10.1016/j.conbuildmat.2018.11.031.
[37] V. W. Y. Tam, C. M. Tam, and K. N. Le, "Removal of cement mortar remains from recycled aggregate using pre-soaking approaches," *Resour. Conserv. Recycl.*, vol. 50, no. 1, pp. 82–101, 2007, doi: 10.1016/j.resconrec.2006.05.012.
[38] V. W. Y. Tam, M. Soomro, A. C. J. Evangelista, and A. Haddad, "Deformation and permeability of recycled aggregate concrete - A comprehensive review," *J. Build. Eng.*, vol. 44, p. 103393, 2021, doi: 10.1016/j.jobe.2021.103393.
[39] J. Wang, J. Zhang, D. Cao, H. Dang, and B. Ding, "Comparison of recycled aggregate treatment methods on the performance for recycled concrete," *Constr. Build. Mater.*, vol. 234, p. 117366, 2020, doi: 10.1016/j.conbuildmat.2019.117366.
[40] D. V. Bompa and A. Y. Elghazouli, "Creep properties of recycled tyre rubber concrete," *Constr. Build. Mater.*, vol. 209, pp. 126–134, 2019, doi: 10.1016/j.conbuildmat.2019.03.127.
[41] C. Gu *et al.*, "Feasibility of recycling sewage sludge ash in ultra-high performance concrete: Volume deformation, microstructure and ecological evaluation," *Constr. Build. Mater.*, vol. 318, p. 125823, 2022, doi: 10.1016/j.conbuildmat.2021.125823.
[42] V. W. Y. Tam and C. M. Tam, "A new approach in assessing cement mortar remains on recycled aggregate," *Mag. Concr. Res.*, vol. 59, no. 6, pp. 413–422, 2007, doi: 10.1680/macr.2007.59.6.413.
[43] L. Evangelista and J. de Brito, "Mechanical behaviour of concrete made with fine recycled concrete aggregates," *Cem. Concr. Compos.*, vol. 29, no. 5, pp. 397–401, 2007, doi: 10.1016/j.cemconcomp.2006.12.004.
[44] A. Verma, "Durability and strength characteristics of concrete through various experiments using treated recycled aggregates," *J. Mater. Cycles Waste Manag.*, vol. 27, no. 4, pp. 2321–2340, 2025, doi: 10.1007/s10163-025-02235-2.
[45] ASTM C131/C131M-20, *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. Pennsylvania: ASTM International, 2020.
[46] IS 2386 (Part IV)–1963, *Methods of Test for Aggregates for Concrete: Mechanical Properties*. Bureau of Indian Standards, 1963.
[47] C. S. Rangel, M. Amario, M. Pepe, E. Martinelli, and R. D. T. Filho, "Influence of wetting and drying cycles on physical and mechanical behavior of recycled aggregate concrete," *Materials (Basel).*, vol. 13, no. 24, pp. 1–20, 2020, doi: 10.3390/ma13245675.
[48] F. Wu, X. Chen, and H. Chen, "A novel rotating drum abrasion apparatus and optimized testing method for concrete considering debris flow parameters," *Constr. Build. Mater.*, vol. 481, p. 141592, 2025, doi: 10.1016/j.conbuildmat.2025.141592.
[49] F. Wu, X. Chen, and X. Li, "Abrasion performance of cement

mortar by debris flow," *Tribol. Int.*, vol. 175, p. 107839, 2022, doi: 10.1016/j.triboint.2022.107839.

[50] M. A. Yazdi, E. Dejager, M. Debraekeleer, E. Gruyaert, K. Van Tittelboom, and N. De Belie, "Bond strength between concrete and repair mortar and its relation with concrete removal techniques and substrate composition," *Constr. Build. Mater.*, vol. 230, p. 116900, 2020, doi: 10.1016/j.conbuildmat.2019.116900.

[51] IS 2386 (Part I)–1963, *Methods of Test for Aggregates for Concrete: Particle Size and Shape*. Bureau of Indian Standards, 1963.

[52] IS 383:2016. (2016), *Coarse and Fine Aggregate for Concrete – Specification*. Bureau of Indian Standards, 2016.

[53] ASTM C136/C136M-19, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. Pennsylvania: ASTM International, 2019.

[54] BS EN 12620:2013, *Aggregates for concrete*. London: British Standards Institution, 2013.

[55] IS 2386 (Part III)–1963, *Methods of Test for Aggregates for Concrete: Specific Gravity, Density, Voids, Absorption and Bulking*. Bureau of Indian Standards, 1963.

[56] ASTM C127-15, *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. Pennsylvania: ASTM International, 2015.

[57] ASTM C128-15, *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. Pennsylvania: ASTM International, 2015.

[58] IS 2386 (Part V)–1963, *Methods of Test for Aggregates for Concrete: Soundness*. Bureau of Indian Standards, 1963.

[59] ASTM C88/C88M-18, *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*. Pennsylvania: ASTM International, 2018.

[60] ASTM C33/C33M-18, *Standard Specification for Concrete Aggregates*. Pennsylvania: ASTM International, 2018.

[61] A. S. Alqarni, H. Abbas, K. M. Al-shwikh, and Y. A. Al-salloum, "Influence of Treatment Methods of Recycled Concrete Aggregate on Behavior of High Strength Concrete," *Buildings*, vol. 12, no. 4, p. 494, 2022, doi: 10.3390/buildings12040494.

[62] A. Verma, V. Sarath Babu, and S. Arunachalam, "Influence of mixing approaches on strength and durability properties of treated recycled aggregate concrete," *Struct. Concr.*, vol. 22, no. S1, pp. E121–E142, 2021, doi: 10.1002/suco.202000221.

[63] M. Wijayasundara, P. Mendis, and T. Ngo, "Comparative assessment of the benefits associated with the absorption of CO2 with the use of RCA in structural concrete," *J. Clean. Prod.*, vol. 158, pp. 285–295, 2017, doi: 10.1016/j.jclepro.2017.03.230.

[64] I. Nováková and K. Mikulica, "Properties of Concrete with Partial Replacement of Natural Aggregate by Recycled Concrete Aggregates from Precast Production," *Procedia Eng.*, vol. 151, pp. 360–367, 2016, doi: 10.1016/j.proeng.2016.07.387.

[65] A. C. Trandafir and B. A. Erickson, "Stiffness Degradation and Yielding of EPS Geofoam under Cyclic Loading," *J. Mater. Civ. Eng.*, vol. 24, no. 1, pp. 119–124, 2012, doi: 10.1061/(asce)mt.1943-5533.0000362.

[66] R. Nålsund, "Influence of mineral grain size, grain size distribution and micro-cracks on rocks mechanical strength," *14 th Euroseminar Microsc. Appl. to Build. Mater.*, pp. 10–14, 2013.

[67] B. Czinder and Á. Török, "Strength and abrasive properties of andesite: relationships between strength parameters measured on cylindrical test specimens and micro-Deval values—a tool for durability assessment," *Bull. Eng. Geol. Environ.*, vol. 80, no. 12, pp. 8871–8889, 2021, doi: 10.1007/s10064-020-01983-9.

[68] M. D. Safiuddin, M. A. Salam, and M. Z. Jumaat, "Effects of recycled concrete aggregate on the fresh properties of self-consolidating concrete," *Arch. Civ. Mech. Eng.*, vol. 11, no. 4, pp. 1023–1041, 2011, doi: 10.1016/S1644-9665(12)60093-4.

[69] S. Ismail and M. Ramli, "Mechanical strength and drying shrinkage properties of concrete containing treated coarse recycled concrete aggregates," *Constr. Build. Mater.*, vol. 68, pp. 726–739, 2014, doi: 10.1016/j.conbuildmat.2014.06.058.

[70] A. Verma, V. Sarath Babu, and S. Arunachalam, "Influence of mixing approaches on strength and durability properties of treated recycled aggregate concrete," *Struct. Concr.*, vol. 22, no. S1, pp. E121–E142, 2021, doi: 10.1002/suco.202000221.

[71] A. Alibeigibeni, F. Stochino, M. Zucca, and F. L. Gayarre, "Enhancing Concrete Sustainability: A Critical Review of the Performance of Recycled Concrete Aggregates (RCAs) in Structural Concrete," *Buildings*, vol. 15, no. 8, pp. 1–25, 2025, doi: 10.3390/buildings15081361.