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Aytekin, B., Holthuizen, P., Nedeljković, M., Schlangen, E., & Copuroglu, O. (2026). Role of parent concrete characteristics and crushing technique on selectively demolished RCA quality. *Construction and Building Materials*, *539*, Article 147484. https://doi.org/10.1016/j.conbuildmat.2026.147484

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Construction and Building Materials 539 (2026) 147484

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Role of parent concrete characteristics and crushing technique on selectively demolished RCA quality

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ARTICLE INFO

Keywords:
Selective demolition
RCA
Parent concrete characterization
Recycling techniques
Microstructure
Smart liberator
Impact crusher
Microcrack

ABSTRACT

This study evaluates how parent concrete characteristics and crushing techniques influence the physical, microstructural, and mechanical properties of RCA. Four parent concretes from an end-of-life viaduct (beam, column, abutment-wall, and foundation) were characterized for cement paste microstructure and volumetric composition prior to recycling. Two crushing techniques were applied: a conventional high-energy Impact Crusher (IC) and the vibration-based Smart Liberator (SL). Feature importance analysis showed that RCA behaviour reflects a combined influence of processing technique and parent concrete. RCA produced from concrete with higher air-void content (≈4%) facilitated mortar detachment and exhibited the lowest water absorption (≈1.7%) and fastest saturation rate (~3 days). Conversely, RCA derived from concrete with a dense, cohesive, and well-hydrated paste retained more attached cement paste, resulting in the highest water absorption (>7%) and slowest saturation (~6 days). Despite exhibiting similar compressive strengths, these two parent concretes produced fundamentally different RCA morphologies and absorption behaviours, highlighting the governing role of W/C ratio–related properties, such as capillary porosity and hydration degree, together with paste volume and air-void content in determining RCA quality. The crushing technique also played an important role in defining coarse RCA morphology and surface texture. The IC produced angular particles with irregular surfaces and localized microcracking, especially in dense, low-porosity concretes. These stress-induced defects increased surface roughness and open porosity, raising water absorption and reducing abrasion resistance. In contrast, the SL applies selective attrition and shear along the aggregate–paste interface, removing attached mortar without fracturing the aggregate core and yielding smoother, denser particles with minimal internal damage.

1. Introduction

In the coming decade, the demand for sustainable construction materials will intensify as the construction industry strives to align with the principles of the Circular Economy (CE) [1]. Driven by global urbanization and infrastructure expansion, there is an urgent need to balance material consumption with environmental responsibility. Recycled Concrete Aggregate (RCA) has emerged as a promising solution to this challenge, to reduce the environmental impact of concrete production by promoting the reuse of construction and demolition waste instead of using natural aggregates. However, despite its environmental benefits and technical potential, the widespread application of RCA remains limited, particularly in structural concrete, due to strict national standards and regulatory barriers [2–4]. These restrictions are largely motivated by concerns over RCA's higher porosity [5,6], and water absorption [7,8], lower abrasion resistance [9,10], inconsistent quality [11,12], and potential contamination with deleterious substances such as chlorides and sulphates [13]. This limitation is not due to a lack of research, but rather to the inconsistency of results reported in the literature, often stemming from the complex and variable composition of RCA. Consequently, despite substantial scientific efforts, uncertainty remains regarding RCA's reliability in structural applications, which continues to hinder its broader acceptance and integration into concrete standards.

A key factor contributing to this variability is the presence of attached cement paste adhering to the original natural aggregates in

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https://doi.org/10.1016/j.conbuildmat.2026.147484
Received 4 February 2026; Received in revised form 9 July 2026; Accepted 15 July 2026
Available online 17 July 2026
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RCA. This attached cement paste is typically more porous, less dense, and mechanically weaker than the natural aggregate (NA) itself, reducing the overall performance of RCA compared to NA. Its quantity and quality are not random; they are fundamentally shaped by the properties of the parent concrete, the crushing process, and the original particle size distribution of the NA in parent concrete [14,15]. While researchers agree that both parent concrete properties and crushing techniques influence RCA characteristics, the complexity of these relationships is often oversimplified in the literature. Most studies rely heavily on parent concrete compressive strength as the key indicator [16–21], yet this single parameter does not fully capture the underlying factors that govern RCA behaviour. For instance, some suggest that [14,20] high-strength concrete leads to denser, less porous RCA, while others [22,23] argue that low-strength concrete yields cleaner RCA due to easier mortar detachment. These inconsistencies reflect the complex nature of RCA and highlight the limitations of compressive strength as a single parameter. In fact, the attached cement paste inherits its properties from the cement paste and aggregate phases of the parent concrete. Cement paste characteristics such as the water-to-cement (W/C) ratio, degree of hydration, porosity, cement paste volume, and the type and amount of supplementary cementitious materials strongly affect the microstructure and quality of the attached cement paste [24]. On the other hand, aggregate properties and mixture design such as aggregate-to-paste ratio, maximum aggregate size (Dmax), and air void content also influence how the concrete breaks apart during crushing and how much cement paste remains attached to the aggregates [9,25]. To address this knowledge gap, it is necessary to move beyond simplified indicators and investigate the intrinsic properties of both the cement paste and aggregate phases of the parent concrete. A more detailed characterization of these components can reveal how and why RCA properties vary, enabling better predictions of performance and supporting strategies like selective demolition, quality control, and high-performance RCA-based concrete.

In addition to the intrinsic properties of the parent concrete, the crushing mechanism and technique critically determine the quality of RCA [15,26]. The way concrete is crushed down during recycling directly affects the physical and morphological characteristics of RCA, including particle size distribution, fine (<0.063 mm) content, particle shape, surface texture, micro-crack development, and attached cement paste content [27,28]. These differences are not merely mechanical side effects; they have implications for the durability, strength, and absorption characteristics of RCA.

Crushing processes are governed by four primary mechanisms: impact, compression, attrition, and shear, often used in combination depending on the crusher type and material characteristic [29]. Impact crushing, horizontal and vertical shaft impactors, involves high-speed collisions that promote fracture along weak planes such as the interfacial transition zones (ITZs), leading to more spherical aggregates with cleaner surfaces and less attached cement paste. These crushers are especially effective in secondary or tertiary stages, producing RCA with reduced flakiness and improved texture [11,30]. Compression, used in jaw and cone crushers, exerts force between two hard surfaces. Jaw crushers, commonly employed as primary crushers, tend to produce angular particles with significant amounts of attached cement paste due to their crushing along major stress planes [26,31]. Cone crushers, on the other hand, apply continuous compressive force in the secondary stage, which enhances particle refinement and promotes further liberation of cement paste. Attrition occurs when particles rub against each other or against machine surfaces, causing gradual material reduction. Although energy-intensive, this mechanism can promote the removal of attached cement paste, particularly in parent concretes containing weaker and more brittle cement paste. Shear, often integrated with other mechanisms in devices like single-roll crushers, causes materials to cleave or trim along weaker zones, aiding selective fragmentation without over-grinding the aggregates.

The choice and configuration of crushing equipment, particularly the number of processing stages, play a decisive role in RCA quality [9,32,33]. Single-stage systems often leave substantial amounts of attached cement paste, while multi-stage setups significantly reduce it [33]. For instance, Nagataki et al. (2004) investigated 5–20 mm RCA using a three-stage crushing sequence consisting of an initial jaw crusher followed by two mechanical grinding stages [34]. They reported a 35–50% reduction in water absorption after the third crushing stage; however, the yield of the coarse fraction decreased from about 60–35%, indicating that a significant portion of the original coarse aggregates was converted into fines during repeated processing. Ulsen et al. (2013) found that using a vertical shaft impactor as a third stage led to a 60% reduction in water absorption for fine RCA, relative to the sand fraction of the reference C&D waste [35]. Similarly, Pedro et al. (2015) demonstrated that a two-stage crushing sequence, jaw crusher followed by a hammer mill, reduced the water absorption of coarse RCA by approximately 10–20% [36]. These improvements originate from enhanced liberation of NA from the porous cement matrix, leading to denser RCA particles with lower porosity [28,36]. However, the higher impact energy and repetitive mechanical loading associated with intensive crushing can also introduce internal stress and consequently damage.

1.1. Research significance

Despite extensive research, the literature continues to report conflicting findings and limited reproducibility regarding RCA quality. The main source of this inconsistency lies in the indiscriminate mixing of demolition rubble from multiple origins, resulting in RCA derived from concretes with unknown microstructural and volumetric characteristics and varying degrees of environmental deterioration. Without distinguishing between these parent concretes, RCA variability cannot be reliably interpreted. Since RCA inherits its physical and chemical characteristics from the parent concrete, the absence of systematic source characterization leads directly to unpredictable RCA performance. Beyond these material differences, the recycling technique also governs how concrete fractures and how much cement paste remains attached to the aggregates, further increasing variability when different crushers are used. High-energy impact crushers, in particular, can induce microcracks within aggregates and residual mortar, increasing porosity and reducing mechanical integrity [15,37]. However, the extent of this microstructural damage and its dependence on parent concrete properties, such as stiffness, porosity, and air-void structure, remain largely unverified. Consequently, most existing research either neglects systematic parent concrete characterization or focuses solely on conventional crushing methods, making it difficult to separate the effects of material composition from those of the processing technique. While selective demolition represents a promising strategy for enhancing RCA quality, it has yet to be discussed or systematically explored in relation to parent concrete characterization, leaving a critical research gap unaddressed. This gap limits our understanding of the fundamental relationships between end-of-life concrete composition, fracture mechanisms, and RCA performance, thereby constraining the reliable structural use of RCA and hindering its integration into performance-based material standards.

To bridge this gap, this study systematically investigates the combined effects of parent concrete characteristics and crushing technique on the physicochemical and morphological properties of RCA. Four different parent concretes, sourced from different elements of an end-of-life viaduct (beam, column, abutment-wall, and foundation), were thoroughly characterized prior to recycling. All structural members were first processed using a conventional IC, followed by the Smart Liberator (SL) an innovative selective attrition-based method designed to remove attached cement paste. While the SL has shown promising results in laboratory-scale trials [38,39] and pilot-scale infrastructure recycling applications [40], limited research has systematically evaluated its performance in relation to detailed parent concrete characteristics. In this study therefore investigates the behaviour of SL-processed

RCA obtained from well-characterized parent concretes with distinct microstructural features, including variations in W/C ratio, porosity, hydration degree, paste volume, and air-void structure. Through integrated microstructural and morphological analyses, including microcrack and surface texture evaluation, this study elucidates how crushing mechanisms and inherited parent concrete characteristics jointly shape RCA morphology, microstructure, and overall performance. By explicitly linking RCA properties to both material origin and processing mechanism, this research improves the understanding of RCA variability and supports the development of selective demolition strategies for high-quality, circular concrete production.

2. Materials and method

2.1. Concrete-rubble sources

In this study, RCA was obtained from a Dutch viaduct. Prior to demolition, the parent concrete was comprehensively characterized using a combination of non-destructive techniques [41] and destructive methods, including core extraction and laboratory testing [24] (Fig. 1 – Step 1).

A total of 35 core samples were extracted from different structural members of the viaduct, namely beams (8 cores), columns (9 cores), abutment-walls (12 cores), and foundations (6 cores), as summarized in Table 1. The sampling procedure followed ASTM C42/C42M and ASTM C823 standards, ensuring representative coverage of each structural element while minimizing local variability.

The extracted cores were used for mechanical and microstructural characterization. The determination of in-situ compressive strength and density was carried out in a previous study by Nedeljković et al. [41], representing commonly measurable properties in practice. The remaining cores were analysed in a subsequent study by Aytekin et al. [24], where thin and polished sections were prepared for detailed microstructural characterization. This included quantification of porosity, hydration degree, estimation of W/C ratio, and determination of volumetric composition (paste, aggregates, and air voids).

In the present study, these previously established datasets were integrated to evaluate the relationship between parent concrete characteristics and the resulting RCA properties. All structural members were originally produced using river gravel aggregates and Portland cement [24,41]; therefore, the main differences between the parent concretes are associated with their mixture proportions and resulting

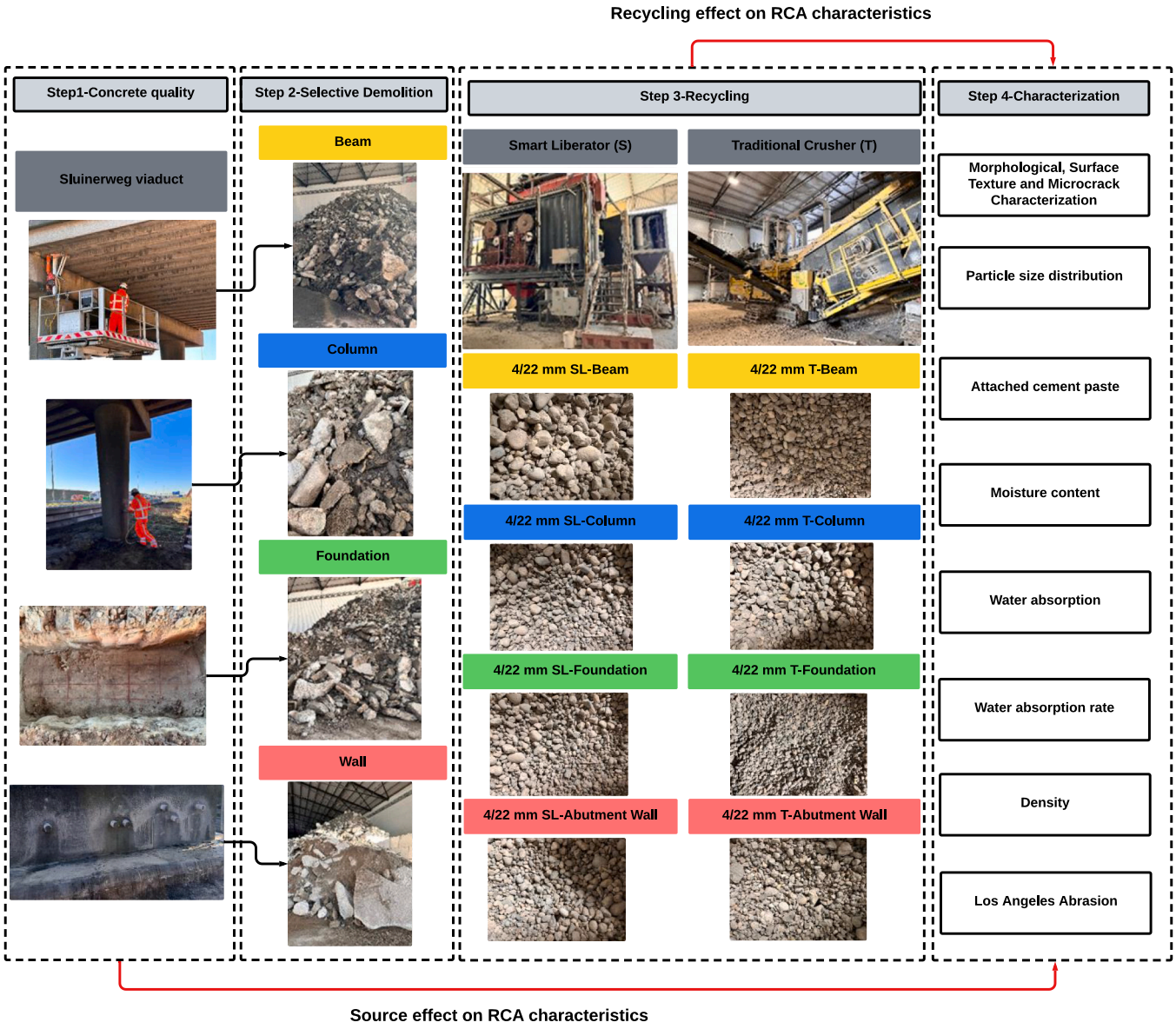

Fig. 1. Overview of concrete demolition, recycling, and characterization processes.

Table 1
Characterization of parent concrete: material composition, mechanical properties, microstructure, and mixture composition.

	Material composition and mechanical properties of parent concrete elements							
	Bridge member	**Cement type**	**Aggregate type**	**Number of cores**	**In situ cylindrical compressive strength [MPa]**		**Density [kg/m3]**	
Nedeljković et al. [41]	Beam	Portland	River gravel and sand	8	87		2432	
	Column	Portland	River gravel and sand	9	71		2397	
	Abutment-walls	Portland	River gravel and sand	12	64		2380	
	Foundation	Portland	River gravel and sand	6	67		2327	
	Quantitative analysis of cement paste microstructure							
Aytekin et al. [24]	**Bridge member**	**Unhydrated cement (%)**	**Hydration products (%)**	**Capillary Porosity (%)**	**Estimated W/C**	**Hydration degree**	**Cement Content (kg/m^3)**	**Water content (kg/m^3)**
	Beam	10.7 ± 4.4	84.0 ± 5.7	5.3 ± 3.0	0.29 ± 0.03	0.80 ± 0.08	390 ± 10	114 ± 4
	Column	6.1 ± 2.4	84.7 ± 3.7	9.2 ± 3.0	0.34 ± 0.03	0.87 ± 0.05	353 ± 11	122 ± 3
	Abutment-walls	3.1 ± 1.1	86.4 ± 3.0	10.5 ± 3.0	0.38 ± 0.03	0.93 ± 0.02	334 ± 10	125 ± 4
	Foundation	6.7 ± 2.9	90.5 ± 2.5	2.8 ± 1.5	0.30 ± 0.02	0.87 ± 0.05	316 ± 11	95 ± 5
	Volumetric percent composition of parent concrete mixtures							
		Paste		**Air void**		**Coarse Aggregate**		**Fine Aggregate**
	Beam	22		1.4		52		25
	Column	27		1		37		35
	Abutment-walls	25		0.9		42		32
	Foundation	17		4.3		52		27
	Coarse aggregate particle size distribution of parent concrete							
		Cumulative Percentage (%)						
	Particle Size (mm)	**40**	**32**	**22**	**16**	**11.2**	**8**	**4**
	Beam	100	100	93	87	71	60	32
	Column	100	95	84	77	65	55	48
	Abutment-walls	100	100	78	72	64	51	41
	Foundation	100	100	78	69	62	54	34

microstructural characteristics rather than differences in constituent material type. The results indicate that structural members exhibit distinct mechanical and microstructural properties, despite originating from the same structure. Although the compressive strength values fall within a relatively narrow range (64–87 MPa), substantial variability is observed in key microstructural parameters, including porosity (2.8–10.5%), estimated W/C ratio (0.29–0.38) and air-void content (0.9–4.3%).

Based on these findings, selective demolition was applied to preserve the distinction between different parent concrete types (Step 2). This approach enables a controlled assessment of the influence of parent concrete variability on RCA properties, which is not possible using conventional mixed-demolition practices. Following demolition, the concrete elements were subjected to primary crushing using an IC, reducing the material to particle sizes below 55 mm to facilitate subsequent processing stages. To investigate the influence of recycling techniques, the materials were further processed using two approaches (Step 3). The first approach represents conventional recycling practice in the Netherlands, namely IC, which induces fragmentation through high-energy impacts [42]. The second approach involves the SL, a technology designed to selectively remove attached cement paste through mechanical abrasion and shear, thereby producing cleaner aggregate surfaces [39,43]. The SL process was applied after the initial IC stage. Therefore, the SL-treated aggregates were pre-conditioned by impact crushing.

In total, eight RCA batches were produced, representing four parent concrete types and two recycling techniques within the 4–22 mm size range. After processing, the physical and mechanical properties of all RCA samples were determined (Step 4). The results were subsequently analyzed to establish relationships between parent concrete characteristics, crushing technique, and the resulting RCA properties.

2.2. Recycling procedure

In this study, two recycling techniques were employed: a conventional Impact Crusher (IC) and the advanced Smart Liberator (SL) system.

The impact crusher used in this study fractures concrete through high-speed impacts rather than compressive forces (Fig. 2). Material fed into the crusher is struck by blow bars on a rotating rotor and propelled against impact plates, where repeated collisions progressively reduce the particle size. Final particle size is controlled by the adjustable aprons, and the processed RCA is discharged through the outlet opening [29,44].

The Smart Liberator is an advanced selective crushing method designed to improve RCA quality by efficiently separating concrete into its constituent materials (cement paste, sand, and gravel) while largely preserving the physical integrity of the aggregates [43]. The purpose of the machine is to achieve liberation of weaker material (such as attached cement paste) rather than intensive communition. In contrast to ordinary crushers, which break concrete mainly by high-energy impacts and compression, randomly crushing through both aggregates and paste, the SL applies controlled shearing, abrasion, and attrition forces at the aggregate–paste interface [45] (Fig. 2). This selective action promotes fracture within the weaker cement paste phase while avoiding excessive breakage of the aggregates themselves. By minimizing destructive fragmentation and emphasizing interface-level failure, the SL produces aggregates that retain their original shape, strength, and grading [43,45].

2.3. Fractionation and sampling of RCA

RCA is widely recognized as a heterogeneous material, with this

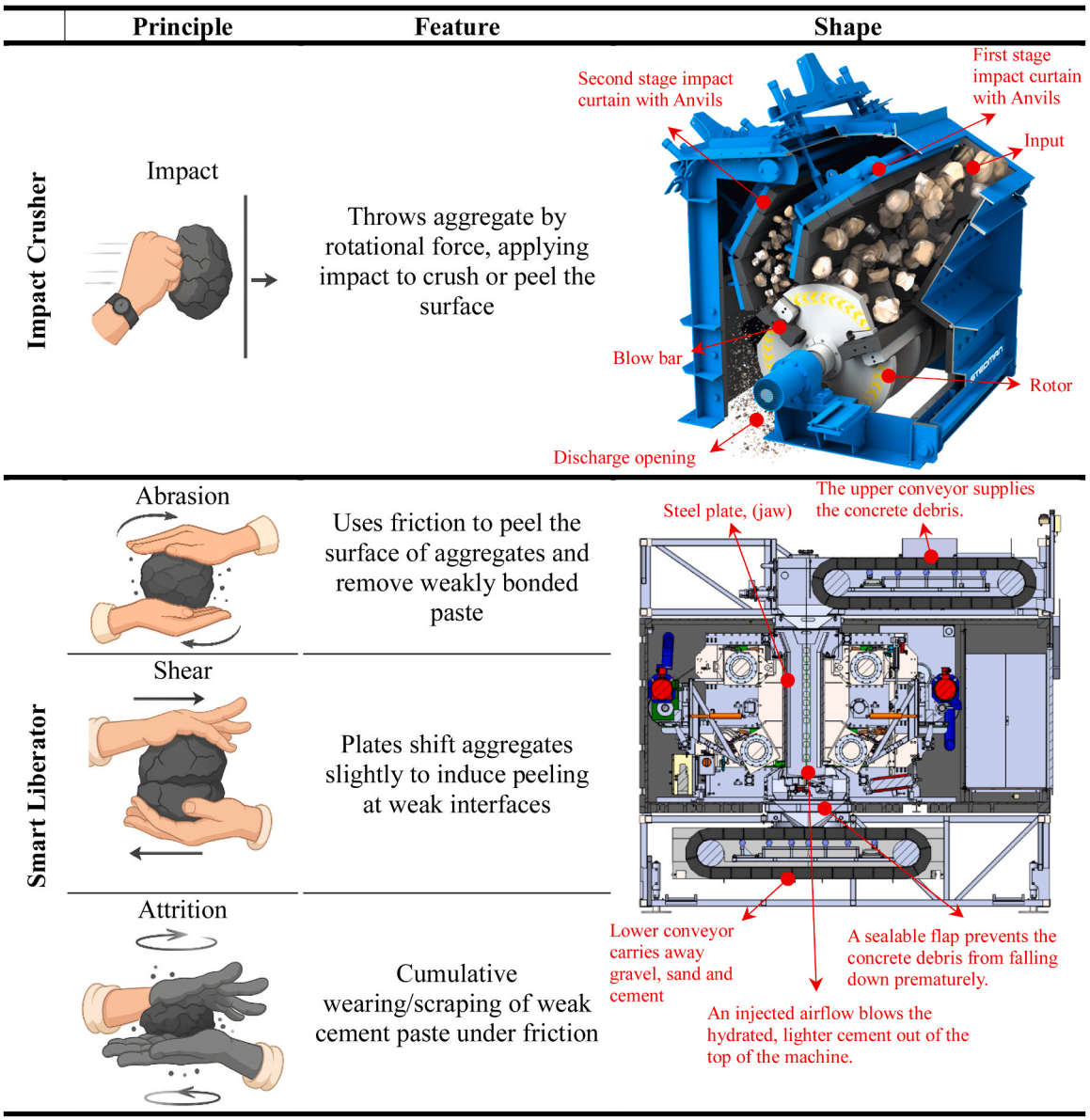

Fig. 2. Schematic representation of the mechanical forces and working principles of the Impact Crusher and Smart Liberator systems for concrete recycling. (The Smart Liberator image is adapted from [45] and the Impact Crusher image is adapted from [46]).

variability typically attributed to its intrinsic material composition. However, part of the observed heterogeneity may also arise from sampling inconsistencies, particularly when RCA is delivered and stored in large bulk bags. To evaluate this effect, the heterogeneity assessment was performed on RCA produced from the column concrete, selected as a representative parent concrete type. Sampling was conducted from three distinct locations within a single 1500 kg bulk bag: upper side, left bottom side, and right bottom side, to examine potential segregation effects during handling, transport, or storage (Fig. 3). This approach allowed the evaluation of how much of the apparent variability could be attributed to sampling practices rather than inherent material differences. Each sampled portion was subjected to sieve analysis to determine its particle size distribution. To ensure representativeness, the collected material was evenly spread on a plastic sheet and subdivided into smaller portions, from which three samples were randomly selected from each section (Fig. 3). This randomized sampling method minimized bias and ensured an accurate representation of the particle size distribution within each fraction.

The sieve analysis revealed noticeable differences in particle size distribution across the three sampling locations, as illustrated by the particle size distribution curves (Fig. 3). These differences indicated that coarse RCA particles were not uniformly distributed throughout the bulk bag, highlighting the occurrence of material segregation a common issue in bulk material handling. As the material was used progressively from the top toward the bottom of the bag, changes in particle-size distribution became apparent. Although such variations could initially be interpreted as material heterogeneity, they were primarily caused by sampling inconsistencies rather than intrinsic differences in the RCA itself. To minimize this effect, a fractionation procedure was applied: the entire content of the bulk bag was sieved to achieve a more uniform representation of RCA properties. This procedure was applied for all types of RCA, encompassing all parent concretes and both crushing techniques. The material was subsequently divided into three standardized size fractions, 4–8 mm, 8–16 mm, and 16–22 mm. This classification ensured that subsequent analyses were performed on well-defined and comparable size classes, thereby reducing variability and enhancing the reliability of the results.

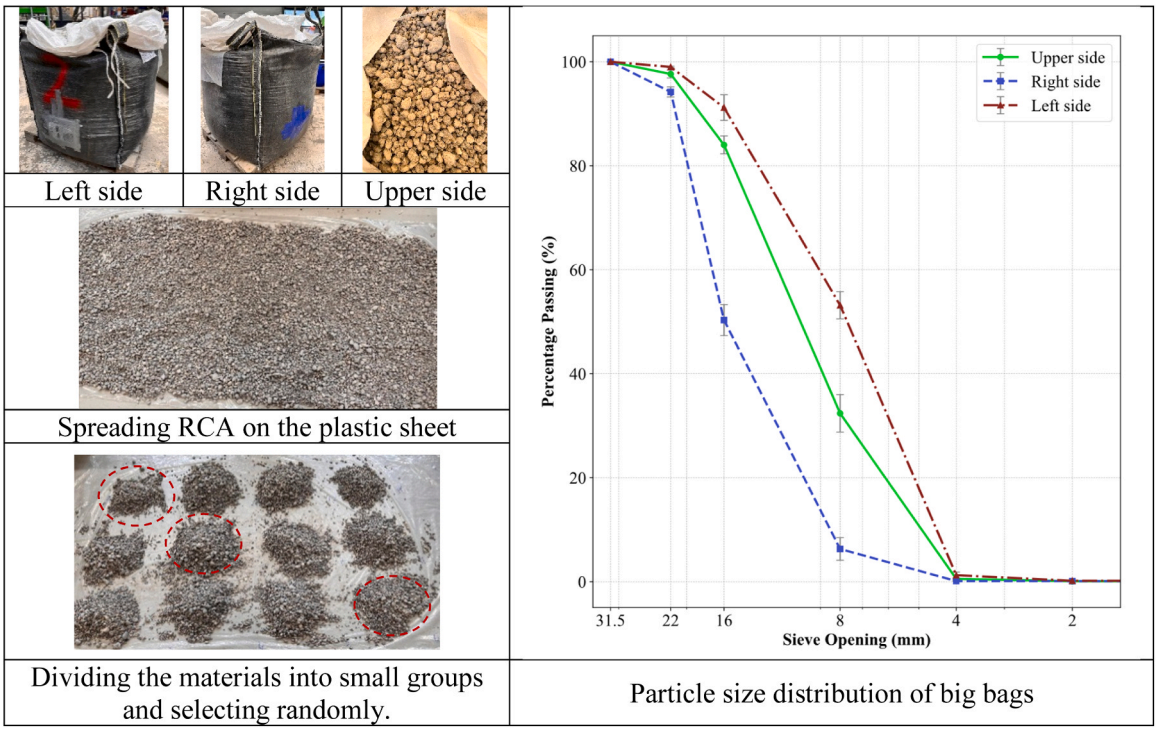

Fig. 3. The process of the coarse RCA heterogeneity assessment (RCA produced from the Column).

2.4. RCA characterization

RCA samples were produced from four parent concretes (beam, column, abutment-walls, and foundation) and processed using two crushing techniques (IC and SL). For each parent concrete and crushing technique, the resulting aggregates were separated into three size fractions: 4–8 mm, 8–16 mm, and 16–22 mm. All physical and mechanical tests were performed for each parent concrete–crusher combination, resulting in eight RCA groups analysed across the three size fractions. Natural river gravel was used as a reference aggregate.

2.4.1. Visual and surface texture characterization

Surface micrographs of aggregates were captured using a Keyence VHX−7000 digital microscope at 100 × magnification (Fig. 4). For each parent concrete and crusher combination, ten particles were randomly selected to obtain a representative and unbiased set of surface images. The surface texture properties of coarse RCA was assessed using GelSight Mobile2 (Fig. 4), a high-resolution (<1 μm) tactile imaging device [47]. The device works by pressing a soft elastomeric sensor onto the aggregate surface, which deforms to replicate the texture at a microscopic level. Using optical imaging and structured lighting, the deformation pattern is analysed to reconstruct the 3D surface topography. This method enables quantification of surface roughness, texture depth, and microstructural features, providing quantitative texture data with sub-micron resolution.

2.4.2. X-ray computed tomography (CT) analysis

High-resolution X-ray CT scans were carried out using a TESCAN CoreTOM system to determine aggregate shape and internal structure. A 0.75 mm Sn filter was applied to optimize image quality, with a resolution of 25 μm, a source–detector distance of 650 mm, and a source–object distance of 151 mm. Each RCA size fraction (4–8 mm, 8–16 mm, and 16–22 mm) was placed in a separate cylindrical plastic container (50 mm diameter × 100 mm height) and scanned individually to ensure sample stability and minimize particle movement during acquisition. The acquired CT projections were reconstructed using Panthera software, and the processed CT slices were analyzed in Dragonfly ORS to quantify aggregate shape parameters (e.g., elongation, flatness, sphericity). In addition to these shape descriptors, 3D surface roughness was computed using the roughness-XYZ method described by Heenan (2020), implemented through Dragonfly's surface-mesh analysis tools [48]. This method evaluates local height variability in the X, Y, and Z directions by extracting the surface mesh of each particle and calculating the standard deviation of vertex coordinates around locally fitted planes. To further investigate internal damage, additional ultra-high-resolution CT scans were performed at a voxel size of 5 μm. The primary objective of this analysis was to verify the presence of internal cracking within RCA particles and to qualitatively compare the internal damage associated with different crushing techniques, rather than to perform a quantitative crack characterization. For each parent concrete type, crusher type, and particle size fraction, five individual RCA particles were randomly selected and scanned one by one to capture internal cracking and defect morphology. This approach enabled the visualization of microcrack formation and propagation within RCA particles, providing insight into the relationship between crushing technique, parent concrete characteristics, and RCA integrity.

2.4.3. Physical and mechanical testing

The physical and mechanical properties of the aggregates were characterized through particle size distribution, Los Angeles (LA) abrasion resistance, and moisture content tests in accordance with the relevant standards [49–51]. In all cases, representative samples were obtained from each RCA group and size fraction to ensure consistency and reproducibility of the results.

Particle size distribution [49] was determined by dry sieving using a stack of standard sieves covering the required size range. Prior to testing, the samples were oven-dried at 75 °C to remove residual moisture. Each sample was then mechanically sieved for 5 min to ensure complete particle separation. The mass retained on each sieve was recorded, and the cumulative passing percentage was calculated to generate the particle-size distribution curve.

LA abrasion resistance [50] was evaluated using a standard LA testing machine. The 5 kg of aggregate, together with a defined number of steel balls, was placed in the rotating drum and subjected to impact

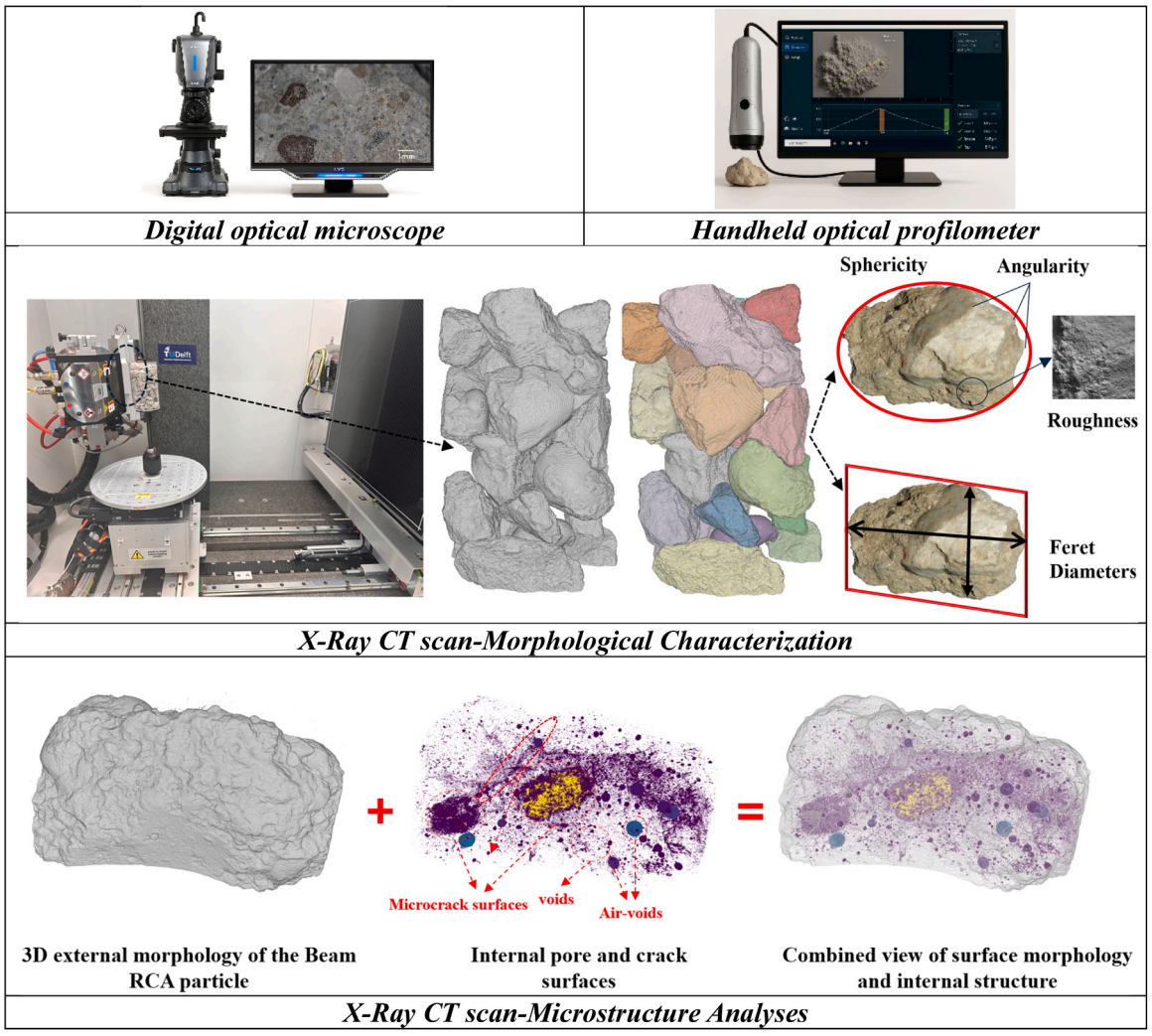

Fig. 4. Imaging and surface characterization techniques used for aggregate analysis.

and abrasion for the prescribed number of revolutions. After completion of the test, the material was removed, sieved through a 1.6 mm sieve, and the mass of the passing fraction was measured. The LA abrasion value was calculated as the percentage loss relative to the initial sample mass, providing an indicator of the aggregate resistance to mechanical degradation.

Moisture content [51] was determined by oven drying the samples at 75 °C until a constant mass was reached. Repeated measurements were taken to verify mass stabilization. The moisture content was calculated as the ratio of mass loss during drying to the final dry mass. The drying temperature of 75 °C was selected to avoid alteration of the attached cement paste and prevent decomposition of cementitious phases, which may occur at higher temperatures [52–54].

2.4.4. *Quantification of attached cement paste*

Determining the attached cement paste content in RCA remains challenging due to the absence of a standardized test procedure. Conventional chemical dissolution methods typically employ hydrochloric acid (HCl) to remove cement paste; however, this approach is unsuitable for RCA containing carbonate-based aggregates, as it can also dissolve calcite and other carbonate phases [55]. The parent concrete in this study primarily consisted of quartz-based aggregates [24], but the presence of chert with minor calcite impurities caused undesired dissolution during preliminary HCl treatments. To address this issue, the EN 1744–5 procedure was modified by replacing HCl with nitric acid (HNO_3) and optimizing the acid concentration to achieve complete paste removal while preserving aggregate integrity. A series of trials was performed using HNO_3 solutions with molarities ranging from 2 M to 8 M. Concentrations below 4 M resulted in incomplete paste dissolution even after prolonged treatment, whereas solutions above 6 M visibly etched the aggregate surface. Consequently, a 6 M HNO_3 solution was selected as the optimal concentration, offering rapid and complete removal of attached cement paste while preserving aggregate integrity. This concentration aligns with findings in the literature, where a 6 M HNO_3 solution has also been used successfully for determining attached cement paste on fine recycled aggregates [56], further supporting its suitability for this study. For each RCA size fraction, approximately 300 g of oven-dried sample was placed in a glass reaction vessel. The aggregates were fully immersed in the 6 M HNO_3 solution and subjected to gentle heating and continuous stirring to accelerate the chemical reaction and reduce the required dissolution time. The acid solution was replaced every 10 min, as its colour darkened due to dissolved cementitious materials. The process was repeated until the solution remained clear, indicating the complete removal of attached cement paste. The treated aggregates were then separated using filter paper to retain the coarse and fine aggregate particles while removing the dissolved cementitious residues and acid solution. Subsequently, the aggregates were thoroughly rinsed with tap water and oven-dried to a constant

mass before further testing. The attached cement paste content is obtained through:

$$\text{Attached cement paste } (\%) = \left(\frac{\text{Oven dried RCA mass before solution} - \text{Oven dried RCA mass after solution}}{\text{Oven dried RCA mass before solution}}\right) x100$$

.

2.4.5. Density and water absorption measurements

The particle density and water absorption capacity of the RCA were determined following the NEN-EN 1097–6 standard [57]. However, previous studies [58–60] have indicated that the standard 24-hour saturation period may not be sufficient for RCA due to its porous nature and prolonged water absorption behaviour. To ensure full saturation, all aggregate fractions were submerged in water for at least five days, a period determined based on the water absorption rate test results.

The water absorption rate (kinetics) of RCA was assessed following the approach proposed by Tam et al. [59]. The absorption rate was measured using a pycnometer method, where oven-dried aggregate samples were placed in a pycnometer, which was then filled with water up to the calibrated level. To remove air bubbles trapped between the aggregate particles, the pycnometer was manually agitated, rotated, and gently shaken multiple times before each measurement [61]. As RCA particles absorbed water, the water level inside the pycnometer gradually decreased. To maintain the original level, water was added incrementally, and the volume of added water was recorded over time. This approach allowed for real-time monitoring of the water absorption rate. Measurements were taken at 2, 5, 15, 30, and 60 min, followed by 2, 8, 24, 48, and 72 h, and continued until the pycnometer mass stabilized, indicating that the aggregates had reached full saturation.

2.4.6. Feature-importance analysis

To evaluate the relative influence of parent concrete characteristics and crushing technique on RCA properties, a data-driven feature-importance analysis was performed using a random forest regressor (scikit-learn, default hyperparameters). For each target property (attached cement paste content, water absorption, and LA abrasion) the model used the parent concrete's microstructural and volumetric parameters (unhydrated cement, porosity, hydration degree, paste content, air-void content, and coarse/fine aggregate proportions), together with a categorical variable representing the crushing technique (IC vs. SL, encoded numerically), as input.

Due to the limited number of RCA batches, the analysis was not intended to develop a validated predictive model. Instead, the model was used as an exploratory tool to provide an order-of-magnitude indication of whether the variability in RCA properties was more strongly associated with inherited parent concrete characteristics or with the applied crushing technique.

After training, the model-derived feature importances (mean decrease in impurity) were extracted and grouped into two categories:

(i) parent concrete–related parameters (all mix and microstructural descriptors), and
(ii) crushing technique (single encoded variable).

The contributions within each group were summed and normalized to 100%, yielding the relative importance (%) of parent concrete versus crushing technique for each RCA property. This procedure provides an interpretable, order-of-magnitude indication of whether variability in RCA behaviour is driven mainly by inherited material characteristics or by the applied crushing method, without overfitting to a specific predictive model.

3. Results

3.1. Appearance of coarse RCA

Fig. 5 illustrates the appearance of aggregates produced using two different crushing methods, IC and the SL, with natural river gravel as a reference. While NA (reference) is mineralogically a single-phase quartzitic rock material with smooth, weathered surfaces, RCA is a multiphase system consisting of NA partially or fully coated with hardened cement paste. As a result, the surface texture of RCA is influenced not only by crushing technique but also by the quality of the residual cement paste. In the images, the NA particle (Fig. 5a) displays a smooth, rounded surface typical of river gravel [62], with the magnified view confirming its homogeneity and minimal surface irregularities. In contrast, the IC RCA particle (Fig. 5b) appears highly angular and rough, with visible heterogeneity. The magnified (×100) view reveals surface fissures and remnants of attached cement paste, suggesting that high-energy impact crushing induces visible surface damage and inefficient removal of cement paste. On the other hand, the SL RCA particle (Fig. 5c) shows a more controlled liberation pattern. Its surface is rougher than the NA but more uniform than that of the impact-crushed RCA. The magnified image shows a large aggregate particle with a thin residual paste layer, suggesting that the SL's attrition and shear-based mechanism promotes selective paste removal without damaging the NA.

Building on the qualitative observations from Fig. 5, Fig. 6 provides a quantitative analysis of the surface morphology and roughness profiles of three different aggregate types. Each row comprises three key visual components: a grayscale image representing surface texture, a 3D surface plot illustrating height variations, and X-Y profile plots depicting surface roughness along two perpendicular directions. The grayscale images capture the macroscopic appearance of the particles, similar to those in Fig. 5 but with higher resolution. The NA particle appears relatively smooth with minor irregularities, characteristic of its rounded shape. In contrast, the IC RCA particle exhibits a significantly rougher and more jagged texture, indicative of the high fragmentation caused by impact crushing. The SL RCA particle presents an intermediate surface roughness, suggesting a more controlled breakage compared to the IC. The 3D surface plots and X–Y profiles further reinforce these observations, clearly distinguishing the relatively smooth and uniform SL surfaces from the more irregular topography of the IC-derived particles.

3.1.1. Morphological characterization of RCA

The roughness distributions of coarse NA and RCA derived from four parent concretes are shown in Fig. 7. Surface roughness varied primarily with crushing technique and particle size, while differences among parent concretes were comparatively limited. NA exhibited the lowest roughness values, reflecting their naturally rounded and compact surfaces. In contrast, RCA particles produced by the IC showed the highest roughness, followed by those from the SL.

Roughness generally increased with particle size, particularly in the 16–22 mm fraction, due to larger exposed fracture planes and more heterogeneous breakage patterns. However, the attached cement paste content (≈6–12% for SL and 13–19% for IC; see Fig. 11) remained relatively consistent across fractions, suggesting that surface roughness

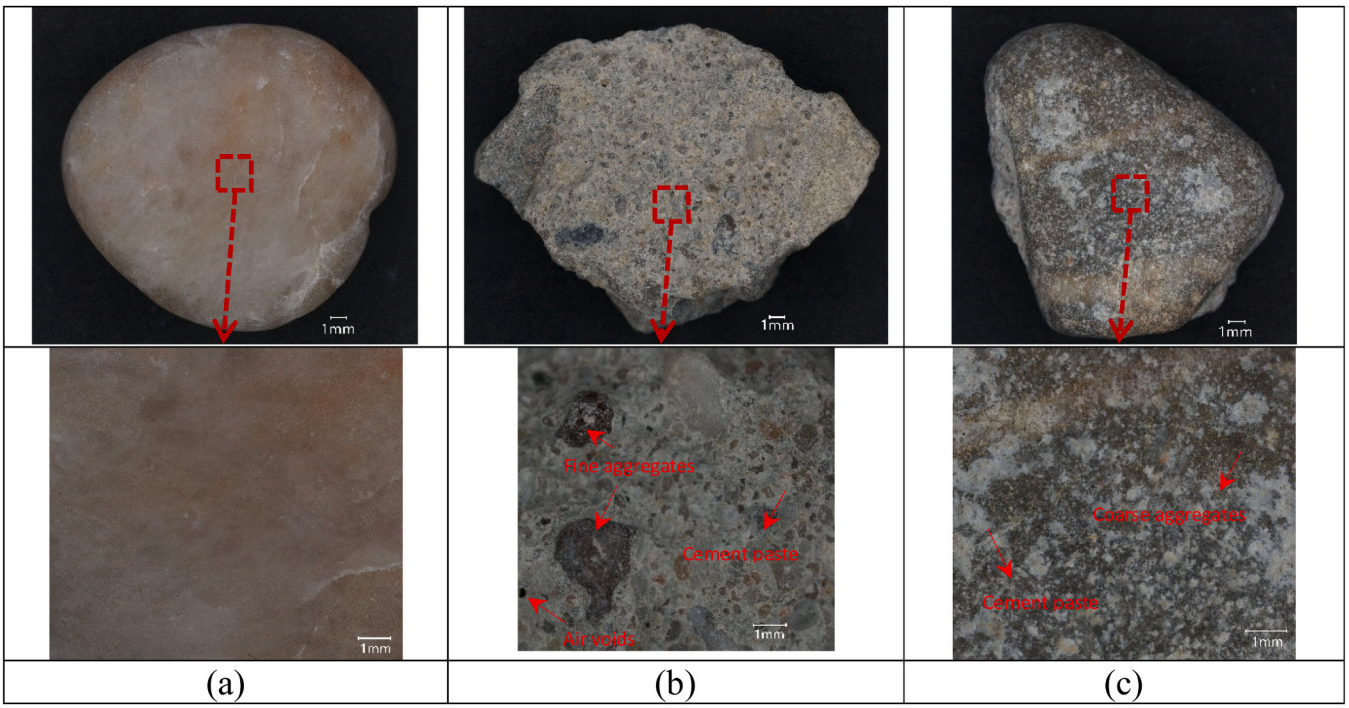

Fig. 5. Visual appearance of aggregate surface texture, a) river gravel particle, b) RCA particle from impact crusher, c) RCA particle from Smart Liberator (RCA produced from the Beam).

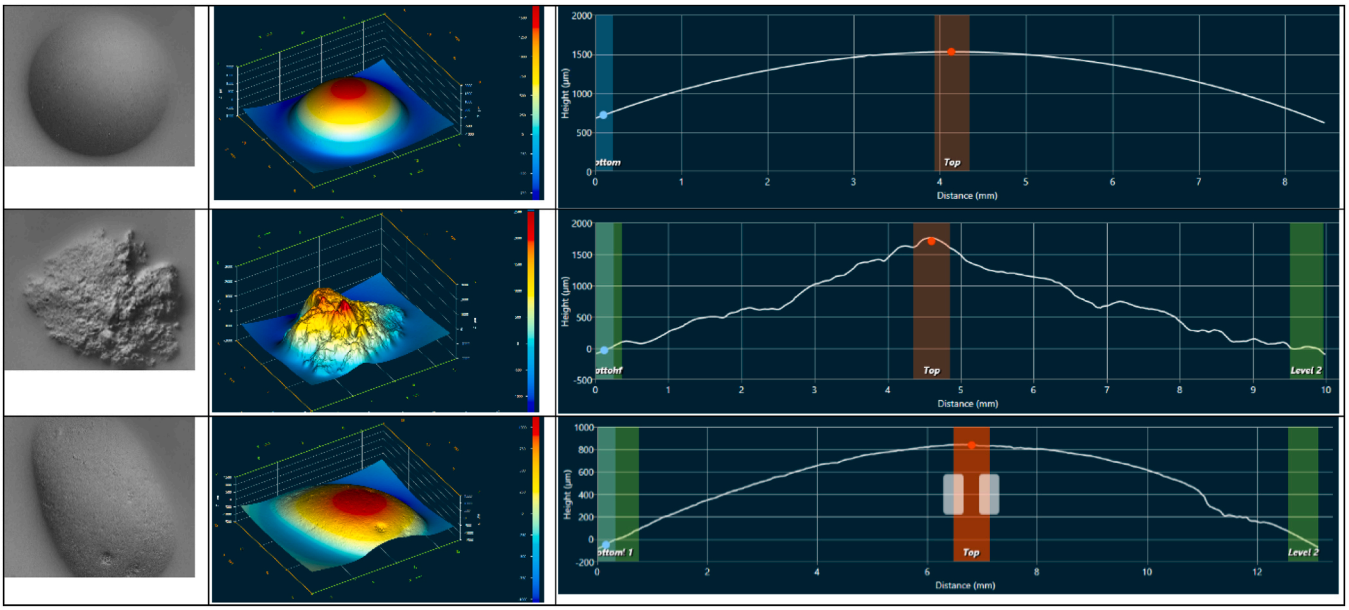

Fig. 6. Surface morphology and profile analysis of NA and RCA from different crushing techniques (Top row: NA, middle row: RCA particle from impact crusher, bottom row: RCA particle from Smart Liberator) (RCA produced from the Abutment-Wall).

is controlled more by fracture mode than by paste quantity. The influence of parent concrete type on surface roughness was negligible. Although Beam and Column concretes showed slightly higher roughness values than Wall and Foundation, these differences were small and within the variability expected for a given crushing technique.

In addition to surface roughness, the shape of aggregates commonly described by their flatness and elongation represents another key aspect of morphological characterization. Fig. 8 presents the distribution of aggregate shapes in terms of elongation (Max/Mean Feret) and flatness (Mean/Min Feret), classified according to the Zingg system [63], with representative aggregate images illustrating typical morphologies. The crushing technique proved to be the dominant factor influencing aggregate shape, while the characteristics of the parent concrete showed no clear effect. Therefore, the data are presented by crusher type and the NA reference, without distinguishing between individual parent concretes. The classification results indicate that most RCA fall within the cubical field, reflecting the predominance of equidimensional particles across both crushing techniques. RCA produced with the IC and the SL exhibit this shared tendency toward cubical geometry, closely aligning with the distribution observed for NA. This similarity arises because

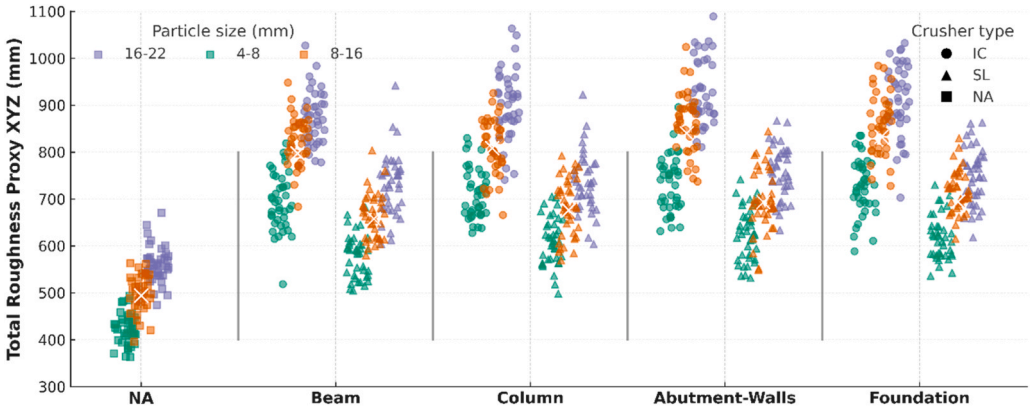

Fig. 7. Roughness distribution of RCA and NA across aggregate size fractions (4–8 mm, 8–16 mm, 16–22 mm) for different parent concretes and crushing techniques (IC vs. SL).

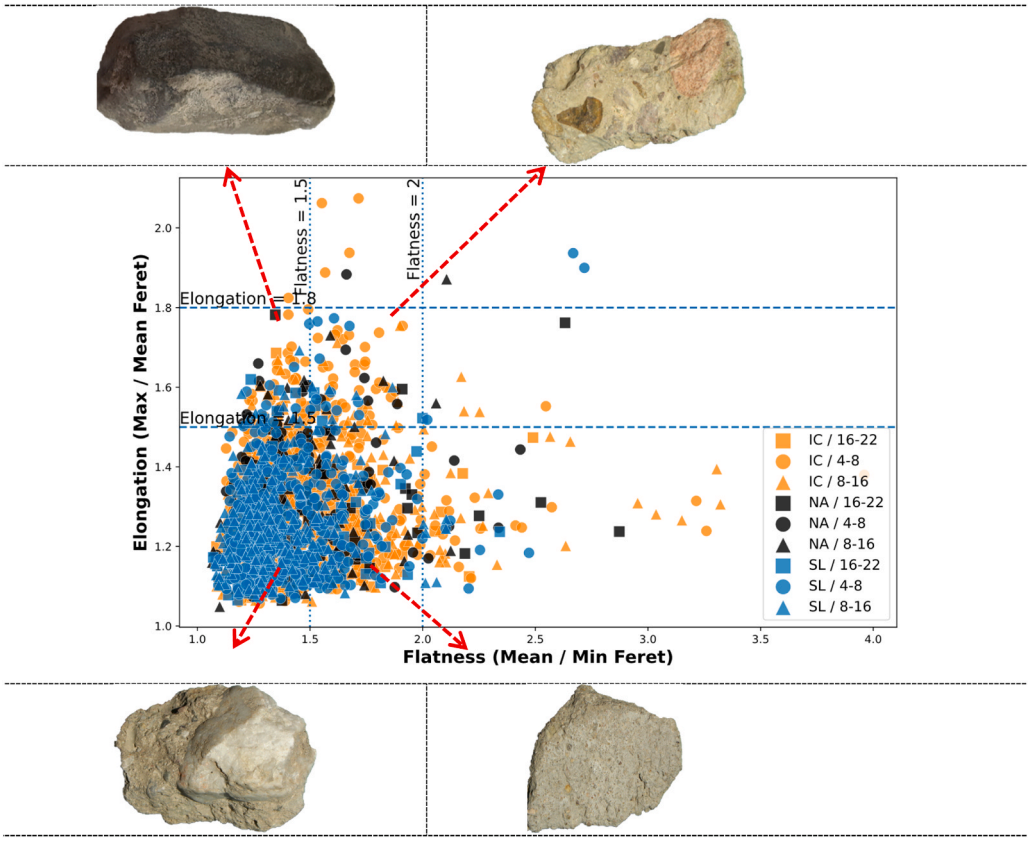

Fig. 8. Morphological classification of aggregates using Feret-based flatness and elongation.

both crushers ultimately generate spherical particles, though through different mechanisms: IC does so through high-energy shattering that can introduce angular edges [15], whereas SL achieves comparable RCA particle shape through selective detachment of mortar while preserving aggregate integrity. Although flaky and elongated particles occur only in small proportions, particularly in RCA produced by the IC, their presence remains relevant because such mechanically unfavourable shapes are more prone to fracture during compaction or under load, thereby reducing the stability and durability of recycled aggregate concrete mixtures [64].

3.1.2. *Microstructure analyses*

The CT scan images in Fig. 9 provide evidence of the crack patterns observed in RCA particles produced from different parent concretes using both the IC and SL techniques. Three representative RCA particles are presented using a combination of 2D CT cross-sections and 3D reconstructions. For each particle, two CT slices are shown on the left to highlight the NA core, the surrounding cement paste, and the presence or absence of cracks or air voids. In the center, the 3D surface morphology of each particle is presented, with two vertical cutting planes indicating the locations of the displayed CT cross-sections. On the right, 3D pore, air-void, and crack maps visualize the internal defect structure of the same particle. Color-coded voxels represent the detected microcracks and voids, allowing comparison of the internal damage and porosity among the different RCA particles. Together, these images provide a combined view of each RCA particle's internal morphology, linking the 2D CT slices with the full 3D distribution of pores, cracks, and residual paste. RCA from the Beam concrete exhibited extensive internal

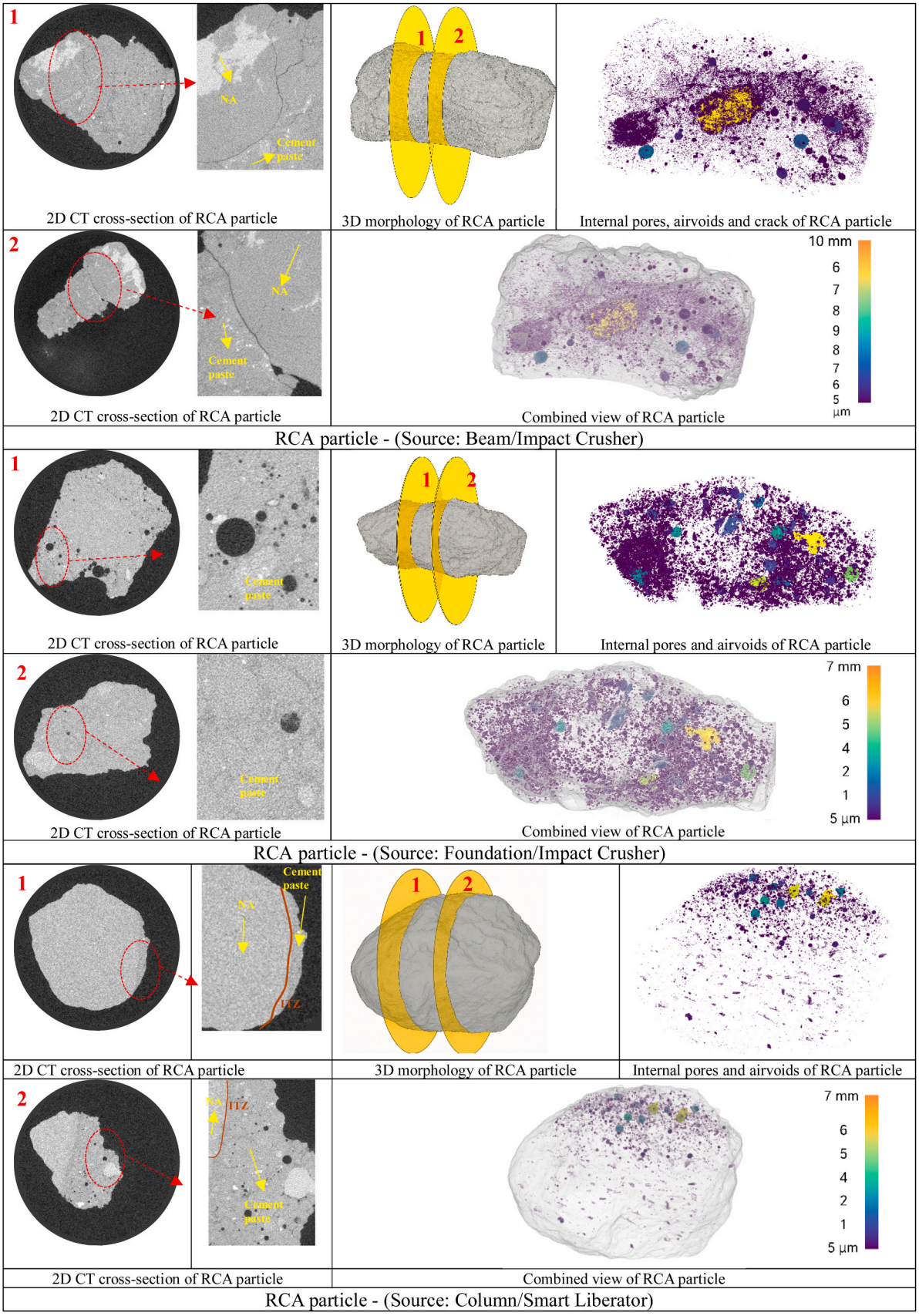

Fig. 9. CT-based visualization of RCA morphology and internal pore–crack networks.

microcrack networks under IC processing, whereas RCA from the Foundation concrete showed almost no visible cracking due to its higher air-void content. For the SL, the Column concrete is shown as an example, as all parent concretes exhibited comparable behaviour under selective crushing, consistently revealing a preserved natural aggregate core with a thin layer of attached cement paste containing air voids.

The formation of microcracks in RCA is closely linked to the microstructural characteristics of the parent concrete and the energy transfer mechanisms of the crushing process. RCA derived from the Beam and Column concretes, characterized by low W/C ratios (0.29–0.34), high hydration degrees (>0.85), and limited capillary porosity, showed pronounced microcrack networks. Under high-energy impacts, the dense and brittle matrix tends to resist fragmentation, causing stress waves to propagate through the aggregate–mortar composite and promoting internal cracking rather than clean detachment. Similar behaviour has been reported for high-strength concretes under impact loading, where higher brittleness promotes crack growth and internal fracture development rather than interfacial separation [65,66]. In contrast, Abutment-Wall and Foundation concretes, with higher porosity and air-void contents, exhibited little evidence of microcracking. In these concretes, impact stresses are dissipated along pre-existing weak zones such as voids or porous mortar, which act as preferred fracture planes. In contrast, the SL applies lower-energy, repetitive shear, attrition, and abrasion forces that progressively strip off attached cement paste at the interface. Because the SL acts selectively on the surface rather than fracturing the bulk particle, it preserves the internal structure of the aggregate and prevents further crack development. Notably, any microcracked surface fragments generated during the impact stage are likely to be abraded and removed in the SL process, explaining the absence of microcracks in SL-produced RCA.

3.2. Particle size distribution

Fig. 10 illustrates the particle size distribution of the coarse RCA obtained from different parent concretes (Beam, Column, Abutment-Wall, and Foundation) and processed using two crushing techniques: SL and IC. All particle size distributions were determined on materials as received, sampled from the top of each big bag. Across all sources, coarse grading is very similar: neither parent concrete nor crushing technique exerts a strong influence on the particle size distribution and both crushers produced well-graded materials falling within the upper and lower specification limits [67]. A minor, systematic difference is evident below 8 mm, where SL yields slightly more passing than IC, indicating a moderately finer product. This trend suggests that SL promotes detachment of cement paste and finer fragmentation along the mortar–aggregate interface, whereas IC produces a greater proportion of angular, coarser particles due to its high-energy impact mechanism. Both crushers were operated to produce the same target size range (4–22 mm); therefore, under comparable screening conditions and oversize recirculation, similar grading curves were obtained.

3.3. Attached cement paste content

Fig. 11 shows the attached cement paste content (%) of the 4–8 mm, 8–16 mm, and 16–22 mm RCA fractions produced using the SL and IC for each parent concrete type. Across all the fractions, the amount of attached cement paste is primarily governed by the characteristics of the parent concrete. Concretes with lower W/C ratios and denser paste microstructures, such as the Beam and Column, produced RCA with the lowest attached cement paste contents, typically below 10% when processed with SL. In contrast, the Abutment-Wall concrete, with its higher W/C ratio (0.38), larger paste volume (25%), and higher capillary porosity (10.5%), exhibited the highest residual cement paste content, reaching up to 9–20% in comparable fractions. The Foundation concrete, despite its low W/C ratio (0.30), contained a relatively high air-void content (4.3%), which facilitated partial retention of mortar on the aggregate surfaces, resulting in higher attached cement paste compared to the Column and Beam. The crushing technique further amplifies these differences: in all parent concretes, the SL produced significantly cleaner aggregates than the IC. For example, in the Beam sample, SL results in only 7.6% attached paste for the 16–22 mm fraction, whereas IC yields 14.7%. Similar trends are observed in the Column (6.2% vs. 16.1%) and Foundation (8.0% vs. 12.5%). This confirms that SL's liberation mechanism effectively detaches the cement paste, while IC's high-energy impacts promote uncontrolled breakage through both paste and aggregate, leading to higher retained mortar.

Although previous studies [9,68] have generally reported a gradual increase in attached cement paste content with decreasing aggregate size, such a systematic trend was not observed in this study. Instead, variations appear to arise from the combined effects of parent concrete composition, intrinsic porosity, and local heterogeneity within the matrix. These findings indicate that cement paste retention in RCA cannot be explained solely by particle size; rather, it is governed by the interplay between the microstructural characteristics of the parent concrete and the fracture mechanisms induced during crushing.

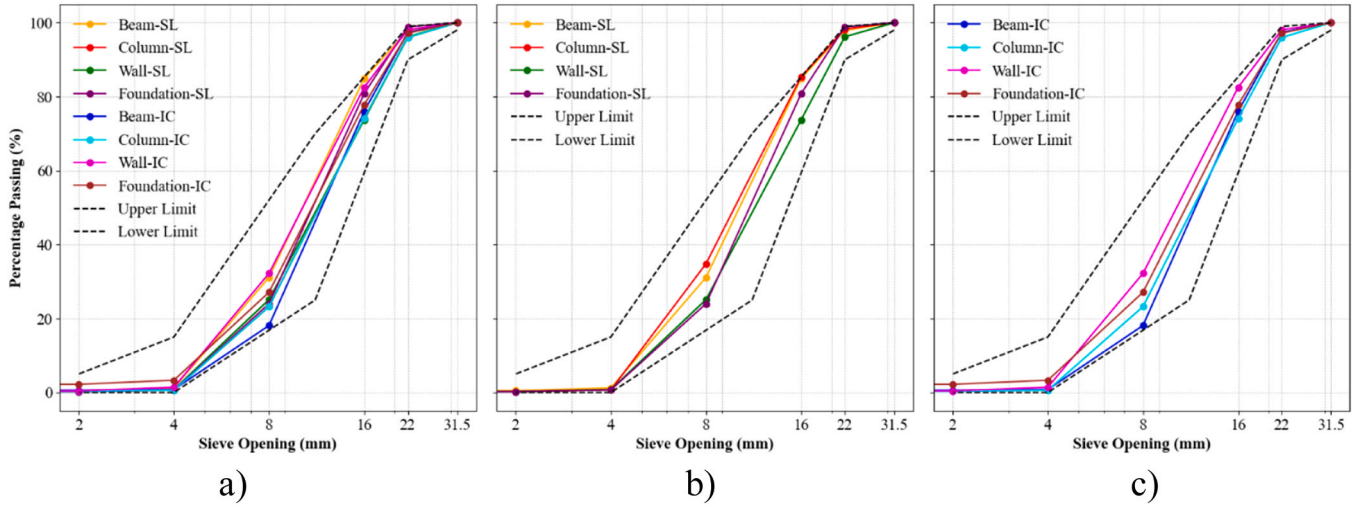

Fig. 10. Particle size distributions of RCA Coarse RCA (4–22 mm) with upper and lower limits according to NEN-EN 12620. Each row of graphs presents: a) all RCA curves, including both Smart Liberator (SL) and Impact Crusher (IC) fractions, b) only SL-derived RCA fractions, c) only IC-derived RCA fractions.

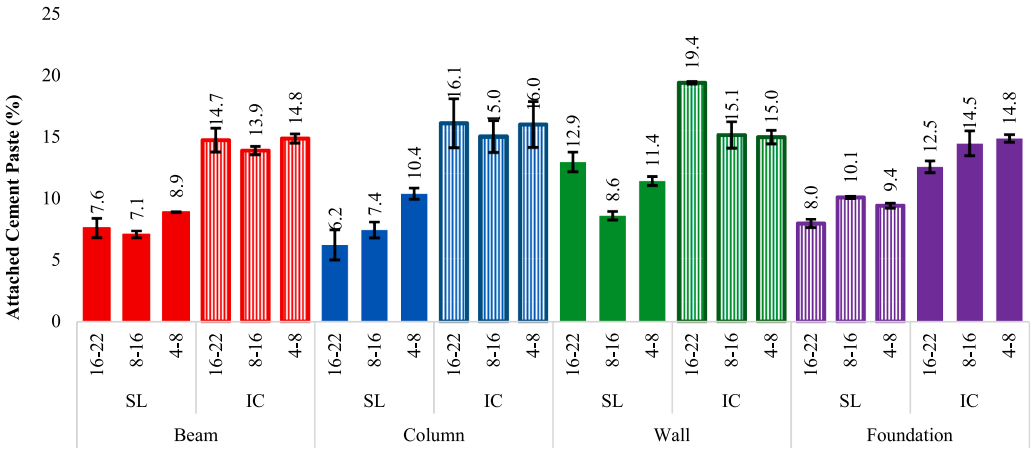

Fig. 11. Attached cement paste content of recycled concrete aggregates.

Table 2
Dry, saturated surface dry (SSD), and apparent densities of natural (NA) and recycled concrete aggregates (RCA).

		Particle Size (mm)	Dry Density (g/cm^3)	SSD Density (g/cm^3)	Apparent specific density (g/cm^3)
NA		16–22	2.56	2.58	2.62
		8–16	2.59	2.61	2.63
		4–8	2.57	2.59	2.62
Beam	**SL**	16–22	2.50	2.55	2.63
		8–16	2.50	2.55	2.62
		4–8	2.49	2.54	2.64
	IC	16–22	2.38	2.47	2.60
		8–16	2.39	2.48	2.61
		4–8	2.35	2.46	2.62
Column	**SL**	16–22	2.56	2.59	2.64
		8–16	2.56	2.59	2.65
		4–8	2.53	2.57	2.64
	IC	16–22	2.41	2.49	2.60
		8–16	2.39	2.48	2.61
		4–8	2.36	2.46	2.62
Abutment-Walls	**SL**	16–22	2.47	2.53	2.63
		8–16	2.47	2.53	2.63
		4–8	2.47	2.53	2.63
	IC	16–22	2.41	2.48	2.60
		8–16	2.42	2.49	2.61
		4–8	2.39	2.47	2.61
Foundation	**SL**	16–22	2.53	2.57	2.64
		8–16	2.52	2.56	2.64
		4–8	2.50	2.55	2.63
	IC	16–22	2.39	2.47	2.60
		8–16	2.37	2.46	2.60
		4–8	2.37	2.46	2.62

3.4. Density

Table 2 summarizes the dry, saturated surface dry (SSD), and apparent densities of RCA and NA. As expected, all RCA types exhibited lower densities than NA, reflecting the presence of residual mortar, internal porosity and microcracks. For NA, dry and SSD densities ranged narrowly between 2.56–2.59 g/cm^3 and 2.58–2.61 g/cm^3, respectively, with apparent densities around 2.62–2.63 g/cm^3, consistent with dense siliceous aggregates.

Among the RCA, clear variations were observed depending on parent concrete and crushing technique. Column and Foundation RCA exhibited the highest SSD densities (≈2.55–2.59 g/cm^3), while the Abutment-Wall produced the lowest (≈2.46–2.53 g/cm^3), with Beam RCA showing intermediate values (≈2.49–2.50 g/cm^3). These differences align with the observed variations in attached cement paste content and parent concrete microstructure: concretes with denser, well-hydrated paste (e.g., Column, Foundation) produced aggregates with more compact, less porous surfaces, whereas those with higher paste volume and weaker interfacial bonding (e.g., Abutment-Wall) yielded RCA with thicker attached cement paste layers and increased internal porosity.

The crushing technique further influenced density outcomes. Aggregates processed with the SL consistently displayed higher SSD and dry densities (e.g., Beam–SL: 2.50–2.55 g/cm^3) than those obtained by the IC (Beam–IC: 2.35–2.48 g/cm^3), corresponding to smoother textures, fewer microcracks, and reduced open pore connectivity observed in the microstructural analyses.

The dry densities followed a similar trend but remained slightly lower than SSD values due to the absence of absorbed water. In contrast, apparent densities were nearly constant across all materials and techniques (≈2.60–2.64 g/cm^3), indicating that the variations in SSD and dry densities primarily stem from differences in open porosity and residual mortar characteristics rather than changes in mineral composition.

3.5. Moisture content and water absorption

Fig. 12a presents the moisture content (%) of RCA produced from different parent concretes and crushing techniques, alongside NA. The NA shows negligible moisture content (<0.1%), consistent with its dense and non-porous structure. Among RCA samples, moisture content values are generally low for the coarse fractions but differ systematically with both parent concrete composition and crushing technique.

Between parent concretes, the Column and Beam RCA display the lowest moisture contents (≈0.3–0.7%), which aligns with their low porosity and dense paste structure (W/C = 0.29–0.34). In contrast, the Abutment-Wall and Foundation concretes exhibit slightly higher moisture contents (≈0.6–0.8%) due to their more porous and air-entrained microstructures. This finding is consistent with earlier studies showing that RCA derived from concretes with higher original porosity or greater paste volume tends to retain more free water after crushing [69].

The crushing technique also exerts a clear influence on RCA moisture behaviour. RCA produced using the IC consistently exhibit higher moisture contents (≈1.3–1.8%) than those obtained using the SL (≈0.5–0.8%). This difference arises from the IC's high-energy impact mechanism, which not only induces surface microcracking but also leaves a greater amount of attached cement paste on the aggregate surface. The combination of microcracks and porous residual mortar increases the accessible pore network and enhances water retention capacity [15,34]. In contrast, the SL's selective peeling and attrition mechanism preserves aggregate integrity, removes weak mortar layers, and minimizes microcrack formation, thereby producing aggregates with lower moisture content.

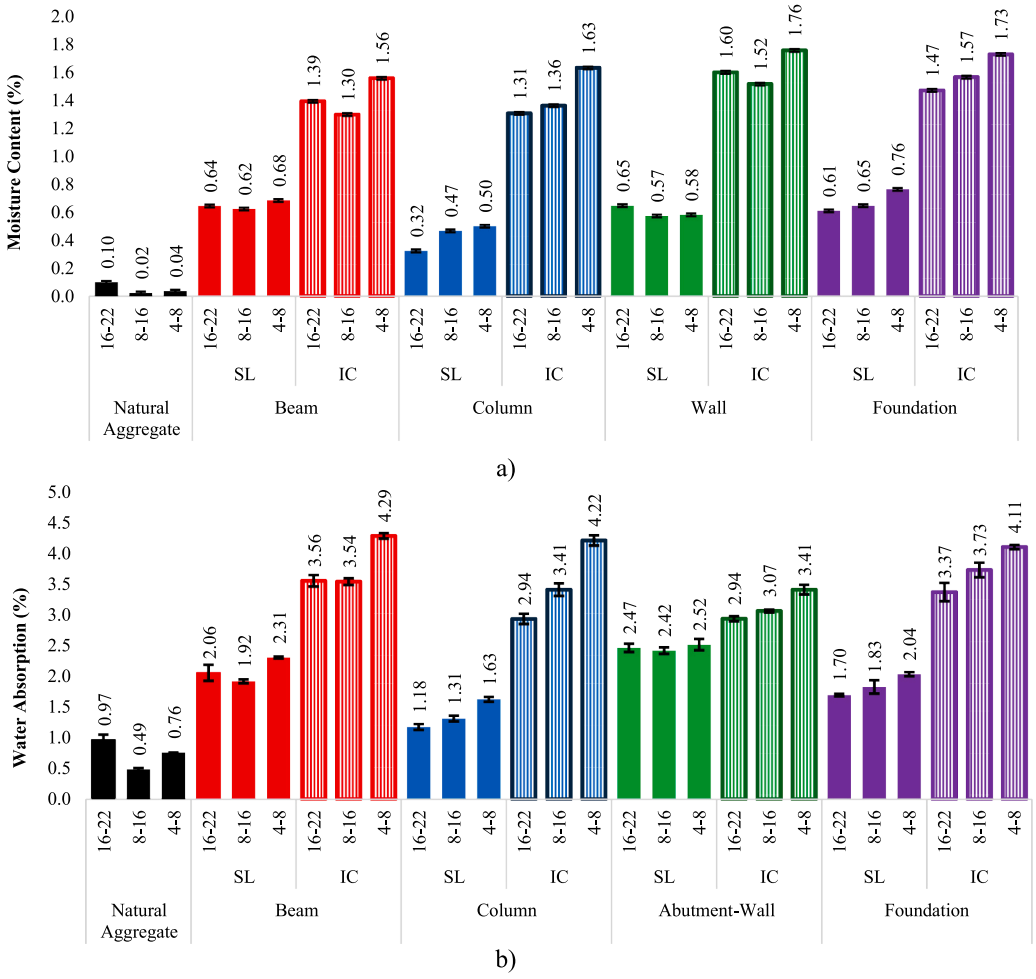

Fig. 12. Moisture Content (a) and Water Absorption (b) of RCA from different parent concretes and crushing techniques.

Fig. 12b shows the water absorption (%) of RCA and NA. NA exhibits minimal absorption (<1%), confirming its compact and non-porous structure. Among the RCA samples, the Abutment-Wall concrete shows the highest water absorption values (2.4–3.4%), indicating a more continuous and permeable paste phase that facilitates water ingress. In contrast, the Beam, Column, and Foundation concretes, which possess denser matrices and lower porosity, display lower water absorption values, ranging from 1.2 to 2.3% under SL and 2.9–4.3% under IC. These differences align with the attached cement paste results (Fig. 11), confirming that higher retained mortar correlates with greater water uptake due to the porous and microcracked nature of the paste phase [8,9,12,23].

The crushing technique further amplifies these differences. Across all parent concretes, RCA produced using the IC exhibits consistently higher water absorption than that generated with the SL. For instance, in the Beam concrete, water absorption increases from 2.06% (SL) to 3.56% (IC), and in the Column from 1.18% to 2.94% for the 16–22 mm fraction, representing nearly a twofold increase in some cases. The observed disparity reflects the fundamental difference in crushing philosophy: IC prioritizes high-impact fragmentation, producing rougher and more porous particles, whereas SL emphasizes selective liberation and aggregate preservation.

Notably, the water absorption values obtained in this study are among the lowest reported in literature. Previous studies indicate that the water absorption of coarse RCA produced with conventional impact crushers typically ranges between 4% and 9% [26,38]. The substantially lower values measured in this work can be attributed to two main factors: (i) the use of selective demolition guided by parent concrete characterization, which ensured the processing of high-quality material; and (ii) the application of advanced recycling technology, namely the SL, which promotes selective mortar removal and minimizes aggregate damage.

3.6. Water absorption rate

The water absorption rate (kinetics) of RCA is a key factor in determining the water demand compensation required in concrete production with RCA. Fig. 13 illustrates the water absorption behaviour of RCA, considering parent concrete properties, recycling techniques, and aggregate fraction size, alongside NA. During the first hour of immersion, all RCA types and fractions exhibited a rapid increase in water absorption, reaching approximately 60–80% of their total saturation capacity.

The absorption rate and final saturation level were strongly influenced by the parent concrete characteristics. RCA from dense, low-W/C concretes such as the Beam (W/C = 0.29) and Foundation (W/C = 0.30) exhibited slower absorption and lower ultimate saturation, whereas RCA from the Abutment-Wall concrete showed the highest absorption rates and prolonged saturation due to its higher porosity and more open paste structure, reaching saturation in 144 h (6 days). This extended absorption period confirms the gradual and time-dependent nature of water uptake in RCA, governed by its residual paste porosity and microcrack connectivity [60,70,71]. Interestingly, the Column RCA exhibited lower-than-expected absorption despite its moderate W/C ratio (0.34). This behaviour can be explained by the high hydration degree (0.87) and fine aggregate content (35%) of the parent concrete,

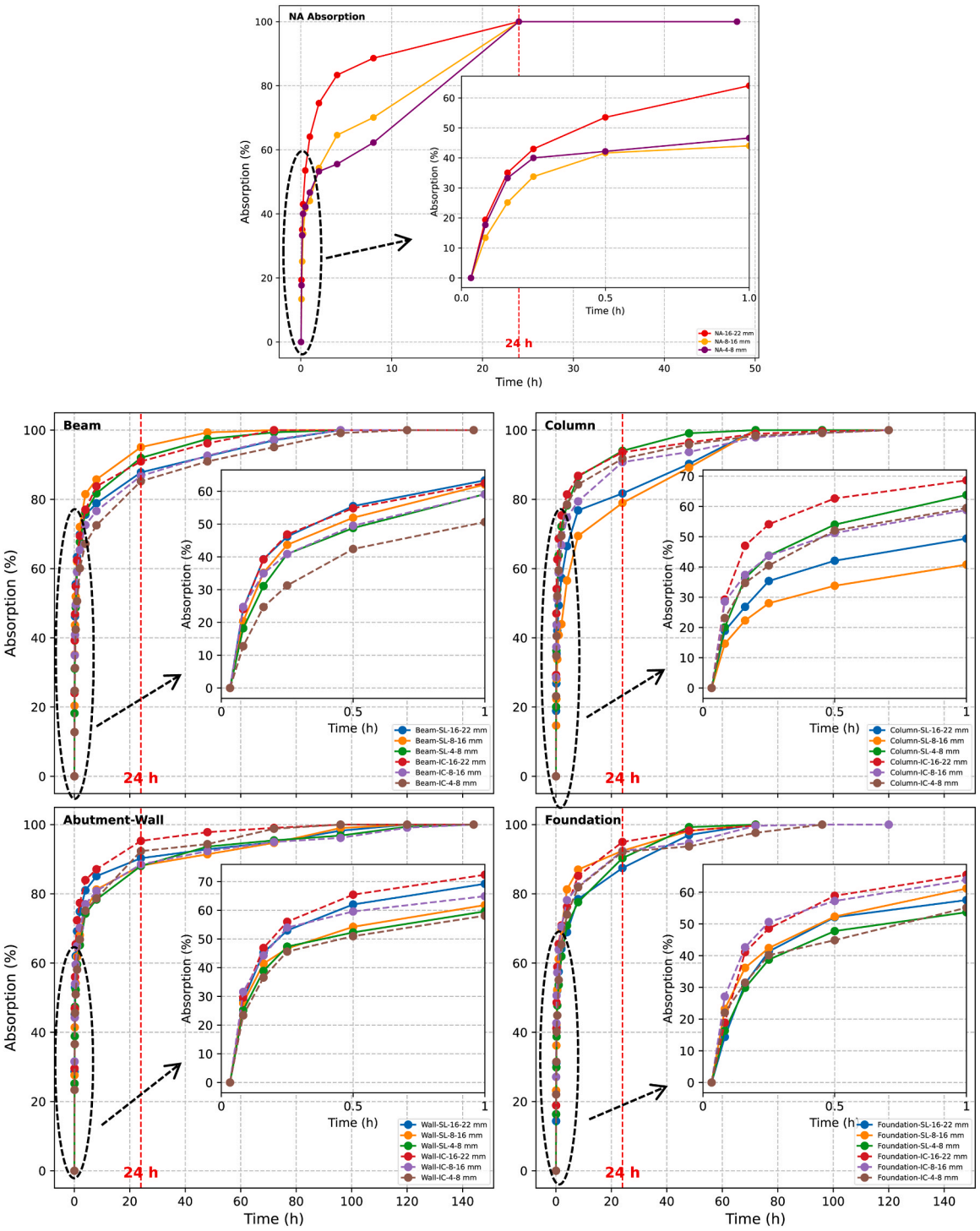

Fig. 13. Water absorption behaviour of NA and RCA over saturation time.

which enhance matrix compactness and reduce pore connectivity, thereby limiting capillary water transport. Similar trends have been reported by Kou and Poon [16] and Evangelista and de Brito [72], who observed that finer particle packing and denser, well-hydrated paste structures effectively suppress water absorption in RCA.

The crushing technique also exerted a clear influence on the water absorption behaviour of RCA. RCA produced using the IC exhibited faster absorption rates and higher final water uptake compared to those produced with the SL. This behavior is consistent with the high-energy fragmentation mechanism of the IC, which can generate additional microcracks and increase the accessibility of the pore network, thereby facilitating water ingress [9,12,73]. Conversely, the SL's selective liberation process minimizes internal damage and preferentially detaches the cement paste, resulting in denser, less permeable aggregates with reduced water absorption.

Variations in particle size also influenced absorption kinetics. The larger RCA fraction (16–22 mm) reached saturation faster, reflecting its lower attached cement paste content and more open, connected pore network that allows rapid water ingress. In contrast, smaller particles (4–8 mm) contained more attached cement paste, which increased overall water absorption but slowed saturation due to the denser and less permeable paste structure.

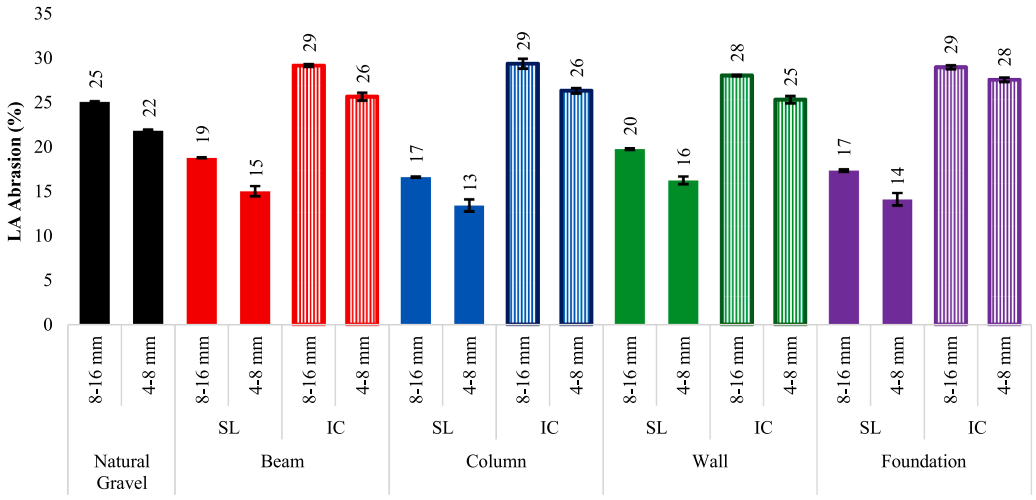

Fig. 14. LA abrasion resistance of NA and RCA processed by smart liberator and impact crusher.

3.7. Los angeles abrasion

The results of the LA Abrasion for all RCA and NA are shown in Fig. 14. The parent concrete type shows negligible influence on the abrasion resistance of RCA, as results across Beam, Column, Abutment-Wall, and Foundation concretes follow similar trends within each crushing technique. In contrast, the crushing method exerts a dominant effect on LA abrasion resistance. RCA produced by the SL consistently achieved the lowest abrasion losses (13–20%), even outperforming the NA (22–25%). This can be attributed to the SL's ability to preserve the original shape and surface integrity of coarse aggregates while detaching weaker attached cement paste, resulting in smoother particle surfaces with fewer micro-defects. As highlighted by EN 1097–2 [50] and ASTM C131 [74], abrasion resistance is governed not only by mineralogy but also by particle shape, surface roughness, and the presence of microcracks. NA, despite their intrinsic strength, may still contain angular edges or microstructural flaws from extraction and processing, which can accelerate wear. By avoiding such damage and removing wear-prone paste, the SL produces aggregates with enhanced resistance to abrasion loss. Conversely, RCA produced using the IC exhibited markedly higher LA abrasion values (25–29%), which is consistent with the increased particle damage and surface irregularities associated with high-energy impact crushing.

4. Discussion

4.1. Combined influence of parent concrete and crushing technique

This study evaluates how parent concrete characteristics and crushing techniques jointly influence the physical and microstructural quality of RCA. Although the parent concretes exhibited comparable strength classifications [41], they differed in microstructural parameters such as W/C ratio, hydration degree, porosity, paste volume, and air-void structure [24], all of which govern not only the way the cement matrix responds to mechanical fragmentation during recycling, but also the resulting physical properties of the produced RCA, including attached cement paste content, water absorption, density, and abrasion resistance. To quantify the relative contribution of these factors to RCA quality, a feature importance analysis was performed for three key parameters: attached cement paste content, water absorption, and LA abrasion resistance. The relative importance values shown in Fig. 15 represent the normalized contribution of grouped input variables, namely parent concrete properties and crushing technique, to the prediction of each RCA property, based on the mean decrease in impurity obtained from the random forest model. These values should be

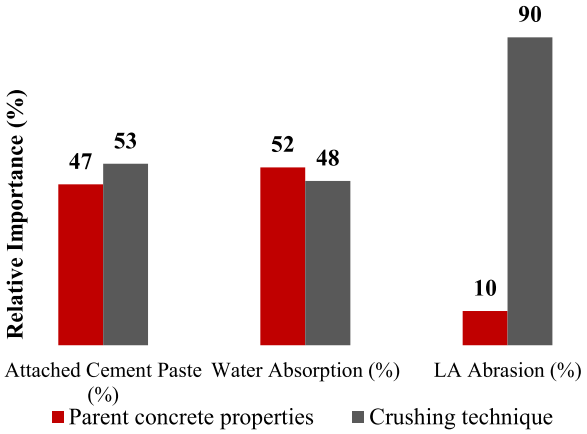

Fig. 15. Feature importance analysis for predicting RCA properties.

interpreted as indicative of the dominant controlling factors rather than absolute quantitative contributions. The results show that the crushing technique exerts a dominant influence on abrasion resistance (≈90%), indicating that LA performance is primarily governed by the mechanical effects of the crushing process. In contrast, attached cement paste content (≈53%) and water absorption (≈52%) are influenced by both inherited microstructural properties and processing conditions.

The limited influence of parent concrete properties on LA abrasion should be interpreted within the context of the investigated structure. All bridge members were produced using the same Portland cement and river-derived siliceous aggregates (Table 1); therefore, the mineralogical and intrinsic mechanical properties of the original natural aggregates remained relatively constant across all parent concretes. Under these conditions, variations in parent concrete microstructure, such as W/C ratio, porosity, and paste quality, had only a minor influence on LA abrasion resistance compared to the crushing mechanism itself. This explains why clear differences were observed between IC- and SL-produced RCA, whereas variations among Beam, Column, Abutment-Wall, and Foundation concretes remained comparatively limited for LA performance. However, previous studies have shown that the type and quality of the original natural aggregate can significantly influence RCA mechanical properties. For example, Zega et al. [25] reported substantial differences in RCA LA abrasion depending on the parent aggregate type, where RCA produced from basaltic aggregates exhibited LA values of approximately 25–30%, while RCA derived from quartzitic aggregates reached significantly higher values of approximately

52–55%, despite being produced under similar crushing conditions. These findings indicate that RCA abrasion resistance is strongly influenced by the mineralogy, surface texture, and mechanical quality of the parent natural aggregates, suggesting that the aggregate type within the parent concrete can become an important factor affecting LA abrasion when mineralogical variability exists.

4.2. Influence of parent concrete on RCA properties

In this study, the effect of parent concrete properties, represented by different structural members, on RCA properties was investigated. All members fall within a similar compressive strength range, with Beam, Column, Abutment-Wall, and Foundation exhibiting strengths of approximately 87 MPa, 71 MPa, 64 MPa, and 67 MPa, respectively [41]. The results demonstrate that parent concrete compressive strength alone does not provide a consistent indication of RCA properties. The parent concretes from the Column, Abutment-Wall, and Foundation all fall within a similar compressive strength range (approximately 64–71 MPa), yet they produce RCA with markedly different properties. The Column concrete, characterized by a higher hydration degree and denser microstructure, resulted in lower water absorption and faster saturation kinetics. In contrast, the Abutment-Wall concrete exhibited a more porous and less compact paste structure, leading to higher water absorption and significantly prolonged saturation, requiring up to six days to reach full saturation compared to approximately three days for Column-derived RCA. A similar difference is observed between the Abutment-wall and Foundation concretes, where comparable compressive strengths (64 MPa and 67 MPa, respectively) resulted in distinctly different moisture transport behaviour. These differences cannot be explained by compressive strength alone but are directly linked to variations in pore connectivity and the microstructural quality of the attached cement paste. This observation is consistent with findings reported in the literature, where parent concretes within the structural strength range of approximately 60–110 MPa show substantial variability in RCA properties [9,16,75]. Despite this similarity in strength range, substantial variability is observed in RCA characteristics. For instance, for parent concretes around 60–65 MPa, water absorption values range from approximately 3.5–6.8%, while reported mortar contents vary between about 23% and 54% [9,16,76]. Even for nearly identical compressive strength levels, significant discrepancies are observed across studies; for instance, at approximately 61 MPa, Kou and Poon [16] report water absorption values of 6.28% for coarse RCA, whereas Akbarnezhad et al. [9] report values of approximately 3.5% for a comparable aggregate size fraction, indicating nearly a twofold difference despite similar strength levels. Similarly, no clear trend is observed for Los Angeles abrasion resistance, where values for comparable strength levels range broadly (e.g., approximately 27%–39%), indicating inconsistent mechanical performance of the resulting aggregates [19]. Considerable variability is also evident in density-related properties, as specific gravity values reported in the literature range from approximately 2.33–2.87 despite similar compressive strength levels. Moreover, higher-strength concretes (≈85–110 MPa) do not systematically yield lower water absorption, improved abrasion resistance, or higher density, with properties remaining within overlapping ranges [9,16,19,75,76].

To explain these discrepancies, it is necessary to consider the role of parent concrete microstructure and composition, which influence RCA behaviour beyond what can be inferred from compressive strength alone. In this context, RCA quality is primarily determined by key parent concrete characteristics, including paste volume, W/C ratio, and associated microstructural properties (such as porosity and degree of hydration), together with aggregate packing and the air-void content, as these factors collectively control fragmentation during recycling and the resulting properties of the produced RCA. Paste volume (vol%) defines the statistical likelihood and thickness of attached layers after fragmentation. Higher paste fractions increase the probability of attached cement paste, thereby elevating accessible pore volume, lowering particle density, and enhancing water absorption capacity due to the increased presence of interconnected pores within the retained paste [59,60,70]. Furthermore, aggregate proportioning and packing constrain the spatial distribution of the paste and the overlap of ITZ. Well-graded, densely packed skeletons restrict the formation of large, connected voids and can therefore produce RCA in which higher paste content does not necessarily translate to higher water absorption, as the retained paste may be denser and less permeable [23,60,70]. This dual effect is reflected in the moderate correlations between attached cement paste and both water absorption ($R^2 = 0.66$) and LA abrasion ($R^2 = 0.69$) shown in Fig. 16. The relatively gentle slopes of these relationships indicate that paste quantity alone cannot fully explain RCA behaviour. Paste quality, influenced by the degree of hydration, porosity, and particle packing density, also plays an important role. This relationship is clearly illustrated by the Column and Abutment-Wall concretes, both of which contained similarly high paste (≈25–27%) and fine aggregate (≈31–35%) contents yet exhibited markedly different behaviours. The Column concrete, with its higher hydration degree (≈0.87) and denser microstructure, developed a cohesive paste network that attached strongly to the aggregates while remaining relatively impermeable, resulting in the lowest water absorption among all parent concretes. In contrast, the Abutment-Wall concrete, despite its comparable paste and fine aggregate proportions, possessed a more porous and less compact paste phase, generating RCA with thicker but weaker attached layers and a continuous capillary network that facilitated greater moisture uptake and slower saturation. Consequently, Abutment-Wall-derived RCA exhibited both higher total absorption and prolonged saturation kinetics, requiring nearly six days to reach full saturation compared with only about three days for Column-derived RCA. This contrast highlights how differences in paste microstructure and pore connectivity directly govern the permeability and moisture transport behaviour of RCA [37,77].

Beyond paste characteristics and packing effects, the air-void system plays an equally critical role in determining how parent concrete fractures and how much mortar remains attached after crushing. The air-void system, including void content, size distribution, and spacing, acts as a network of stress concentrators that governs how the cement matrix fractures during recycling. Depending on their morphology, uniformly distributed spherical voids can act as crack-propagation paths, that promote interfacial detachment and facilitate the release of attached cement paste [9,78], whereas interconnected or irregular voids may accelerate crack linking and increase capillary porosity, thereby enhancing water absorption [23,70]. This relationship is evident in the Foundation and Beam concretes, which share similar low W/C ratios (≈0.30) but differ markedly in air-void content. The Foundation, with its higher air-void content (4.3%), contains numerous internal stress concentrators that localize crack propagation and enable easier mortar detachment under applied forces, limiting microcrack formation within aggregates [60]. Conversely, the Beam concrete, despite comparable strength and composition, exhibits a lower air-void content (1.4%), resulting in a denser yet more brittle matrix prone to internal microcracking rather than clean interfacial separation. This finding aligns with the fracture mechanics perspective proposed by Zhang and Ansari [79] which emphasizes that the distribution and connectivity of voids control whether energy dissipation occurs through detachment or internal cracking.

The influence of air-void characteristics may also extend beyond the RCA stage. The void morphology inherited from the parent concrete continues to govern durability-related behaviour in RAC, particularly freeze–thaw performance. RCA originating from air-entrained concretes can improve frost resistance by introducing stable, well-distributed voids that provide pressure-relief zones during freezing [80]. Conversely, RCA from non-air-entrained concretes lacks this protective system, making RAC more vulnerable to freeze–thaw damage even when strength and absorption appear similar. Thus, the microstructure of the

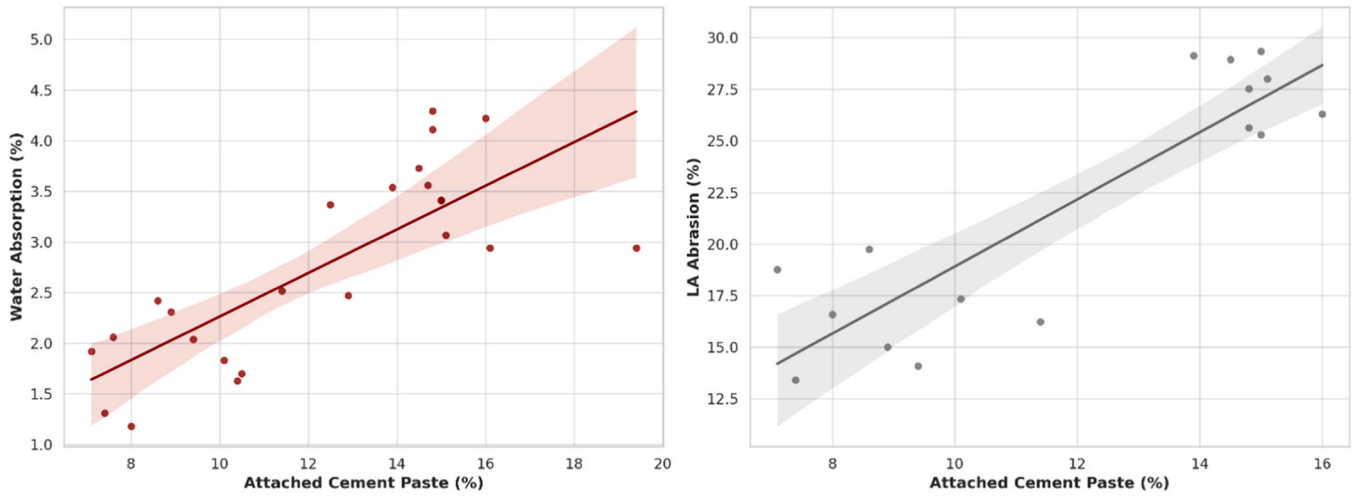

Fig. 16. Effect of attached cement paste content on RCA water absorption and LA abrasion.

parent concrete exerts a dual influence, it determines fragmentation and mortar detachment during recycling, and it also shapes the durability and long-term performance of the new concrete made from these aggregates.

4.3. *Influence of crushing mechanism on RCA quality*

When comparing the two crushing techniques, the mechanical forces applied during comminution play a decisive role in determining RCA morphology, surface texture, and microstructural integrity. The IC operates through high-velocity impacts that generate dynamic stress waves within the concrete, causing rapid crack initiation and propagation across both mortar and aggregate phases [15,31,81]. This high-energy fragmentation mechanism produces highly angular particles with irregular surfaces [82], open pore networks, and localized internal microcracks [34], as also confirmed by the X-ray CT observations. The extent of this damage strongly depended on the parent concrete microstructure. Dense, low-W/C concretes such as Beam and Column exhibited more pronounced sub-surface cracking because their strong and cohesive cement matrix resisted selective fracture, causing stresses to accumulate and propagate through both mortar and aggregate phases simultaneously. In contrast, parent concretes with higher porosity and air-void contents, such as Abutment-Wall and Foundation, fractured more readily through weaker paste regions, dissipating the impact energy before extensive crack networks could form within the aggregates. Consequently, the IC-induced microcracks increased accessible porosity and capillary pathways, thereby increasing water absorption and reducing abrasion resistance through weakening of the aggregate integrity and residual mortar layer [9,69,71,83].

These observations are consistent with previous studies demonstrating that crushing efficiency is strongly governed by parent concrete quality. Akbarnezhad et al. reported that RCA produced from low-W/C ratio parent concretes (W/C = 0.26; compressive strength ≈ 85–88 MPa) still retained relatively high attached cement paste contents of approximately 50–60% even after repeated crushing stages, whereas RCA produced from higher-W/C ratio parent concretes (W/C = 0.69; compressive strength ≈ 27–29 MPa) showed lower attached cement paste contents of approximately 20–30% [9]. This indicates that the stronger aggregate–paste bond in dense low-W/C concretes limits selective mortar detachment during crushing. Similarly, Dao et al. [84] observed that RCA produced from parent concretes with W/C ratios of 0.32 exhibited lower water absorption values (5%) than RCA from higher-W/C concretes (W/C=0.65–0.9; WA ≈6.8–8.7%), but the stronger and denser paste also reduced mortar liberation efficiency during crushing. Nedeljković et al. [85] likewise reported that decreasing the parent concrete W/C ratio from 0.65 to 0.31 reduced RCA water absorption from approximately 3.8–2.9% while increasing particle density and aggregate integrity. Collectively, these findings suggest that although low-W/C parent concretes contain denser and less porous mortar, their stronger aggregate–paste bond limits selective mortar detachment during crushing. As a result, under high-energy impact loading, a greater portion of the applied energy may be transferred through the particle rather than dissipated through interfacial separation, thereby increasing the tendency for internal damage and crushing-induced microcracking.

Previous studies demonstrated that sequential crushing stages and selective liberation techniques can substantially improve RCA quality through progressive attached cement paste removal [28,34,69]. Florea et al. [38] reported that repeated jaw crushing cycles enhanced cement paste recovery and mortar detachment, although additional crushing stages significantly increased energy consumption. Similarly, Trivedi et al. [86] showed that multi-stage crushing combined with mechanical abrasion and sodium silicate treatment reduced RCA water absorption from 3.6% to 1.05%, increased specific gravity from 2.56 to 2.63, and improved aggregate mechanical resistance, with aggregate crushing, impact, and LA abrasion values decreasing from 39.2% to 22.64%, 28–19.82%, and 25.6–22.02%, respectively. These improvements also enhanced RAC performance, increasing slump from 26 mm to 50 mm and 28-day compressive strength from 42.2 MPa to 50.2 MPa while significantly reducing chloride penetration. However, intensive crushing introduces an important trade-off. Although mortar removal is improved, repeated impact loading can also generate internal cracks and surface defects that may increase accessible porosity and weaken aggregate integrity [87].

In contrast to the IC, the SL applies selective attrition, abrasion, and shear forces that gently peel the attached cement paste from the aggregate surface without extensively fracturing the aggregate core. Rather than generating new fracture surfaces, the SL progressively removes weak paste layers at the aggregate–paste interface, producing smoother and denser aggregates with fewer visible internal defects. As a result, SL-derived RCA exhibited lower water absorption, higher density, and better abrasion resistance [40]. The different crushing mechanisms were further reflected in the relationship between attached cement paste and water absorption. While SL-produced RCA showed a very strong correlation between attached cement paste and water absorption ($R^2 \approx 0.96$), the weaker relationship observed for IC-produced RCA ($R^2 \approx 0.77$) indicates that water absorption in IC RCA was additionally governed by crusher-induced microcracks and internal damage. It should be noted that all materials were initially subjected to primary size reduction using the IC before further processing with the SL. Therefore,

SL-treated RCA originated from particles that may already have contained impact-induced defects generated during the first crushing stage. However, these damaged regions also represent mechanically weak zones within the attached cement paste and outer aggregate shell. During SL processing, the applied attrition and shear forces preferentially target and remove these weakly bonded and damaged surface regions rather than propagating new cracks into the aggregate core. Consequently, the SL does not simply process undamaged particles but instead acts as a selective liberation step that removes previously weakened paste-rich layers and unstable fractured zones generated during initial impact crushing. This explains why SL-treated RCA still exhibited lower water absorption, higher density, and fewer observable internal defects despite the prior IC pre-conditioning stage. Therefore, the improved RCA quality is not solely related to reduced attached cement paste content, but also to the removal of crack-sensitive and mechanically weak surface regions created during earlier crushing stages.

4.4. Water absorption kinetics and implications for mix design

The water absorption behaviour of RCA is governed by their pore structure, particularly the capillary porosity of the attached cement paste and the characteristics of the old ITZ. Unlike NA, RCA consists of dense aggregate cores surrounded by porous mortar and an old ITZ, forming connected capillary network that facilitates rapid water ingress [88,89]. As a result, 40–70% of the total absorption reached within the first 30–60 min, whereas NA exhibits lower and more stable absorption rates [59]. This rapid initial uptake is associated with transport mechanisms through the porous ITZ and crushing-induced microcracks, which act as preferential pathways and significantly enhance pore connectivity.

As saturation progresses, the absorption rate decreases due to reduced capillary pressure, and the total water absorption becomes primarily governed by the overall porosity and volume of attached cement paste [89,90]. This highlights the dual role of pore structure: the ITZ and crack network control the rate of absorption, while the bulk mortar porosity controls the total absorption capacity. The influence of recycling technique further supports this mechanism. IC introduces additional microcracking and disrupts the ITZ, resulting in higher pore connectivity and accelerated water transport, whereas the SL selectively removes attached cement paste and better preserves structural integrity, leading to lower porosity and more controlled absorption behaviour [40].

The W/C ratio of the parent concrete further influences this behaviour by controlling the development of the capillary pore system within the attached cement paste [91,92]. Higher W/C ratios generally produce a more porous and better-connected pore network, promoting faster capillary transport and higher water absorption. This is reflected in the RCA derived from the abutment-wall concrete (W/C $\approx$ 0.40), which showed substantial water uptake during the first 30–60 min. However, the abutment-wall RCA also required a longer time to approach full saturation, indicating that its moisture transport was not governed only by rapid capillary uptake, but also by slower filling of finer or less accessible pores within the attached paste. In contrast, RCA originating from the beam and column concrete (W/C $\approx$ 0.30) showed comparatively slower absorption kinetics, consistent with their denser and less connected microstructures. However, the results also demonstrate that water absorption behaviour cannot be explained by W/C ratio alone. Crushing-induced microcracks and damage introduced during impact crushing further increased accessible porosity and accelerated water ingress, particularly during the early absorption stage [34]. Therefore, the absorption behaviour of RCA is governed by the combined influence of parent concrete microstructure and crushing mechanism. In this regard, RCA produced from higher-W/C parent concrete and processed by IC represents the highest absorption tendency, whereas RCA produced from denser low-W/C parent concrete and further treated by SL exhibited lower water absorption and more controlled absorption behaviour.

It should be noted that RCA does not reach full saturation within 24 h, and water absorption continues beyond this period [59,93]. Therefore, the commonly used 24 h water absorption represents a standardized reference rather than the true saturation capacity of RCA. This is attributed to the complex and partially inaccessible pore structure of the attached cement paste, which delays complete saturation. Consequently, the 24 h value reflects neither the rapid absorption occurring during mixing nor the ultimate absorption capacity of RCA.

These findings have direct implications for recycled concrete mix design. A substantial portion of RCA water absorption occurs within the first 30–60 min, which directly coincides with mixing, placing, and the early stages of cement hydration. Consequently, relying solely on 24 h water absorption values for water compensation may lead to inaccurate estimation of the actual effective W/C ratio during mixing. In practice, dry or partially saturated RCA rapidly absorbs mixing water into its connected pore network and microcracks, reducing the amount of free water available in the cement paste and thereby lowering the effective W/C ratio and workability [94]. To compensate for this behaviour, additional water is often added based on the measured 24 h water absorption capacity. However, because RCA may continue absorbing water beyond 24 h, this approach can still underestimate the total water demand required to achieve true SSD conditions. Consequently, partially saturated RCA may continue absorbing water during mixing and early hydration, leading to unintended variations in the effective W/C ratio and overall mixture performance. In contrast, over-saturated or surface-wet RCA may release stored water back into the surrounding cement matrix, locally increasing the effective W/C ratio and altering fresh and hardened concrete behaviour [94–97]. These dynamic moisture interactions can significantly influence fresh properties, hydration kinetics, strength development, and long-term durability. Therefore, the parent concrete microstructure, attached paste quality, and resulting absorption kinetics of RCA must be considered not only for understanding fragmentation and water absorption behaviour, but also for accurately predicting and controlling RAC performance in practical concrete production.

5. Further research and recommendations for practice

The results of this study indicate that RCA variability is strongly influenced by the microstructural heterogeneity of the parent concrete, in addition to the effects of the recycling process itself. Previous classification approaches have relied on macroscopic indicators such as compressive strength and water absorption [59,81,98] assuming these to be sufficient predictors of RCA quality. However, the present findings show that such strength- and absorption-based classifications overlook the decisive influence of intrinsic microstructural factors, including W/C ratio, paste content, porosity, and air-void structure, that govern fracture behaviour, the quality of the attached cement paste, and the degree of mortar detachment during recycling. Therefore, a shift toward a microstructure-based classification framework is essential to understand and reduce RCA variability and improve the reliability of both aggregate and RAC performance. Variations in parent concrete W/C ratio (0.29–0.38) and air-void content (1–4%) were found to cause substantial differences in RCA morphology, porosity, and integrity. This confirms that the microstructural composition of the parent concrete is a stronger determinant of RCA quality than strength class or crushing stage alone. Accordingly, selective demolition strategies should prioritize the identification and separation of concretes with compact matrices and balanced air-void systems, as these are more likely to yield uniform, high-quality RCA. Characterizing end-of-life structures based on microstructural and volumetric parameters prior to recycling can significantly reduce RCA variability and lessen the need for energy-intensive post-processing, such as multiple crushing or thermal/mechanical cleaning.

For practical implementation, pre-demolition coring or non-destructive testing can be employed to map W/C ratio, paste volume, and air-void characteristics across structural elements, enabling recyclers to selectively dismantle or sort concrete expected to produce superior RCA. This microstructure-informed selective demolition approach aligns with the principles of EN 12620 [2] and EN 206 [99], which emphasize that the origin and composition of RCA must be known and documented to ensure consistent quality. Such characterization-based demolition offers a more reliable and resource-efficient alternative to current practices that indiscriminately process mixed demolition waste of unknown provenance or composition.

While this study establishes the basis for such classification, further research should extend the framework to a broader range of concretes. Future work should explore the influence of cement type, aggregate mineralogy, gradation, and maximum aggregate size (D_{max}) on fragmentation behaviour and attached paste characteristics. Establishing these relationships will be crucial to developing a comprehensive, standardized classification system that supports performance-based selective demolition and ensures consistent RCA quality in circular concrete production.

6. Conclusion

This study provides a comprehensive understanding of how parent concrete microstructure governs the quality of RCA and how crushing mechanisms modulate these effects.

- Even within a limited W/C ratio range (0.29–0.38), substantial variability in RCA properties was observed, with attached cement paste contents varying from 9.4% to 26.7% and water absorption from 1.7% to over 7%. Parent concretes with similar compressive strengths produced RCA with markedly different properties, demonstrating that RCA behaviour is governed by the combined influence of parent concrete microstructure and crushing mechanism rather than compressive strength alone.
- The LA abrasion results highlight the dominant influence of the crushing mechanism on RCA mechanical performance, since all parent concretes were produced using similar river gravel and cement types. The consistently lower abrasion losses of SL-derived RCA compared to both IC-derived RCA and the reference NA indicate that selective mortar removal with limited crushing-induced damage can significantly improve RCA abrasion resistance.
- The SL outperformed the conventional IC, consistently producing aggregates with lower attached paste (e.g., Beam 16–22 mm: 7.6% vs. IC: 14.7%), lower water absorption (2.06% vs. 3.56%), and higher abrasion resistance (19% vs. 29%).
- This study provides evidence of microcrack formation in IC-derived RCA, highlighting the importance of considering fracture mechanisms during recycling. Understanding these damage patterns is essential for predicting RCA performance and guiding the selection of appropriate crushing and demolition strategies for high-quality recycled concrete production.
- Microcrack formation was mainly associated with the high-energy impact mechanism of the IC, while the extent and distribution of cracking were strongly governed by the stiffness and porosity of the parent concrete. Dense, low-porosity concretes (e.g., Beam and Column) were more prone to internal cracking under impact, whereas porous, moderately air-entrained concretes (e.g., Foundation) fractured with minimal internal damage.

By revealing the dominant role of inherited concrete properties, this work shifts the understanding of RCA production from process-driven to material-driven variability. The findings establish a direct link between parent concrete heterogeneity and RCA performance, providing a scientific foundation for quality assessment. Ultimately, the results emphasize that controlling RCA variability begins with characterizing the parent concrete, an essential step toward more reliable, high-value recycling and future circular concrete design.

CRediT authorship contribution statement

Burcu Aytekin: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Erik Schlangen:** Writing – review & editing, Supervision. **Oguzhan Copuroglu:** Writing – review & editing, Supervision, Conceptualization. **Patrick Holthuizen:** Writing – review & editing. **Marija Nedeljković:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The first author acknowledges the financial support provided by the Turkish Ministry of National Education for her PhD research. The research was also supported by funding from the Ministry of Infrastructure and Water Management of the Netherlands (Rijkswaterstaat). The authors thank Arjan Thijssen, Maiko van Leeuwen and Ton Blom for their assistance with laboratory equipment and technical support.

Data availability

No data was used for the research described in the article.

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