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Selective demolition and recycling of Dutch infrastructure concrete

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ABSTRACT

This study advances understanding of how selective demolition combined with advanced recycling techniques affects the quality of recycled concrete aggregates (RCA) from Dutch infrastructure concrete under industrial conditions. A 60-year-old highway viaduct in the Netherlands was selectively demolished, including T-beams, columns, abutments, and foundations. Powder, fine, and coarse RCA fractions were produced from these pre-selected members using a conventional impact/rotor crusher and two advanced recycling technologies (Smart Liberator and Mangeler) and compared with RCA obtained from unknown-origin concrete rubble. Experimental relationships were established between adhered mortar content and key physical, mechanical, and chemical properties of RCA across particle size fractions. Selective demolition combined with advanced recycling produced materials with substantially improved performance. Fine RCA (0–4 mm) exhibited water absorption values of 2–6%, compared to approximately 8% for fine RCA from unknown-origin concrete rubble, while coarse RCA (4–22 mm) reached 1.5–4%. These improvements were accompanied by the high-performance characteristics of RCA produced using the Smart Liberator, including a Los Angeles abrasion value of approximately LA15 and particle density up to 2610 kg/m^3. The results highlight the importance of both parent concrete selection and the choice of comminution technique in achieving high-quality RCA. Unlike conventional high-energy impact crushing, advanced recycling relies on controlled friction, shearing, and selective abrasion, which preserves aggregate integrity and allows efficient removal of adhered mortar. The resulting RCA exhibits mechanical and physical performance comparable to natural aggregates and meets Eurocode 2 requirements. This study demonstrates, at full industrial scale and within a single reinforced concrete structure, how selective demolition combined with advanced recycling enables direct control over adhered mortar content and aggregate performance, narrowing the gap between conventional RCA and natural aggregates for high-performance structural applications.

1. Introduction

The need for more sustainable products, projects, and construction processes has been recognized by international organizations and government policies, which now promote standards requiring functional, technical, environmental, social, and economic performance to meet defined sustainability benchmarks [1]. Concrete infrastructure constitutes a primary structural subsystem within the built environment. Across the project life cycle, including inception, design, construction, operation, and demolition [2], studies addressing demolition specifically to provide guidance for optimized practices and demonstrate the benefits of selective demolition, such as those by Pani et al. [3] and Kaewunruen et al. [4], remain limited, with most research focusing predominantly on demolition waste management [5]. Conventional demolition of end-of-life structures generates substantial construction and demolition waste (CDW), limiting the recovery, valorization, and reuse of high-quality materials into new construction. It combines multiple demolition streams derived from concretes with varying mixture designs, water-to-cement ratios, and exposure histories. This heterogeneity at the parent concrete level translates into a broader distribution of adhered mortar contents and pore structures in the resulting RCA, thereby increasing variability in physical and mechanical performance.

The recycling of concrete from demolished structures offers a

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pathway to improve resource efficiency, reduce environmental impacts, and support the circular economy, provided that the recycled material preserves the performance characteristics necessary for new concrete production [5,6]. Achieving these benefits requires systematic assessment of material properties, optimized demolition strategies, and methods to maximize the quality and performance of RCA. This study focuses on selective demolition and recycling of Dutch infrastructure concrete, evaluating how parent concrete characteristics, demolition strategy, and recycling methods influence the quality and performance of RCA. The following Introduction defines selective demolition and high-quality RCA, reviews Dutch regulations and current practices, and then presents the study objectives.

1.1. *Motivation and selective demolition*

The high-quality recycling of concrete from end-of-life infrastructure has substantial potential to enhance resource efficiency in the construction of new infrastructure. However, the full benefits of this approach remain largely unrealized due to the absence of standardized mechanisms for assessing the quality of end-of-life concrete in structural members. Effective recycling and reuse require a thorough evaluation of concrete quality, as this determines the suitability of recovered material for high-grade applications. Currently, on-site assessment of concrete properties remains the primary method for evaluating performance and recycling potential. This process can be further optimized through selective demolition practices.

In the context of concrete structures, selective demolition refers to the careful identification and separation of structural members prior to demolition to enable controlled dismantling and optimize the recovery of RCA [3,7–9]. This approach allows cleaner separation of material fractions and improves the quality of RCA [10,11]. Consistent with this, Pantini and Rigamonti [12] emphasize that CDW from selective demolition produces higher-quality RCA, enabling full replacement (replacement factor = 1) of natural aggregates in high-grade applications such as concrete production.

The benefits of selective demolition are further reinforced by research showing that pre-demolition identification of parent concrete quality using systematic classification frameworks further improves RCA quality and reuse potential [13,14]. A representative example is the framework developed by Nedeljković et al. [8], which employs non-destructive concrete quality assessment to classify structural members before demolition, enabling targeted dismantling and maximizing the quality of recycled fractions. Similar methodologies have been applied internationally. In Italy, concrete recovered from the demolition of the old Stadio Delle Alpi was incorporated into the construction of the new Juventus Stadium, demonstrating practical recycling of demolition materials [15].

Experimental studies support the technical viability of high-quality RCA. Pani et al. [3] investigated RCA obtained from both the beams and foundations of the old Cagliari stadium and showed that recycled aggregate concrete can achieve mechanical performance comparable to conventional concrete at high replacement levels when parent concrete quality and mix design are appropriately managed [3]. Similarly, using RCA derived from a demolished old concrete bridge in Serbia, an experimental study demonstrated that the flexural performance of reinforced recycled aggregate concrete beams under short-term loading was satisfactory for both service and ultimate limit states, comparable to natural aggregate concrete beams [16]. Under sustained loading over 450 days, recycled aggregate concrete beams exhibited greater long-term deformability (creep and deflection) than natural aggregate concrete beams [17]. These findings highlight the importance of ensuring high-quality RCA, which can be facilitated in practice through selective demolition.

1.2. *High-quality RCA*

The environmental and resource efficiency benefits of selective demolition and high-quality recycling align directly with climate commitments [18,19]. Achieving ambitious recycling targets requires RCA that not only meets quantity demands but also satisfies strict durability and mechanical standards. Dutch infrastructure concrete is designed for service lives of 50–100 years and may be exposed to carbonation (XC4), chloride ingress (XD3), freeze-thaw cycles with de-icing agents (XF4), and chemical attack from soils or groundwater (XA2) (EN 206, Eurocode 2). These exposure classes impose strict durability and mechanical requirements for concrete containing RCA, emphasizing the critical importance of aggregate quality, particularly density and water absorption.

Concrete performance generally correlates with the quality of the aggregates. Virgin natural aggregates provide the highest mechanical and durability performance. Preserved-quality RCA produced through controlled recycling protocols can approach the properties of natural aggregate concrete [20]. Traditional and commercially available RCA, with high variability, porous adhered mortar, and weaker interfacial transition zones, tend to yield more moderate or reduced concrete performance [21].

Residual adhered mortar in RCA governs water absorption and mechanical performance, with variability driven by parent concrete quality, recycling process, and storage history, highlighting the need for controlled RCA production [22–24]. The resulting RCA quality strongly depends on both the quantity and the intrinsic quality of the old mortar adhered to the aggregate surface [25]. Previous studies have shown that the presence of adhered mortar reduces aggregate density and overall quality, while mechanical properties systematically decrease with increasing mortar content [22,26–28].

Removing adhered mortar or improving the characteristics of this mortar are critical factors for enhancing RCA performance [29–31]. Techniques for the removal or modification of adhered mortar on RCA, including mechanical, chemical, thermal, and combined treatments, as well as polymer emulsions treatment, surface coatings, and accelerated carbonation, are employed to optimize the physical and mechanical characteristics of RCA and to improve the performance and long-term durability of recycled aggregate concrete [21,29,30,32–35]. Systematic reviews confirm these trends, highlighting global advances in RCA treatment and quality control [35,36]. Specialized advanced technologies, including the Smart Liberator [37] and Mangeler [38], have been successfully employed in the Netherlands to remove adhered mortar from RCA. Nevertheless, conventional recycling methods remain the most widely applied, producing aggregates with considerable variability, particularly in fine RCA [22]. Advanced recycling techniques, in contrast, are highly effective for fine fractions (<2 mm), reducing adhered cement mortar and water absorption, and enhancing RCA suitability for high-performance applications [39]. Despite this, systematic data on industrial-scale advanced recycling of infrastructure concrete, especially for fine fractions, remain scarce, highlighting a critical knowledge gap that requires experimental investigation.

1.3. *Dutch regulations and current practice*

RCA production in the Netherlands is approximately 18 million tonnes per year, representing 20–22% of total aggregate use, and the sector is projected to grow at a compound annual growth rate (CAGR) of ~8.4% due to urban renewal projects, circular economy initiatives, and advanced recycling technologies [40,41]. Dutch-specific conditions, including well-sorted demolition waste, advanced recycling infrastructure, and strict environmental regulations, support the scaling of high-quality RCA production.

The transition toward sustainable concrete in the Netherlands is guided by national regulations complementing European standards. The Rijkswaterstaat Technical Document RTD 1033 "Verduurzaming beton" sets project-level requirements for high-quality concrete reuse and reduction of environmental impacts [42]. CUR Aanbevelingen 106, 112, 127 [43–45] provide industry-specific guidance for fine and coarse RCA applications. In particular, CUR Aanbeveling 127 [45] defines a class-based framework linking maximum replacement percentages of primary sand and gravel to RCA quality while retaining Eurocode 2 (NEN EN 1992–1–1) structural rules [46]. Key quality indicators include water absorption, density, and adhered mortar content, with lower water absorption correlating with higher material quality [47]. Despite these advancements, RCA derived from infrastructure concrete remains heterogeneous due to merging with lower-grade concrete at recycling plants, variability in parent concrete composition, and differences in recycling methods.

1.4. Objectives

This study systematically evaluates RCA derived from Dutch infrastructure concrete, focusing on:

1. Differences between RCA from preselected structural members (T-beams, columns, abutments, foundations);
2. Differences between RCA produced using traditional rotor crushers and advanced recycling technologies;
3. Differences between RCA from preselected versus unknown origin concrete rubble. Unknown-origin concrete rubble represents a mixture of varying-quality concretes originating from different demolition sites.

Three recycling plants (Urban Mine, Twee R Recycling Group, and Attero) provided traditional rotor crusher facilities, while two advanced technologies (Smart Liberator and Mangeler) were applied to the same structural members. Multiple particle size fractions (<0.125 mm, 0.125–4 mm, 0–4 mm, 4–22 mm) were characterized to establish relationships between adhered mortar content and the physical, mechanical, and chemical properties of RCA.

This research provides the first systematic experimental assessment of RCA quality from selectively demolished Dutch infrastructure concrete across multiple structural members, recycling methods, and particle size fractions, linking parent concrete properties, recycling strategy, and RCA performance, and informing performance-based acceptance under Eurocode 2 as well as circular economy practices in structural concrete applications.

2. Selective demolition and recycling of the viaduct

2.1. Viaduct description

The source of the concrete batches investigated in this study is the Ardeweg viaduct, a representative example of Dutch infrastructure from the 1960s–1970s. The Ardeweg viaduct has a total length of 79.5 m and a width of 16.25 m. The deck has four spans made of 25 prestressed concrete T-beams per span. The beams rest on in-situ cast support beams, columns, abutments, foundations, and piles. The existing viaduct had to be demolished because it could not accommodate the ongoing widening of the A1 motorway (the primary north-south highway) [48]. In 2024, the viaduct demolition was announced and became available for this research.

2.2. Parent concrete quality assessment

The concrete compositions of the structural members were determined through thin-section analyses [49]. The mixes consisted of Portland cement with gravel and river sand as coarse and fine aggregates, respectively.

Mechanical characterization revealed clear differences between structural members. The mean compressive strength of the support beams, based on six extracted cores, was 69.7 MPa, with a standard deviation of 14 MPa. The prefabricated T-beams showed a higher mean compressive strength of 83.9 MPa, with a standard deviation of 5.9 MPa [49]. Mean strength values for the abutments and foundations were inferred from the Sluinerweg twin viaduct [13], constructed in the same period using identical design specifications and raw materials.

Durability assessments revealed further heterogeneity. The Ardeweg viaduct exhibited localized damage near the prestressed T-beam heads, along with joint leakage, insufficient concrete cover, visible corrosion products, and elevated chloride exposure in the support beams [49]. Chloride ingress was generally superficial, limited to the near-surface layers relative to the concrete cover, with chloride contents below 0.25% by mass of concrete in most locations. However, at one support beam, chlorides penetrated to a depth approaching the cover thickness and exceeding the critical threshold of 0.4%. Carbonation depths measured on concrete cores, reported by Zhong [49], ranged from 2 mm to 24 mm in support beams and T-beams, respectively, remaining within the concrete cover (average 44 mm for support beams and 57 mm for T-Beams).

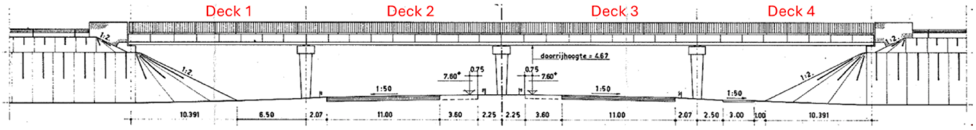
Surface treatments also differed among structural members. Support beams, abutments, and columns were coated with a Kristal Cement Graniet (KCG) layer, a mortar-based coating embedding granite granules, whereas prefabricated T-beams were uncoated [49]. Columns and foundations below ground level were protected with a bituminous layer.

These variations in mechanical performance, exposure conditions, protective systems, and deterioration mechanisms demonstrate that the viaduct did not represent a homogeneous concrete source. Recycling all components as a single material stream would therefore compromise aggregate quality control. Consequently, a targeted demolition strategy was implemented to enable separate processing of structural members and to maintain traceability of parent concrete properties during recycling.

2.3. Selective demolition and recycling

Before demolition, surface impurities were removed from the structure, including soil works and the scraping of asphalt from the deck. The high-pressure water jetting was applied after mechanical removal of the asphalt layer to eliminate residual bitumen. The bituminous protective coating applied to the concrete structural members located below ground level (foundations and the underground sections of columns) was not removed prior to demolition.

The demolition sequence commenced with the Self-Propelled Modular Transporter (SPMT)-assisted removal of the main-span T-beams as entire elements, as shown in Fig. 1, whereas the T-beams in the end spans, were mechanically fragmented in situ using a multi-jaw. Thereafter, the columns were demolished together with support beams using a multi-jaw. Finally, the foundations and abutments were demolished separately with a jackhammer. Most of the prestressing steel and conventional reinforcement is removed during the crushing of concrete structural members using scissor crushers, while the remaining ferrous metals are subsequently recovered at the recycling plant by magnetic separation, which may involve either electromagnets or solid-state (permanent) magnets. After the demolition of the four distinct structural members, the resulting concrete rubble was separated and sorted into designated containers for subsequent transport to the certified recycling plants. For each category (T-Beams, Columns, Abutments, Foundations), a minimum of 20 tonnes of concrete was processed for recycling. Five different recycling techniques were used in this study. Namely, the concrete rubble was recycled using two advanced recycling techniques Smart Liberator and Mangeler (0–0.125 mm, 0.125–4 mm, 4–22 mm), as well as three traditional rotor/impact techniques (0–4 mm, 4–22 mm). To simulate typical recycling conditions as a reference, unknown concrete rubble was processed in regular operation (0–4 mm, 0–31.5 mm).



a) Technical drawing of the Ardeweg viaduct.

b) View of the Ardeweg viaduct from the A1 motorway, facing north [49].

c) SPMT is positioned under the deck 2 to support and enable controlled movement of the structure [48].

d) The deck 2 is gradually being dismantled and removed to the designated drop-off location [48].

Fig. 1. a) Technical drawing of the Ardeweg viaduct; b) View of the Ardeweg viaduct from the A1 motorway, facing north; c) SPMT is positioned under the deck 2 to support and enable controlled movement of the structure [48]; d) The deck 2 is gradually being dismantled and removed to the designated drop-off location [48], e) Demolition of deck 1 (T-beams); f) Simultaneous demolition of support beams and columns; g) Demolition of the foundation.

e) Demolition of deck 1 (T-beams).

f) Simultaneous demolition of support beams and columns.

g) Demolition of the foundation.

Fig. 1. (*continued*).

2.3.1. *Process step (1) Traditional rotor crusher recycled materials*

A traditional rotor crusher, shown in Fig. 2, processes concrete rubble into RCA through high-energy impact forces. In these machines, concrete enters a chamber where it encounters a high-speed rotor equipped with steel blow bars or hammers, which project the material against stationary impact plates [50,51]. The repeated impacts generate fracture by dynamic stresses, breaking both the adhered mortar and the aggregate particles into smaller sizes suitable for reuse. The particle size distribution and shape of the resulting RCA are controlled by rotor speed, blow bar configuration, and the spacing between rotor and impact surfaces, with higher impact energies generally producing a broader range of fines and more irregular particle shapes compared with compressive or friction-based recycling mechanisms, such as advanced separation techniques.

All batches were directly collected from demolition site, see Fig. 1. The quantities of each batch after demolition are shown in Table 1.

A pre-crushing operation was necessary before recycling. This operation consisted of crushing the fraction greater than 60 mm. In order to facilitate sorting of different samples, a sieving separation was first performed on each of them. The sample was fed on a conveyor belt equipped with a magnetic pulley at its end which removed the ferrous materials from the flow of material. Then, a double pass was provided on a double-stage vibrating screen in order to obtain four particle size fractions in order to carry out the visual characterization: fraction

Fig. 2. Traditional rotor crusher.

Table 1
Viaduct concrete quality and recycled fractions.

Viaduct	**T-Beams**	**Support beams***[*]	**Columns**	**Abutments**	**Foundations**
Cement type	Portland	Portland	Portland	Portland	Portland
Aggregate type	river gravel and sand	river gravel and sand	river gravel and sand	river gravel and sand	river gravel and sand
Compressive strength	84 ± 6	70 ± 14	71 ± 6.2	64 ± 3.0	67 ± 5.3
Chloride ingress	localized in concrete cover	localized in concrete cover	not detected	not detected	not detected
Surface treatments	uncoated	partially coated with KCG layer	coated with KCG layer and bituminous layer	coated with KCG layer	coated with bituminous layer
Demolition method	multi jaw	multi jaw	multi jaw	jack-hammer	jack-hammer
Totals	800 m^3	120 m^3		250 m^3	80 m^3
Recycling	**T-Beams**	**Columns**		**Abutments**	**Foundations**
	Traditional rotor crushers (Urban Mine, Twee R Recycling groep)				
	0–4 mm	0–4 mm		0–4 mm	0–4 mm
	4–22 mm	4–22 mm		4–22 mm	4–22 mm
	Advanced recycling techniques Smart liberator and Mangeler				
	0–0.125 mm	0–0.125 mm		0–0.125 mm	0–0.125 mm
	0.125–4 mm	0.125–4 mm		0.125–4 mm	0.125–4 mm
	4–22 mm	4–22 mm		4–22 mm	4–22 mm

[*] Support beams and columns were demolished simultaneously; for clarity, this batch is hereafter labeled ‘columns’.

(+40 mm); fraction (−40 + 22 mm); fraction (−22 + 4 mm); and fraction (−4 mm). The contaminants were removed as much as possible by hand picking. Two samples (these represent the fraction under 4 mm and between 4 and 22 mm) were collected per batch (batch T-beams, batch Columns, batch Abutments, batch Foundations and batch Unknown rubble). All samples were delivered fresh to the laboratory for characterization (no storage after production).

2.3.2. *Process step (2) Advanced recycled materials*

2 A: The demolition concrete was initially pre-crushed by the rotor crusher. The reduced material was then processed through the Smart Liberator. Specifically, RCA were produced in three size fractions (<0.125 mm, 0.125–4 mm, 4–22 mm) by further crushing the 4–22 mm rotor-crushed material. The Smart Liberator (Fig. 3) is designed to separate sand, gravel, and cement, while minimizing damage to the aggregate. This is achieved by precisely adjusting the crushing force to the particle strength and the compressive strength of the cementitious matrix. This technique integrates both crushing and grinding in a single process [37].

2B: The demolition concrete was initially pre-crushed to a 0–40 mm fraction and fed into the Mangeler system. All (pre-crushed) materials were dried naturally in the open air as much as possible. The material to be processed was then fully mangled twice. This material was then sieved to 0.125 mm and 4 mm. The Mangeler (Fig. 4) processes concrete rubble into RCA primarily through inter-particle friction, rather than conventional crushing. During processing, aggregates rub against each other, initiating the separation of adhered mortar from the aggregate surfaces. The system consists of a feed tube combined with eccentric discs that generate controlled frictional forces [38]. In addition, a sieve is integrated to separate fine fractions from the coarser concrete rubble. A heated double horizontal swing sieve, equipped with a rack containing cleaning balls beneath each sieve, was used.

3. Material characterization

3.1. *Materials*

Table 1 provides an overview of the concrete quality of the Ardeweg viaduct and the corresponding size fractions produced, categorized by concrete origin and recycling technique. In addition to the viaduct-derived material, a reference batch of unknown-origin concrete rubble was processed by the recycling plant Attero using a traditional rotor

Fig. 3. Smart Liberator, industrial-scale recycling technique for concrete.

Fig. 4. Mangeler, industrial-scale recycling technique for concrete.

crusher to produce two size fractions (0–4 mm and 4–31.5 mm). This batch, of unknown quality, originates from multiple demolition projects and represents a heterogeneous mixture of concretes with varying composition, strength, and degree of deterioration.

3.2. Experimental methods

Buckets of all studied materials (described in the materials section) were collected (about half a tonne for each batch), and representative samples (about 30 kg for each sample) were obtained by coning and quartering. Table 2 presents a summary of the experimental program conducted in this study. Physical properties testing included the particle size distribution of aggregates, density and fineness, water absorption after 60 min and 24 h, moisture content, cement paste content, fines content, Los Angeles coefficient, flakiness index, and constituents of aggregates. The chemical properties investigated were water soluble sulfate content, water-soluble and acid-soluble chloride ion content, clay content, loss on ignition, total organic carbon and chemical composition. Recycled powders have been characterized with different tests: moisture, density, water demand (βp), Blaine fineness, the total organic carbon (TOC) content, methylene blue, chemical composition, and loss on ignition.

4. Results

This section first describes the constituents of the coarse RCA, followed by the physical and chemical characterization of both coarse and fine RCA. The properties of the powder fractions are presented next.

4.1. Constituents of coarse RCA

Table 3 shows the contents of various constituents in coarse RCA in relation to five recycling techniques and different origins of RCA (T-beams, columns, abutments, foundations, and unknown concrete rubble). The abbreviations T, C, A, F, UR in Table 3 are used to state that these refer to RCA obtained from different structural members (e.g., T-beams, Columns, Abutments, Foundations) and from unknown concrete rubble (UR).

Table 2
Characterization of recycled materials.

Coarse RCA (4–22 mm)	**Method/Standard**
Constituents of coarse recycled aggregates	EN 933–11
Material appearance	Image acquisition per sieve size
Particle size distribution of aggregates	EN 933–1
Particle density and water absorption	EN 1097–6 (60 min and 24 h)
Moisture content	EN 1097–5
Los Angeles coefficient	EN 1097–2
Fines content (< 0.063 mm)	EN 933–1
Flakiness index	EN 933–3
Cement paste content	EN 1744–5
Water soluble sulfate content	EN 1744–1
Water-soluble chloride ion content	EN 1744–1
Acid-soluble chloride ion content	EN 1744–5
Fine RCA (< 4 mm)	
Material appearance	Image acquisition per sieve size
Particle size distribution of aggregates	EN 933–1
Particle density and water absorption	EN 1097–6 (60 min and 24 h)
Moisture content	EN 1097–5
Fines content (< 0.063 mm)	EN 933–1
Methylene blue test	EN 933–9
Cement paste content	EN 1744–5
Water soluble sulfate content	EN 1744–1
Water-soluble chloride ion content	EN 1744–1
Acid-soluble chloride ion content	EN 1744–5
Chemical composition	X-ray fluorescence spectrometry
Recycled powders (< 0.125 mm)	
Material appearance	Image acquisition per sieve size
Moisture content	EN 1097–5
Particle density	EN 1097–7
Fines content (< 0.063 mm)	EN 933–1
Blaine fineness	EN 196–6
Methylene blue test	EN 933–9
Water demand βp-value	EN 196–1 spread-flow test
Water soluble sulfate content	EN 1744–1
Water-soluble chloride ion content	EN 1744–1
Acid-soluble chloride ion content	EN 1744–5
Cement paste content	EN 1744–5
Loss on ignition	EN 196–2
Total organic carbon (TOC)	EN 13639
Chemical composition	X-ray fluorescence spectrometry

For structural concrete applications, only high-quality RCA classified as Type A are permitted. For this type of aggregate, limits for constituents such as concrete, unbound aggregates, clay masonry units (i.e., bricks and tiles), calcium silicate masonry units, bituminous material, floating material, and glass, plastic, rubber, ferro, and cohesive materials are set to be Rc90 ($Rc \geq 90\%$), Rcu95 ($Rcu \geq 95\%$), Rb10 ($Rb \leq 10\%$), Ra1 ($Ra \leq 1\%$), FL0.2 ($FL \leq 0.2$ cm^3/kg), and XRg1 ($XRg1 \leq 1\%$). It can be seen that most aggregates comply with these requirements in Table 3, with several exceptions for Rc and Ra results. In particular, Ra values for columns and foundations exceed the specified limit (<1) by up to threefold, independent of the recycling technique. This elevation indicates the presence of bituminous material within these aggregates. The concrete recycled from the deck's T-beams, in contrast, contained very little contamination. The elevated Ra can be attributed to bituminous coatings and surrounding brick masonry associated with the demolished structural members. Archival records of the viaduct indicate that all concrete surfaces in contact with soil, with the exception of reinforced concrete piles, were coated twice with a project-approved bituminous product. These records are supported by photographs presented in Fig. 5. Based on these findings, it is evident that cast-in-place concrete members located below ground level, which were coated with a bituminous protective layer prior to demolition, produced RCA contaminated with bitumen. To mitigate such contamination in future recycling operations, enhanced pre-demolition cleaning and preparation procedures are recommended for structural members in direct contact with soil or bituminous materials, ensuring effective removal of soil, masonry, and bituminous coatings before demolition.

In the present dataset, Rb values range up to 0.9%, with this maximum occurring only in certain samples. The slightly elevated Rb contents can be attributed to brick masonry surrounding specific structural members of the demolished structure (see Fig. 5), which was locally incorporated during processing. Nevertheless, for Type A RCA, the maximum allowable Rb content is 10%, which is substantially higher than the values measured in this study.

Constituents such as crushed bricks and similar materials are known to increase water absorption, consequently raising porosity and reducing the density of the resulting concrete, thereby potentially compromising mechanical performance and durability when present in elevated quantities [52]. In contrast, RCA production in this study consistently achieved Rcu values between 96% and 100% (mean = 99%). Accordingly, from a classification perspective, limiting the Rb content to below 1% appears more appropriate for Type A, high-quality RCA intended for structural applications.

Furthermore, if the advanced recycling process is used, it could help decrease clay content (Rb value) but not entirely remove contaminants such as bituminous materials, as indicated by the Ra value of 2 (>1) for recycled materials produced by Smart Liberator. For special applications requiring a high-quality surface finish, the constituent FL should be limited to category $FL_{0.2}$. This is the case for the infrastructure projects, and the limit value is set to 0.2 cm^3 /kg. The results show that FL is lower than or equal to 0.2. Under normal operating conditions, washing would be applied, and FL would be significantly reduced or recycled materials would be free of floating material.

Regarding performance of Smart Liberator in terms of Rc and Ru values, it differs from those of the traditional rotor crushers. Rotor crushers break concrete into particles consisting of natural aggregates with residual adhered mortar, without fully separating the original aggregates. In contrast, the Smart Liberator employs a selective liberation mechanism, applying controlled mechanical forces to detach the mortar from the aggregates and recover the original gravel and sand fractions. Consequently, in the EN 933–11 classification, the Rc (recycled concrete) percentage appears lower, since part of what would normally be categorized as "concrete" in rotor-crushed RCA is instead separated into unbound aggregate (Ru) fractions. This results in a relatively higher Ru

Table 3
Classification of coarse RCA according to EN 933–11 (Rc, Ru, Rb, Ra, Rg, X and FL refer to percentages of concrete products, unbound aggregate, clay masonry units, bituminous materials, glass, other non-floating materials and volume percentage of floating material in %, respectively).

	Traditional Twee R				Mangeler				Traditional Urban Mine				Smart Liberator				Attero	EN
	4/22				4/22				4/22				4/22				4/31.5	12620
	T	**C**	**A**	**F**	**T**	**C**	**A**	**F**	**T**	**C**	**A**	**F**	**T**	**C**	**A**	**F**	**UR**	**Limit**
FL	0	0	0.2	0.1	0	0	0	0.1	0	0	0	0	0	0	0	0	0.2	**≤ 0.2**
Rc	98	95	98	94	97	97	98	94	97	95	97	95	**86**	**85**	90	**88**	96	**≥ 90**
Ru	1.5	2.3	1.6	2	2.5	2.5	1.7	3.7	2.3	3.7	3	1.9	**14**	**13**	9.3	**10**	2.5	**≤ 10**
Rb	0	0.1	0	**0.9**	0	0	0	**0.4**	0.4	0.1	0	**0.8**	0	0	0.2	0.1	**0.9**	**≤ 10**
Ra	0.7	**3.1**	0.3	**2.6**	0.1	0.3	0.1	**2.2**	0	**1.6**	0.1	**2.7**	0.2	**2**	0.2	**2**	0.3	**≤ 1**
Rg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**≤ 2**
X	0	0	0.1	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0.1	**≤ 1**
Rcu	**99**	**97**	**100**	**96**	**100**	**100**	**100**	**97**	**100**	**98**	**100**	**97**	**100**	**98**	**100**	**98**	**99**	**≥ 95**
Rcug	99	97	100	97	100	100	100	97	100	98	100	97	100	98	100	98	99	**≥ 90**
XRg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**≤ 0.5**
Rcb	98	95	98	95	97	97	98	94	98	95	97	95	86	85	90	88	97	

Fig. 5. Exposure environments of structural members: (left) columns partially coated with bituminous layer at the lower section of their height and surrounded by soil and brick masonry; (right) foundations coated with a bituminous layer, in direct contact with soil and brick masonry.

content, as the Smart Liberator produces cleaner natural aggregates that are no longer bound to mortar. As a direct outcome of this selective process, the Smart Liberator material does not fully meet the EN 12620 specification for coarse RCA conform type A of EN 206, specifically the requirements of Rc $\geq$ 90% and Ru $\leq$ 10%. This deviation is therefore not a reflection of poor quality, but rather of the distinct working principle of the Smart Liberator, which prioritizes the recovery of clean aggregates over compliance with the conventional Rc/Ru classification balance.

4.2. *Physical properties*

4.2.1. *Appearances of RCA*

Figs. 6–9 show the morphology of freshly broken surfaces of individual RCA particles. The most characteristic visual appearance of RCA produced with traditional technique Rotor crusher in this study include:

- elongated irregular grains,
- rough surfaces,
- display predominantly a concrete colour and, to a lesser extent, a variety of colours of original aggregates,
- discontinuities,
- presence of cement mortar,
- presence of masonry, ceramics, and ferrous materials.

Most of coarse RCA are composed of concrete and sporadically, mainly in columns and foundations from brick materials. Fine RCA particles show highly angular shapes and rough surfaces for rotor crusher.

Recycled materials produced with advanced technique Smart Liberator have the following characteristics:

- rounded grains and angular grains,
- smooth and rough surfaces,
- display predominantly color of original concrete aggregates,
- minimal presence of cement mortar due to higher number of stage-crushing processes,
- presence of masonry, ceramics, and ferrous materials.

For both, traditional and advanced recycled materials, the variation of particle morphology within a particle population is low and the

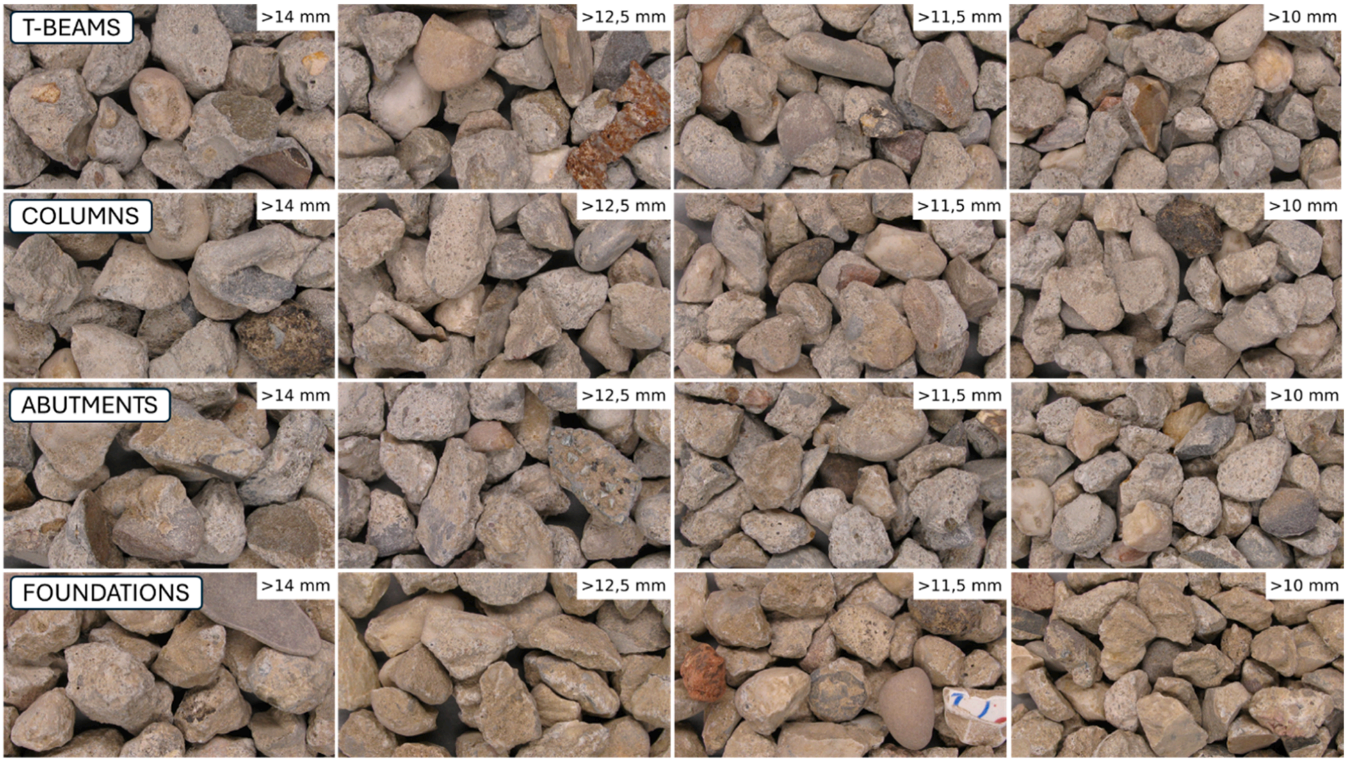


Fig. 6. Overview of the particle morphology of coarse RCA produced using a rotor crusher (Twee R Recycling Group).

Fig. 7. Overview of the particle morphology of coarse RCA produced using the Smart Liberator.

variation of particle morphology between different RCA (T-Beams, columns, abutments, foundations) is small compared to that between RCA and reference sand [53].

The key observations for the fine powders (<0.125 mm) are presented in Fig. 10. The batches are distinguished by their characteristic colors: powders from T-beam recycling exhibit a concrete-gray color, whereas powders from foundation recycling appear dark yellow.

4.2.2. *Particle size distribution*

The particle size distributions of natural sand and gravel, and also of

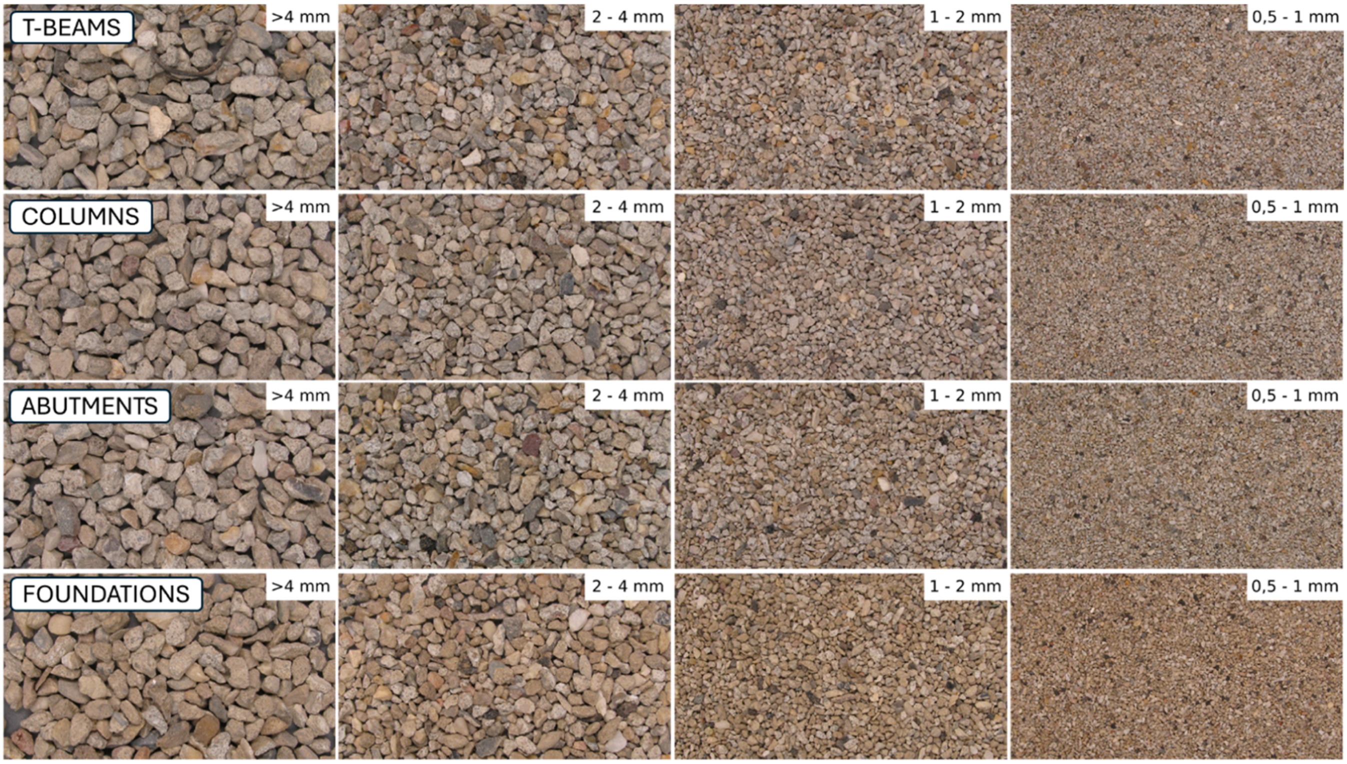


Fig. 8. Overview of the particle morphology of fine RCA produced using a rotor crusher (Twee R Recycling Group).

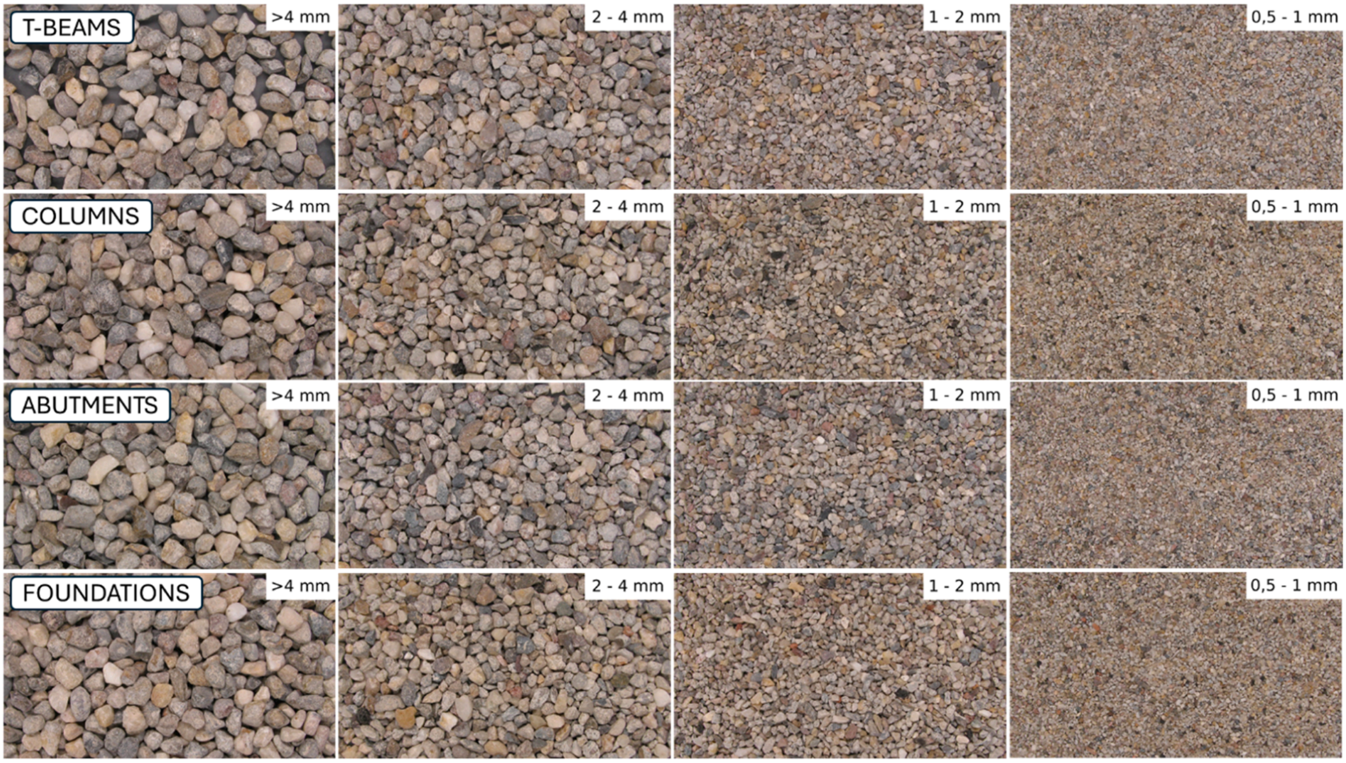
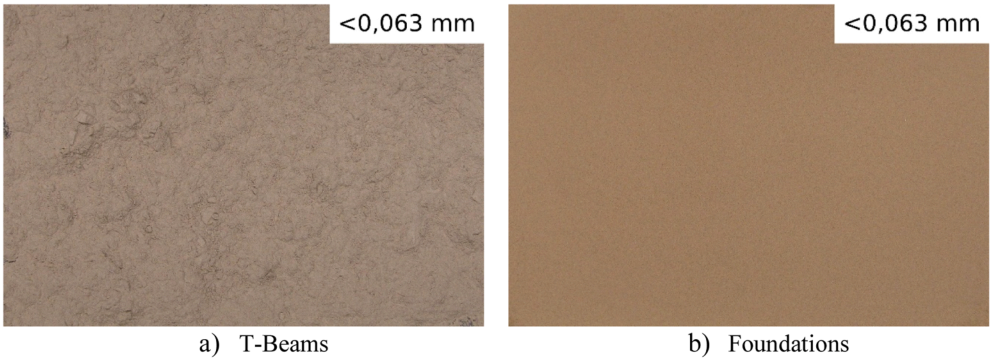


Fig. 9. Overview of the particle morphology of fine RCA produced using the Smart Liberator.

materials produced by rotor crusher and from unknown concrete origin, are presented in Fig. 11. Different RCA with range 0–4 mm is shown in Fig. 12. In addition, lower and upper limits according to NEN-EN 12620 [54] are shown for assessment of the suitability of fine RCA for use as a sand for concrete mix design. It can be seen that the particle size distribution of material obtained from one source concrete is dependent on the recycling technique, and that fine RCA from different batches complies with the overall limits in NEN-EN 12620 [54], except fine RCA



a) T-Beams b) Foundations

Fig. 10. Recycled powders (<0.063 mm) from rotor-crushed concrete: (a) T-beams, (b) foundations (Twee R Recycling Group).

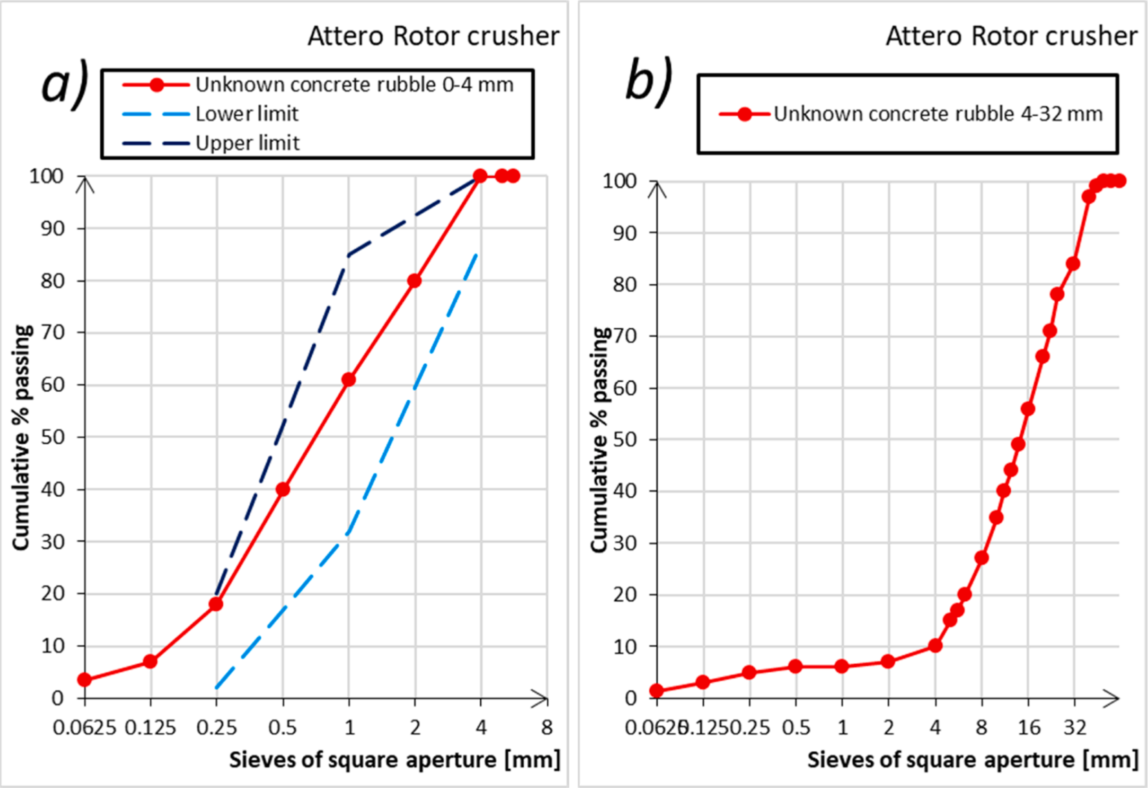


Fig. 11. Particle size distribution of (a) fine and (b) coarse RCA obtained from unknown-origin concrete rubble.

from abutments and foundations. The variations in different percentages for grain size fractions of various fine RCA, such as the higher percentages of the fraction 0–0.125 mm (7–30 wt%) compared to natural sand (~6 wt%) (Fig. 13), are significant, except for materials produced with Smart Liberator. Regardless of the concrete's origin, Smart Liberator yields uniform percentages for grain size fractions, except for foundations, see Fig. 13. Coarse RCA (Fig. 14) exhibited highly similar particle size distributions, irrespective of the viaduct structural member type or recycling technique. A similar observation was reported by Pani et al. [3], who found comparable particle size distributions for coarse RCA derived from beams and foundations of the former Cagliari stadium, despite differences in parent concrete characteristics.

4.2.3. Density

Table 4 shows saturated and surface-dried (SSD) particle density results. As can be seen, density is higher as the fraction size is higher. Importantly, the coarse RCA types exhibit similar densities, despite being produced from four different parent concretes, whereas fine RCA and powder fractions display greater variability in density. Similar findings were reported by Kou and Poon [55], who observed that coarse RCA densities were largely independent of parent concrete strength. For fine RCA the density is lower than for river sand; the largest difference occurs in the finest fraction, i.e. < 0.125 mm. The density of preselected fine RCA is reduced compared to density of pure quartz 2650 kg/m^3, but it is higher than that of recycled materials from concrete of unknown origin (Attero) 2380 kg/m^3.

Regarding the density separation for the RCA (Table 4), about 74% of insoluble matter of sample mass is concentrated in density above 2380 kg/m^3 containing 21% of cement paste; 85% in density above 2500 kg/m^3 with 13% of cement paste; 89.8% insoluble matter of sample mass is concentrated in density above 2600 kg/m^3 and just 8.5% of cement paste. The composition of the fine RCA sink at 2580 kg/m^3 is outstanding. There is also a remarkable increase in the content of SiO_2 (83%); 11.2% of the cement paste from the sample (88.8% is sand) is concentrated in this product, which leads to an amount of SiO_2 of 90.7% in the sand part, i.e. quartz (Table 9). These results show that higher-

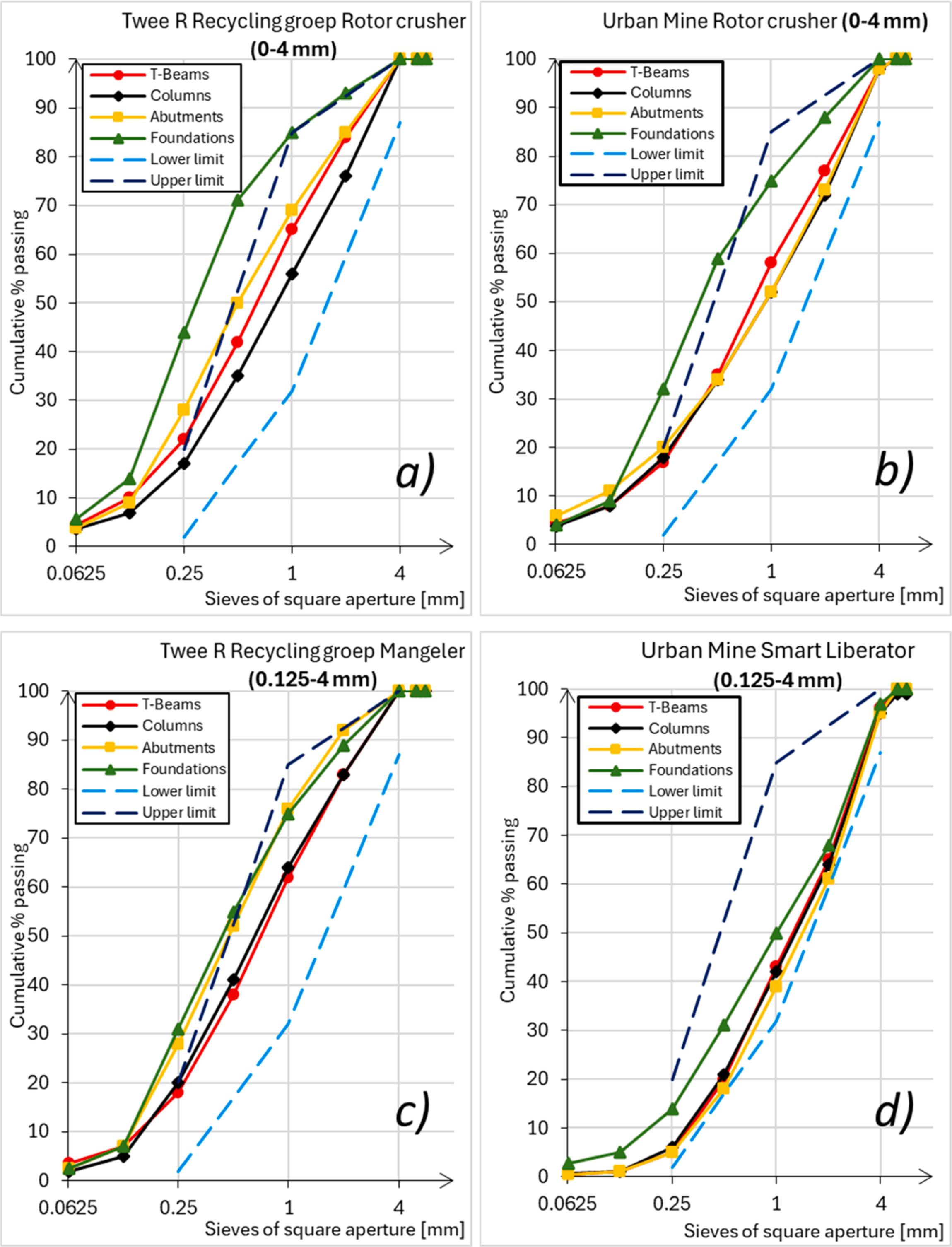


Fig. 12. Sieving curves of fine RCA, obtained by dry sieving method, upper and lower limits according to NEN-EN 12620 [54], a) Twee R Recycling groep Rotor crusher 0/4, b) Urban Mine Rotor crusher 0/4, c) Twee R Recycling groep Mangeler 0.125/4, d) Urban Mine Smart Liberator 0.125/4.

density particles tend to contain lower amounts of adhered mortar, while lighter particles are enriched in adhered mortar. Although no active density-based separation (e.g., jigging) was applied in this study, this trend explains why the removal of lighter fractions could improve the quality of RCA by reducing adhered mortar content.

4.2.4. Moisture content and water absorption

Fig. 15 shows the moisture content of fine (0–4 mm) and coarse (4–22 mm) RCA upon delivery. All RCA samples were stored, handled, and tested under identical laboratory conditions. Although different structural members experienced different environmental exposures during approximately 60 years of service life, these exposures influenced the internal pore structure of the parent concrete rather than the moisture measurement itself. Consequently, the observed differences in moisture content reflect differences in RCA porosity and crushing-induced microstructure, not differences in handling or measurement.

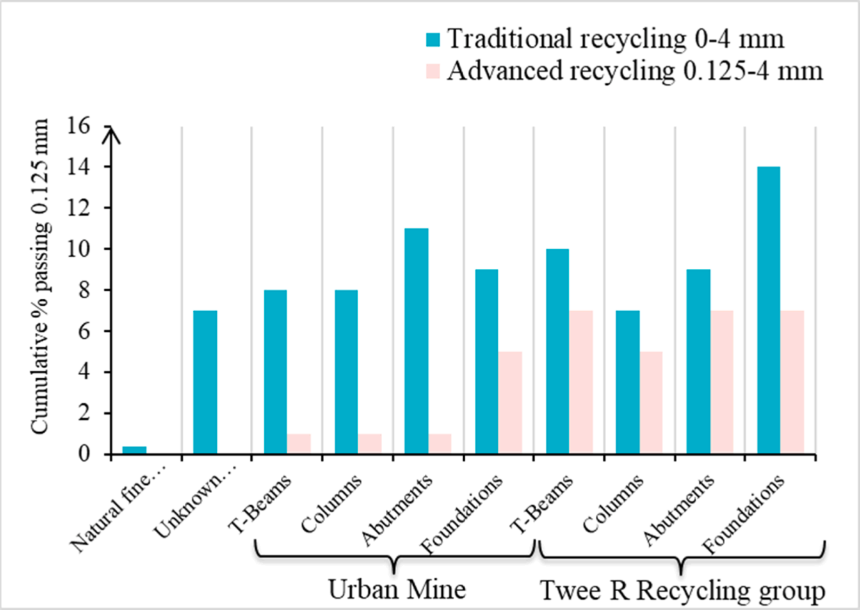


Fig. 13. Cumulative percentage passing 0.125 mm for the 0.125–4 mm and 0–4 mm fractions.

In contrast, the moisture content of RCA from concrete of unknown origin reflects the heterogeneous pore structures of different parent concretes and potentially longer or less controlled storage and handling, leading to higher measured values as it can be observed in Fig. 15a, b.

Recycled materials from traditional rotor crushers exhibited higher free water content than those processed with advanced techniques, likely due to the absence of the fraction 0- 0.125 mm in the latter (Fig. 15a). The presence of 0- 0.125 mm fraction increases porosity. This higher porosity, which is more pronounced in finer fractions due to greater surface area and mortar content, leads to increased moisture retention [35]. The moisture content of the studied fine RCA was lower than that of recycled materials from unknown concrete rubble (8.9%) and below the value reported in the literature (12 wt%) [56].

Moisture was systematically lower for the 4–22 mm fraction, nearly a factor of two or more compared with the 0–4 mm aggregates. Coarse RCA exhibited lower moisture content than fine RCA, as shown in Fig. 10b. This behavior can be attributed to several factors: coarse aggregates have a lower specific surface area, which reduces the amount of water retained on particle surfaces. They contain proportionally less adhered mortar, which is more porous and retains water and the larger particle size limits the volume of capillary pores that can hold free water.

Moisture content is a key parameter for RCA characterization, as it directly affects measured physical properties, handling, storage, and the reproducibility of laboratory tests, enabling meaningful comparisons between different sources and processing methods. Furthermore, the moisture state of RCA plays a critical role in governing both the microstructural characteristics and the macroscopic behavior of recycled aggregate concrete [57].

Fig. 16 presents the water absorption of fine (0–4 mm) and coarse (4–22 mm) RCA. For RCA produced from selectively demolished structural members, water absorption values are substantially lower than those of conventional RCA. The difference is particularly significant when compared with RCA of unknown parent concrete origin, such as the 0–4 mm fractions from unknown concrete rubble (~8%). This reduction, with water absorption ranging from 2% to 6% for fine RCA and 1.5–4% for coarse RCA, is primarily due to the high quality of the parent concrete and the application of advanced recycling techniques [9,13,14].

Due to high moisture content, clogging occurred within the feeding tube of Mangeler, necessitating a reduction in the feeding rate. This led to an incompletely filled tube and insufficient removal of fines, resulting in elevated water absorption values compared to those obtained for materials processed using the Smart Liberator (Fig. 16a, b). It was concluded that demolition rubble should be maintained as dry as possible throughout the entire demolition, transportation, and storage process. Pre-crushing should be performed to the desired maximum particle size (D_{max}), and all feasible techniques should be applied to remove contaminants. Furthermore, the fine fraction (0–4 mm) should be separated before subsequent advanced processing methods are applied.

The water absorption values measured at 60 min and 24 h show a limited rate of increase after the first hour, with this effect more pronounced for coarse RCA. The water absorption kinetics of RCA are consistent with literature findings [16,58–63], showing rapid initial uptake within the first 5–10 min, during which approximately 90–100% of the total 24-hour water absorption is achieved [59,64,65], followed by a gradual decline in the absorption rate. This initial rapid uptake is primarily due to the filling of large, accessible pores within the adhered mortar and at the interface between adhered mortar and the original aggregates [61]. Subsequently, the absorption rate decreases as water gradually penetrates smaller capillary pores [60], with the transition corresponding to the wetting front reaching the center of the RCA particle [58].

The heterogeneous porous structure of RCA, characterized by a broad distribution of pore sizes and variable accessibility to external water, governs RCA water absorption behavior [66]. This mechanism is analogous to the Terzaghi capillary rise model [58]. The ultimate water absorption value of RCA can therefore be interpreted as the cumulative uptake of water into the pore network of the adhered mortar, the interfacial zone between adhered mortar and original aggregates, and, to a lesser extent, the original natural aggregate, driven by capillary forces within micro- and mesopores [67].

As a direct consequence of this rapid and multi-scale absorption behavior, uncontrolled water uptake during mixing can significantly affect workability and the effective water-to-binder ratio of recycled aggregate concrete. To mitigate these effects, pre-saturation of RCA prior to mixing is widely recognized as an effective strategy to ensure stable fresh-state behavior and optimal concrete performance. Alternative approaches may also be adopted depending on the application, including RCA drying [68], adjustment of mixing procedures [69–76],

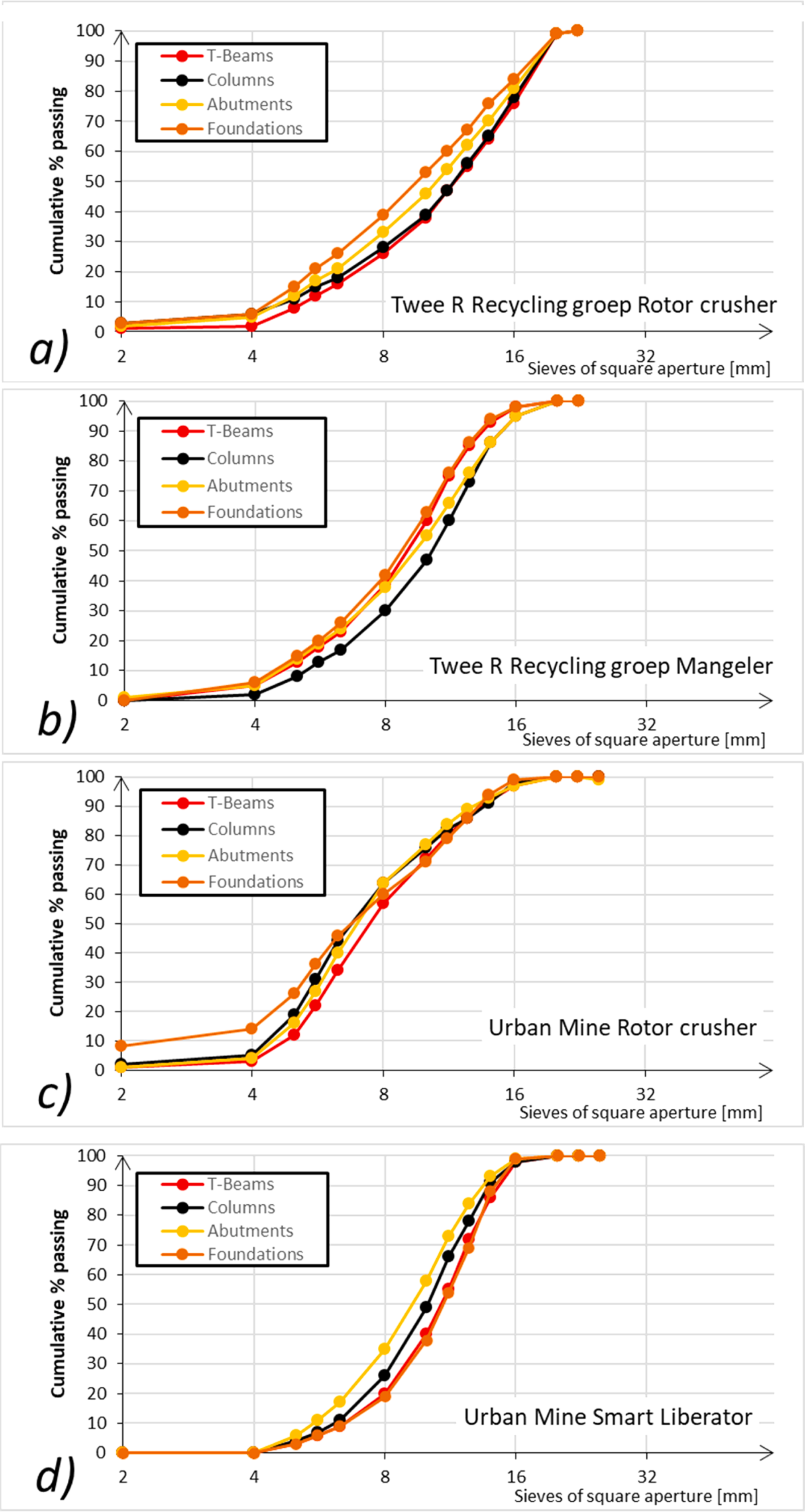


Fig. 14. Sieving curves of RCA 4/22 mm, obtained by dry sieving method, a) Twee R Recycling groep Rotor crusher, b) Twee R Recycling groep Mangeler, c) Urban Mine Rotor crusher, d) Urban Mine Smart Liberator.

Table 4
SSD density of fine RCA and coarse RCA [kg/m^3]. Density of powders (<0.125 mm) was obtained by pycnometer method.

		T-Beams	Columns	Abutments	Foundations
Urban Mine	<0.125	2420			
Smart Liberator	0.125-4	**2580**	**2580**	**2540**	**2540**
	4-22	**2580**	**2610**	**2590**	**2600**
		T-Beams	**Columns**	**Abutments**	**Foundations**
Twee R Recyling groep	<0.125	2390	2430	2430	2490
Mangeler	0.125-4	**2530**	**2490**	**2510**	**2530**
	4-22	**2490**	**2490**	**2500**	**2490**
		T-Beams	**Columns**	**Abutments**	**Foundations**
Urban Mine	0-4	**2440**	**2450**	**2440**	**2520**
Rotor crusher	4-22	**2480**	**2460**	**2460**	**2480**
		T-Beams	**Columns**	**Abutments**	**Foundations**
Twee R Recyling groep	0-4	**2430**	**2450**	**2490**	**2510**
Rotor crusher	4-22	**2470**	**2450**	**2450**	**2440**
		Unknown rubble			
Attero	0-4	**2380**			
Rotor crusher	4-22	**2420**			

modification of ingredient sequencing or the use of chemical admixtures [23].

Regarding pre-saturation, different strategies are researched both prior to mixing, with conditioning periods ranging from 24 h to 7 days [77] and during mixing, typically for short durations of approximately 10 min [68,78,79]. When fine RCA is pre-saturated before incorporation into the mix, the aggregates act as internal water reservoirs, moderating water exchange during mixing and early hydration.

Two principal pre-saturation approaches are commonly distinguished: (1) partial saturation, achieved by adding a precisely calculated amount of water based on the measured water absorption of fine RCA, and (2) full immersion. For example, mortars produced with fine RCA pre-saturated with water absorption + 5% for 24 h exhibited improved workability compared to mortars prepared with fully immersed fine RCA for the same duration [68]. De Andrade et al. [80] applied 80% of the 24-hour water absorption capacity during the mixing stage, assuming that RCA does not reach full saturation during the short mixing process. Water uptake during casting and hardening was not considered. These findings are consistent with reported workability trends for concretes incorporating coarse RCA [81,82]. Despite its effectiveness, achieving precise saturation of RCA without introducing excess free water remains a major challenge in industrial ready-mix concrete production [67]. Advancing this practice requires a deeper understanding of the early-stage water absorption behavior and governing mechanisms of RCA. Duan et al. [60] demonstrated, using modeled RCA, that water uptake is strongly controlled by pore structure characteristics at the micro-scale. These insights are relevant for interpreting and managing water absorption in RCA, enabling more accurate adjustments of effective water-to-binder ratios in concrete mixes.

4.2.5. *Los Angeles coefficient*

The results of the Los Angeles test for the studied samples are summarized in Table 5. No significant differences were observed in the Los Angeles (LA) of RCA from different structural members when a single crushing technique was applied. This is attributed to the use of the same river gravel in the parent concrete (T-beams, columns, abutments, foundations, see Table 1). For unknown origin RCA, a higher LA coefficient (35) may be attributed to weak physical interfaces between the adhered mortar and aggregates in the parent concretes, or due to presence of microcracks. The results were lower than the standard limit of 40 for structural applications, indicating higher resistance to fragmentation for all studied RCA. In the Los Angeles abrasion test, all the attached mortar of RCA is powdered, in addition to the abrasion suffered by the natural aggregates. All samples were found to have a Los Angeles coefficient higher than 20, the typical value of high-quality natural aggregate. The Los Angeles values for materials produced with Smart Liberator were lower than 20. The explanation for such low LA, even lower than LA for gravel, may lie in the degree of particle flakiness. Benediktsson [83] varied the amount of flaky particles in samples for mechanical testing, and found that flakiness affects the results of mechanical testing. It is reported that the general trend observed was that Los Angeles abrasion improves with a reduction in flakiness in the sample [83,84]. The flakiness index for aggregates produced with Smart Liberator is much lower (2) compared to a flakiness index of 4 or higher for aggregates produced with traditional recycling techniques (Table 6).

4.2.6. *Flakiness index*

The particle shape of the product material was measured using the flakiness index method (EN 933–3), which is valid for materials in the size range of 4–100 mm. All RCA samples satisfy the maximum flakiness index requirement ($\leq$ 15, FI_{15}); see Table 6 and are consistent with values reported in the literature [3]. With the use of traditional crushers, the product becomes less well-graded and increases the flakiness of particles smaller than the crusher setting [85]. For this reason, employing advanced recycling techniques improves particle shape, and the flakiness index reduces to 2. The improvement of particle shape in coarse RCA can be visually observed in Fig. 7.

4.3. *Chemical properties*

4.3.1. *Cement paste, chlorides and sulfates*

Table 7 lists cement paste content, chlorides, sulfates, methylene blue in different fractions. The content of old cement paste in the fraction < 0.125 mm ranges from 27.6 wt% to 41.2 wt%, in the fraction 0–4 mm it ranges from 11.6 wt% to 21.5 wt%, and in the fraction 4–22 mm it ranges from 8.5 wt% to 17.2 wt%, depending on the origin (T-beams, columns, abutments, foundations, unknown rubble) and recycling technique (rotor crusher or advanced technique).

Engelsen et al. [86] reported a cement paste content around 28% in fine RCA, 0–4 mm, prepared in laboratory. Angulo et al. [87] found an average of 17.7% of cement paste in the fine fraction of mixed CDW and 38% in the powder sized below 0.150 mm. Nedeljkovic et al. [53] found a cement paste around 26% in 0–4 mm and up to 29.8% in fraction < 0.250 mm, in fine RCA from industrial crushing. This study also shows that the cement paste content varied significantly in powders (<0.125 mm), with 40 wt% for T-Beams and 27 wt% for foundations-derived powders. In general, the cement content is considerably higher in prestressed concrete girders, such as T-beams, compared to other structural members within the viaduct. This difference is also reflected in the fine (0–4 mm) RCA, with an average cement content of approximately 21% for T-beams and 13% for foundations, indicating that the original concrete mixes used for T-beams and foundations contained different cement proportions. The T-beams, constructed in 1970s, had an estimated cement dosage of 375 kg/m^3 based

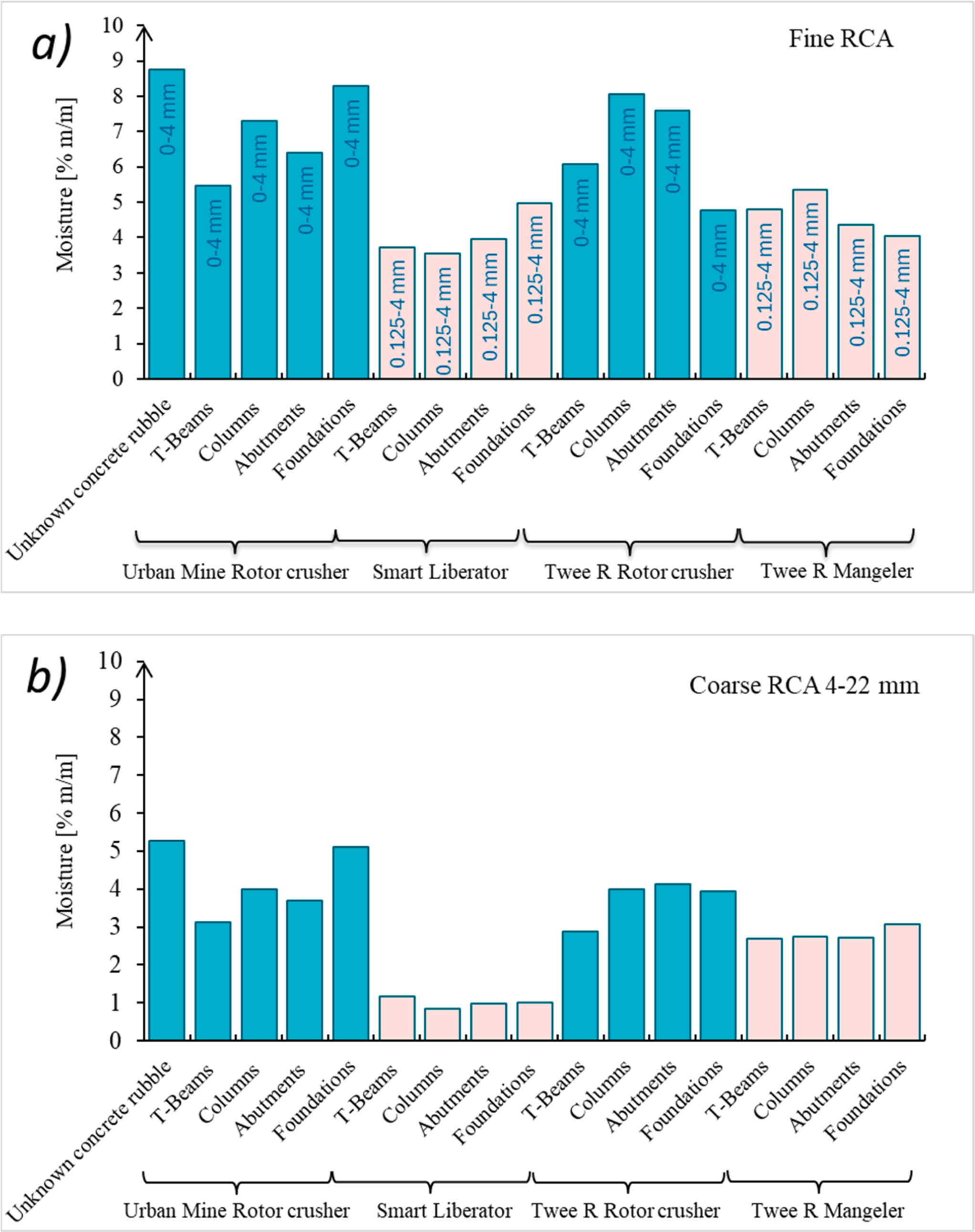


Fig. 15. Moisture content of a) fine RCA and b) coarse RCA.

on archive drawings.

The results of chemical analyses presented in Table 7 indicate very low chloride content of RCA, although concrete was contaminated with chlorides in the support beams [49] which were demolished together with the columns. Chloride content ranged from 0.005% to 0.01% of acid-soluble RCA as shown in Table 7. An example of chloride content calculation relative to cement content based on results in this study for an average concrete mix is shown in Table 8. For an average concrete mix assuming 100% replacement of sand and gravel with fine and coarse RCA, the maximum chloride content, expressed as percentage of cement paste is 0.11% m/m. This is well below the NEN-EN 206 limit of 0.4% m/m, indicating that chloride from RCA would not compromise concrete durability even at full aggregate replacement. The absolute quantity of chloride is small compared to potential thresholds for steel reinforcement corrosion, suggesting minimal impact on structural performance.

According to the literature, chloride-related concerns may arise when concrete rubble originates from marine structures. Elevated chloride levels (0.07–0.244%) were reported in samples obtained from the demolition waste of two such structures [88]. Chloride content in RCA measured in current study is systematically low and below critical limits which suggest their use in structural concrete.

This approach can be used for other applications to evaluate whether chloride in recycled concrete could be important, depending on the source and intended use of RCA. In addition, when the chloride concentration profile decreases with depth in parent concrete as for structural members in this study [49], no adverse implications are expected for the quality of RCA. In contrast, a non-decreasing chloride profile may indicate the intentional addition of chlorides during construction to accelerate concrete hardening. In such cases, chloride content should be considered a critical factor when evaluating the suitability of the concrete for recycling.

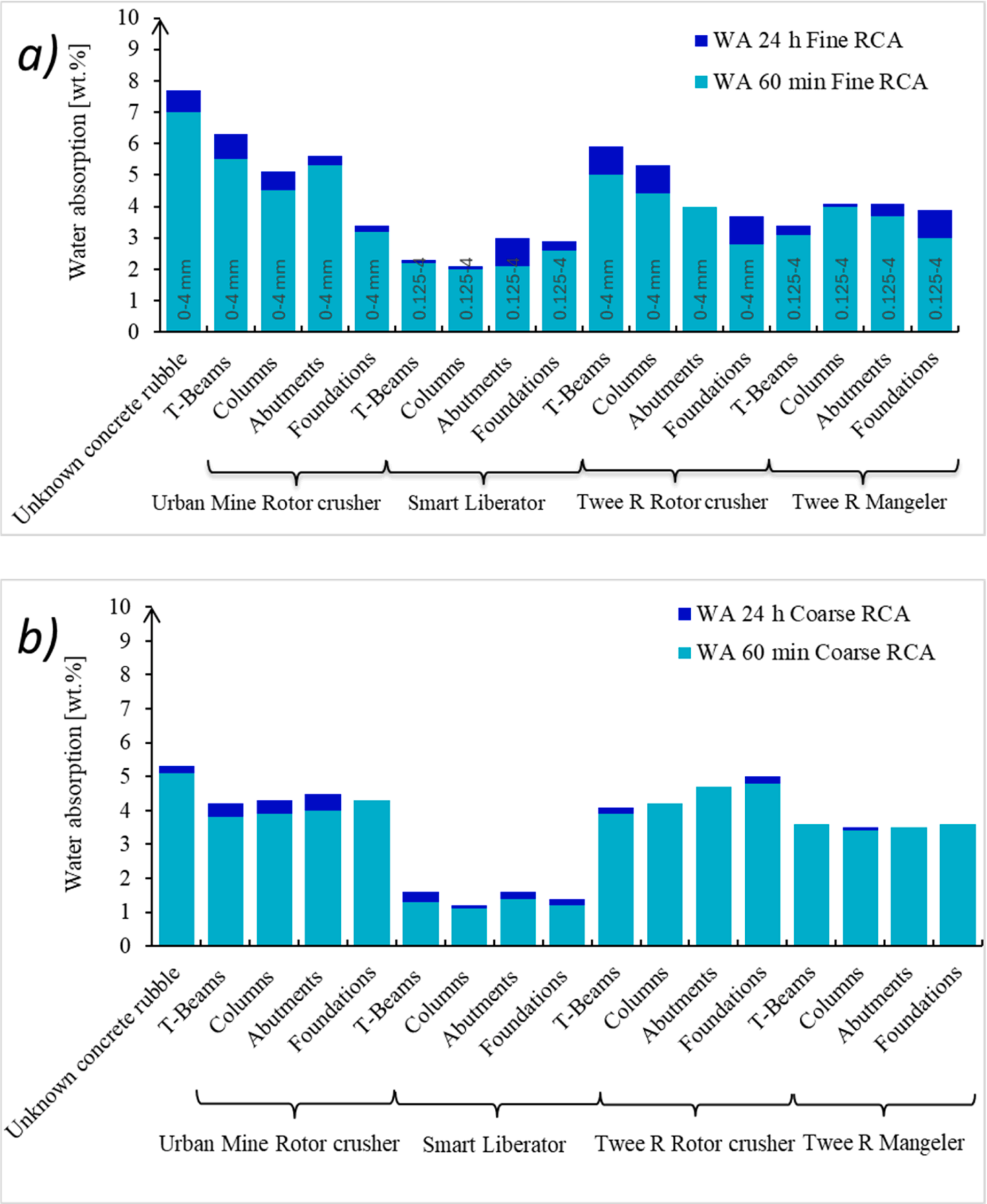


Fig. 16. Water absorption of a) fine RCA and b) coarse RCA after 60 min and after 24 h.

Table 5
Los Angeles coefficient.

		T-Beams	Columns	Abutments	Foundations
Smart Liberator	4-22	**14**	**13**	**15**	**13**
		T-Beams	**Columns**	**Abutments**	**Foundations**
Mangeler	4-22	**25**	**26**	**26**	**25**
Urban Mine		**T-Beams**	**Columns**	**Abutments**	**Foundations**
Rotor crusher	4-22	**28**	**30**	**29**	**29**
Twee R Recyling groep		**T-Beams**	**Columns**	**Abutments**	**Foundations**
Rotor crusher	4-22	**32**	**31**	**33**	**35**
Attero		**Unknown rubble**			
Rotor crusher	4-31.5	**35**			

Table 6
Flakiness index (FI).

Urban Mine Smart Liberator	Twee R Recyling groep Mangeler	Urban Mine Rotor crusher	Twee R Recyling groep Rotor crusher	Attero Rotor crusher
T-Beams	T-Beams	T-Beams	T-Beams	Unknown rubble
4–22	4–22	4–22	4–22	4–31.5
FI 2	**FI 4**	**FI 5**	**FI 4**	**FI 5**

The water-soluble sulfate content, which according to NEN-EN 12620 must be lower than 0.2% ($SS_{0.2}$), for RCA in this study meets the requirement, except for powders (T + C+A+F) < 0.125 mm. It also shows that recycled fines (< 0.125 mm) samples with higher cement content also have higher sulfate content. The high water-soluble sulfates might be due to various causes, including the breakdown of ettringite

Table 7

Cement paste content, acid soluble Cl^{-} and water soluble SO$_4^{2-}$, methylene blue in RCA.

	Cement paste	Acid soluble Cl^{-}	Water soluble SO$_4^{2-}$	Methylene blue
	[wt.% of dry sample]	[wt.% of dry sample]	[wt.% of dry sample]	g/kg
<0.125 mm				
Mangeler				
T-Beams	41.2	<0.01	0.19	5
Columns	37.1	0.02	-	
Abutments	36.2	0.02	-	
Foundations	27.6	<0.01	-	
Smart Liberator				
T+C+A+F	40.9	0.02	0.26	3.3
0.125-4 mm				
Mangeler				
T-Beams	21.5	<0.01	<0.16	0.5
Foundations	13.8	<0.01	-	
Smart Liberator				
T-Beams	11.6	<0.01	<0.16	1.4
Foundations	12.2	-	-	
0-4 mm				
Rotor crusher 2R				
T-Beams	21	<0.01	<0.16	0.8
Foundations	13.4	<0.01	-	
Rotor crusher UM				
T-Beams	20.9	<0.01	<0.16	0.7
Foundations	13.9	-	-	
Rotor crusher Attero				
Unknown rubble	17.0	0.01	0.19	0.8
4-22 mm				
Mangeler				
T-Beams	14.8	<0.01	<0.16	
Smart Liberator				
T-Beams	8.5	<0.01	<0.16	
Rotor crusher 2R				
T-Beams	12.7	<0.01	<0.16	
Rotor crusher UM				
T-Beams	16.2	<0.01	<0.16	
Rotor crusher Attero				
Unknown rubble	17.2	<0.01	<0.16	
EN 12620 Limit		**-**	**<0.20**	**1**

Table 8

An example of chloride content calculation relative to cement content based on results in this study for an average concrete mix.

Concrete ingredients	Chloride content	Ingredients content	Cl^{-}
	% m/m Cl^{-}	kg/m^3	kg/m^3
Cement CEM III/A	0.03	333	0.0999
Fine RCA	0.02	753	0.1506
Coarse RCA	0.01	1126	0.1126
Water	0.011	104	0.01144
Total Cl^{-}			0.37
Chloride content relative to cement content (333 kg)			0.11%

due to the carbonation of cement paste [89] or contamination by gypsum.

The Methylene blue test can be performed on the 2 mm fraction (expressed as MB value) or on 0.063 mm fraction (expressed as MBf value). For the purpose of this study, both values were defined. For the aggregates considered in this research, the upper limit value of MB seems to be 1 g/kg for aggregates (0.125–4 mm) according to EN 12620: 2015. It is 1.2 g/100 g for recycled fines (<0.125 mm) according to EN 197–6: 2023. Higher MB values will be obtained with a higher specific surface of the clay [90]. From the results, as listed in Table 7, it is clear that MB values are higher than standard limits. MB value is critical to determine for foundation batches in the future since more clayey material is expected there.

4.3.2. *Chemical composition of fine RCA*

Table 9 summarizes results for all batches and reference materials.

The river sand is composed mainly of more than 96 wt% SiO_2 and minor CaO, Al_2O_3, MgO, K_2O, Fe_2O_3 and total sulfur expressed as SO_3. Fine RCA and powders (<0.125 mm) are made up mainly by SiO_2 (59–83 wt%), CaO (8–28 wt%), Al_2O_3 (2.9–5.2 wt%) and Fe_2O_3 (1.37–3 wt%). In comparison to river sand, the fine RCA contain lower amounts of SiO_2 and higher amounts of CaO, Al_2O_3, MgO, K_2O, Fe_2O_3, SO_3 similar to fine RCA composition with predominant quartzite content [53]. This is due to presence of old cement paste in fine RCA. The powder < 0.125 mm has a different composition compared to 0.125–4 and 0–4 mm with a reduced SiO_2 content (59–71%) and increased CaO (16–28%). The LOI was 11 wt%.

The results are very similar for 0.125–4 mm batches produced by Smart Liberator, showing efficiency in removing adhered mortar during recycling. The chemical composition of 0.125–4 and 0–4 mm foundations-derived batches have the same chemical composition (83 wt% SiO_2 and 8 wt% CaO) regardless of the recycling technique.

The results differ significantly between literature [53] (e.g., batches B and D fine RCA) and the currently investigated unknown rubble fraction (0–4 mm). The SiO_2 content ranges from 62% to 80.1%, while CaO varies from 10% to 22%, emphasizing the importance of using sorted concrete rubble of known origin when considering CaO-rich recycled fines for cement production or CO_2 sequestration.

4.4. *Properties of powders (< 0.125 mm)*

Table 10 shows the properties of five powders produced using advanced recycling techniques (Mangeler and Smart Liberator).

The moisture content of as-received powders is 8.5–12.6% w/w, while the maximum moisture content of as-received coarse and fine RCA is 5% and 8% w/w, respectively. The particle density is 2390 – 2490 kg/m^3, where the natural sand density is 2730 kg/m^3 and density for recycled materials (<0.250 mm) of unknown concrete origins was reported to be 2470 – 2500 kg/m^3 [39,53]. Blaine fineness is found to be as low as 2160 cm^2/g in foundations-derived powders and as high as 3630 cm^2/g for (T + C+A+F) powder. As a reference, 3800 cm^2/g was reported for CEM I 42.5 N [91]. The recycled powders exhibit a uniform colour within the batch and a structure with about 60–85% of grain size < 0.063 mm. In the case of foundation, the powder was a very dark yellow in color (see Fig. 10) and had a significantly higher total organic carbon (TOC) of 0.89, which is above the limit requirement specified by EN 197–6:2023 (TOC content $\leq$ 0.8% by mass). This means that the reactive carbon, which, for example, originates from humic substances (humic acid and fulvic acid), is elevated. Values are comparable to those of Engelsen et al. [93] for recycled sands.

Since powders provide the largest part of the total specific surface area, they have the strongest influence on the total water demand of a concrete mix [94]. The βp-value has been obtained for every powder type, ranging from 0.763 to 0.96 (Table 10). For reference, the βp-value for CEM III/B 42.5 N B is reported to be 1.124, and for limestone and marble powders, it is 0.754 and 0.874, respectively [94]. All values obtained in this study fall within the range of 0.754–1.124.

Table 9
Bulk chemical composition of reference materials and different fractions of fine RCA.

		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Cl	SO_3	Na_2O	K_2O	LOI
	Reference materials	wt%									
	Quartz sand M300 [91]	99.5	0.20	0.03	0.02	-	-	-	-	0.04	
	River sand 0/4 [53]	96.00	1.80	0.50	0.50	0.10	-	0.05	0.20	0.20	1.84
	CEM I 42.5 N [92]	20.23	4.80	3.28	63.86	1.65	0.02	2.83	0.26	0.64	1.13
	Limestone powder [92]	0.60	0.22	0.08	55.52	0.35	-	-	-	-	43.19
	Advanced recycling	wt%									
< 0.125 mm	Mangeler T-Beams	60.90	4.17	2.96	27.60	0.84	-	0.98	0.42	0.22	11.9
	Mangeler Columns	63.80	4.85	3.48	23.40	0.85	0.06	1.00	0.59	0.92	
	Mangeler Abutments	64.35	4.79	3.87	22.95	0.87	0.06	0.93	0.63	0.90	
	Mangeler Foundations	70.90	5.42	2.88	16.35	0.86	0.07	0.73	0.81	1.24	
	SL (T + C+A+F)	59.20	5.24	2.67	27.95	1.17	0.06	1.23	0.52	0.92	11.0
0.125–4 mm	Mangeler T-Beams	79.60	2.94	1.53	13.45	0.47	0.06	0.49	0.34	0.64	-
	Mangeler Columns	79.80	3.28	1.60	12.70	0.48	0.06	0.48	0.41	0.78	
	Mangeler Abutments	82.00	3.06	1.56	11.00	0.46	0.07	0.39	0.39	0.77	
	Mangeler Foundations	83.80	3.37	1.36	8.81	0.45	0.06	0.40	0.47	0.86	
	SL T-Beams	83.85	3.34	1.50	8.04	0.44	0.04	0.32	0.48	0.87	-
	SL Columns	85.65	3.29	1.36	6.62	0.41	0.05	0.20	0.48	0.89	
	SL Abutments	84.45	3.28	1.31	7.51	0.74	0.06	0.31	0.44	0.81	
	SL Foundations	83.85	3.64	1.43	7.64	0.52	0.05	0.30	0.51	0.95	
	Traditional recycling	wt%									
0–4 mm	Attero unknown rubble	80.13	4.42	1.37	10.1	0.96	-	0.55	0.46	0.95	-
	Twee R T-Beams	75.90	3.10	1.64	15.80	0.56	-	0.57	0.35	0.73	-
	Twee R Columns	78.60	3.38	1.54	13.20	0.52	-	0.59	0.49	0.83	-
	Twee R Abutments	80.40	3.62	1.42	11.30	0.51	-	0.40	0.49	0.85	-
	Twee R Foundations	83.4	3.92	1.32	7.80	0.49	0.05	0.34	0.60	0.99	-
	UM T-Beams	77.2	3.06	1.58	14.75	0.59	0.04	0.65	0.34	0.7	-
	UM Columns	79.35	3.28	1.43	12.55	0.54	0.06	0.55	0.41	0.75	
	UM Abutments	78.65	3.23	1.44	13.10	0.57	0.05	0.87	0.39	0.75	
	UM Foundations	82.75	3.70	1.32	8.53	0.50	0.05	0.35	0.55	0.96	
	Fine RCA batch B [53]	62.80	5.80	3.30	22.50	1.50	0.03	1.16	0.60	1.50	-
	Fine RCA batch D [53]	75.80	4.30	1.70	14.40	0.90	0.04	0.89	0.40	1.10	-

Table 10
Index properties of fines < 0.125 mm produced with advanced recycled techniques.

Property		Mangeler				Smart Liberator
		T-Beams	Columns	Abutments	Foundations	T + C+A+F
Moisture	%	11.78	11.08	10.66	8.58	12.8
Specific gravity	kg/m^3	2390	2430	2430	2490	2420
Blaine fineness	cm^2/g	2950	2310	2770	2160	3630
Fines < 0.063 mm	%	64.8	62.6	67.3	60.4	84.3
Total organic carbon (TOC)	(%)	0.38	0.76	0.61	0.89	< 0.20
Insoluble matter	(%)	50.5	55.48	56.52	66.87	50.92
Water demand βp-value	By weight	0.812	0.873	0.823	0.763	0.96

5. Correlation analysis of RCA properties

5.1. Relationship between cement content and CaO, SSD density and SiO_2

In RCA, the availability of various elements is controlled by the cement paste content, which in turn will determine the content of CaO. This can be seen from the strong linear relationship obtained between cement paste content in various recycled powders and fine RCA and CaO for studied samples (Fig. 17) with an R^2 value of 0.982:

$CM = 1.47CaO + 1.08$ (1).

Another important observation is that the densities of the recycled concrete fractions (<0.125 mm, 0–4 mm) have a correlation with silica content as shown in Fig. 18. The density strongly depends on insoluble matter, inert part of aggregates (most of aggregate portions, except when reactive aggregates are present) which can be estimated based on silica content if it is known that parent concrete is made of silica rich aggregates such as river gravel and sand, as it is the case for this study.

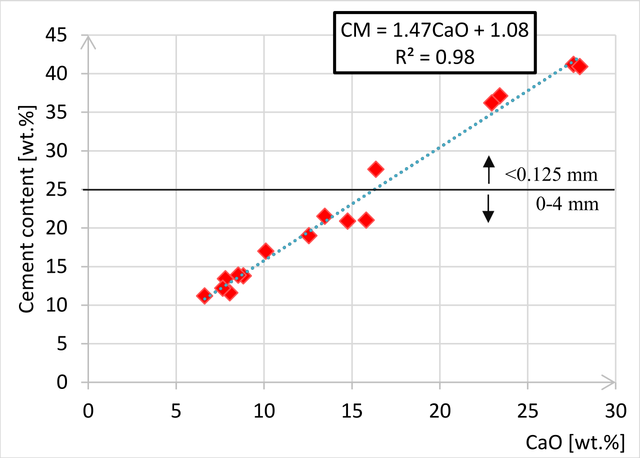


Fig. 17. Relationship between CaO and cement content.

5.2. Relationship between cement content and aggregates size fractions

A significant reduction in adhered mortar content can be achieved through advanced recycling, effect being dominant for aggregates size fractions smaller than 2 mm [39]. Fig. 19 illustrates that larger-sized RCA are cleaner than smaller RCA in terms of cement paste content.

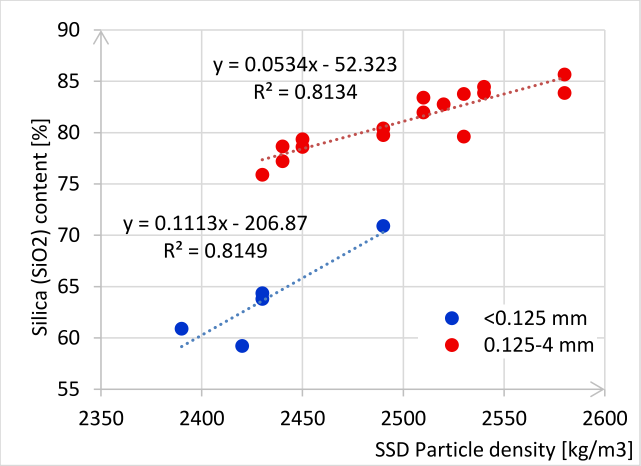


Fig. 18. Relationship between SSD Particle density and silica (SiO_2) content.

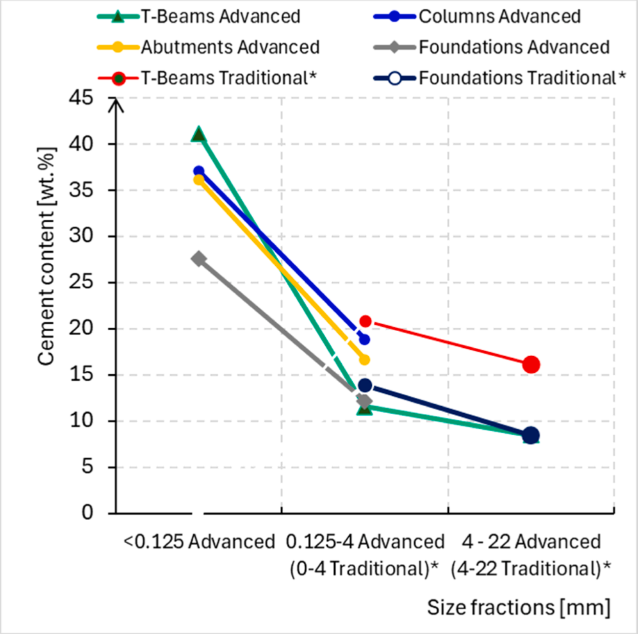


Fig. 19. Relationship between the content of cement paste and different size fractions.

This explains why fine RCA have higher water absorption values than coarse RCA, as reported also by Florea [39].

5.3. *Water absorption; traditional versus advanced recycling techniques*

Fig. 20 and Fig. 21 present the improvement of water absorption particle size 4–22 mm and particle size 0–4 mm with advanced recycling of concrete. Fig. 20 shows that for Urban Mine results are more clustered because water absorption values of coarse RCA from different sources (T-Beams, Columns, Abutments, Foundations) are similar. On the other hand, the clustering effect is not that strong for 0–4 mm batches as it can be observed in Fig. 21. The reason for this is that 0–4 mm have higher adhered mortar content, sometimes, adhered mortar being the definition of individual particles in 0–4 mm. In addition, the adhered mortar introduces additional fines, resulting in the formation of more interfacial transition zones, which, in turn, introduces greater porosity in the 0–4 mm aggregates [95].

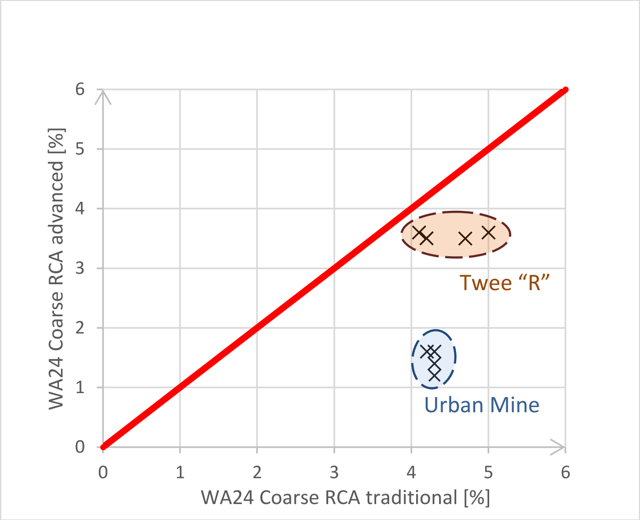


Fig. 20. Water absorption in coarse RCA (traditional 4–22 mm vs advanced 4–22 mm).

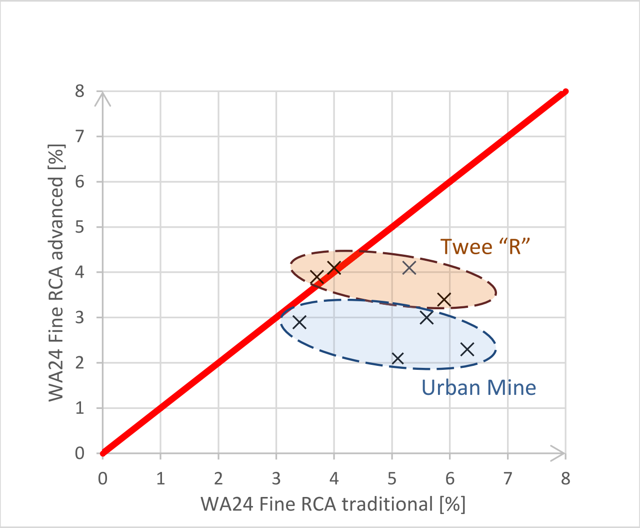


Fig. 21. Water absorption in fine RCA (traditional 0–4 mm vs advanced 0.125–4 mm).

6. Discussion

6.1. *Influence of parent concrete on RCA properties*

6.1.1. *Structural members within one viaduct*

This study assessed the effect of four structural member types on the properties of RCA. No notable differences were found in LA abrasion values among RCA derived from different structural members. Chemical composition also exhibited similar uniformity across structural members. This uniformity is attributed to the use of the same aggregate type, river gravel and sand, and Portland cement in the parent concretes across all four structural members (Table 1). Although the aggregate and cement types were identical, variations in their proportions and in the degree of adhesion between cement paste and aggregates are likely, which is consistent with the observed differences in water absorption values. For instance, the fine RCA obtained from foundations exhibits significantly lower water absorption compared to RCA derived from T-beams and columns. In addition, the RCA from foundations, and occasionally of the fine RCA from abutments, show a distinct particle size distribution relative to other structural members RCA, outside the standard lower and upper limits. T-beams-derived powders (<0.125 mm) contain higher amount of cement paste (41%), rich in CaO, compared to foundations (27%), columns, and abutments. This suggests higher cement content used in the original mix design of T-Beams compared to other structural members. This aligns with the manufacturing history of the T-beams, controlled production conditions and subjected to prestressing, with an average cement dosage of approximately 375 kg/m^3 , indicative of a high-strength concrete mix typical for such structural members.

6.1.2. Viaduct concrete vs mixed rubble of unknown origin

The quality of RCA derived from selectively demolished members of a single viaduct, including T-beams, columns, abutments, and foundations, was higher than that of RCA from mixed rubble of unknown origin (batch from Attero). Rb values were elevated in the unknown-origin RCA and were comparable to those of foundation RCA, suggesting that mixed rubble is more likely to contain clayey material at elevated concentrations due to the frequent inclusion of soil-attached or foundation elements. Their presence alters the setting of concrete and decisively affects its strength and durability [96].

The CaO content of fine RCA from unknown-origin rubble was 10%, compared to 16% in T-beam RCA. In the unknown rubble, CaO may originate not only from cement but also from fillers or aggregates. These observations emphasize the necessity of characterizing the parent concrete prior to demolition, enabling accurate attribution of constituents to the original concrete and facilitating their reuse in appropriate applications. Furthermore, the observed variations in CaO content demonstrate the importance of using sorted concrete rubble of known origin when utilizing CaO-rich recycled fines for cement production or CO_2 sequestration.

Chloride and sulfate contents are minimal in preselected concrete streams. In contrast, the water-soluble sulfate content of 0/4 aggregates from unknown-origin concrete rubble was 0.19%, approaching the critical limit of 0.2%.

Water absorption values further illustrate the differences in quality between the materials, all of which were processed using a rotor impact crusher. Fine RCA from unknown-origin rubble exhibited a water absorption of 7.7%, markedly higher than that of fine RCA from T-beams (5.9%), abutments (4%), and foundations (3.2%). Although the cement paste content in the unknown-origin fine RCA was lower (17 wt%) than in T-beam RCA (21 wt%), the elevated water absorption indicates that the adhered mortar in 0–4 mm T-beams RCA is denser and exhibits a stronger bond to the original aggregates compared to the unknown-origin rubble RCA.

6.2. Influence of recycling processes on RCA properties

Comminution governs the transformation of larger material fragments into smaller particles through mechanical action, fundamentally altering the dispersed solid structure and defining the resulting grain size distribution [97]. In the context of RCA, this process critically influences particle morphology, adhered mortar content and ultimately material performance [98–101]. The literature review indicates that most studies on RCA either omit details of the crushing process or consider only a single crushing step. This aspect is critical, as the crushing method directly affects the amount of adhered mortar, which is a primary factor influencing the characteristics of RCA. The quality of adhered mortar is governed by the water-to-cement ratio of the parent concrete, while its quantity is controlled by the crushing process which determines how much mortar remains attached to the aggregate and by the parent concrete's strength, which influences the mortar's bond to the original aggregates and its resistance to fracture [9,102]. Previous studies have demonstrated that increasing the number of crushing cycles leads to a progressive reduction in adhered mortar [39,103,104], highlighting the sensitivity of RCA properties to the applied mechanical treatment. In this study, an impact crusher and advanced separation technologies the Smart Liberator and Mangeler were employed to investigate their effects on RCA properties. The impact crusher is a mechanical comminution device that reduces particle size primarily through high-energy collisions. Particles fed into the crusher are accelerated by a rotor with fixed hammers and projected toward impact plates, where they undergo repeated impacts and rebound events that induce internal stresses leading to fracture. The kinetic energy transferred during impact creates dynamic crack propagation distinct from compressive breakage mechanisms [50,51,105]. The Smart Liberator represents a mechanically driven selective separation device based on controlled compressive and shear stresses, designed to promote liberation of concrete constituents while minimizing gravel fracture [37]. The Mangeler operates on a mechanical adhesive separation principle, wherein an eccentrically surfaced rotating element inside a longitudinal container generates alternating compression and shear on particulate feed, promoting removal of adhered cementitious material from aggregate surfaces without relying on high-stress crushing [38].

The comminution mechanism forms the foundation for understanding and controlling the intrinsic properties of RCA. It will be discussed in detail from the following four aspects.

6.2.1. Appearances of RCA

The presence of a large amount of natural aggregate particles (with none or little adhered cement mortar) is clearly apparent in Smart Liberator RCA because of the better phase detachments promoted by comminution. It is noteworthy that RCA produced with the Smart Liberator exhibit a more rounded morphology, whereas those obtained with rotor/impact crushing are predominantly angular. The selective liberation mechanism employed by the Smart Liberator limits angular fracturing and microcracking, yielding smoother, more rounded particles compared with the impact-dominated rotor crusher. Images of the Smart Liberator (Figs. 7 and 9) show that the natural aggregates used in construction of concrete structural members are composed of sand and gravel, e.g. river rounded pebbles, with a more spherical and regular shape.

6.2.2. Particle size distribution

The mode of comminution governs both fragmentation selectivity and mortar liberation, resulting in systematically different particle size distributions for the same feed material, as observed for fine RCA in this study (Fig. 12). Fig. 12 indicates that advanced processing techniques produce aggregates with particle size distributions closer to the upper and lower specification limits. A high dispersion is observed for foundation-derived RCA, regardless of the recycling process, particularly toward the upper limit, indicating a higher proportion of fine particles.

In contrast, coarse RCA (Fig. 14) exhibited highly similar particle size distributions, irrespective of parent concrete origin or recycling technique. The close alignment of particle size distributions in the 4–22 mm range suggests that coarse RCA formation is predominantly governed by mechanically constrained fragmentation. In this regime, crusher geometry and applied fragmentation energy control crack propagation paths and particle size limitations, effectively dominating over differences in parent concrete properties. Material heterogeneity becomes increasingly influential at finer scales, where selective mortar detachment and microstructural weaknesses govern fragmentation behavior.

6.2.3. Density

The impact crusher tends to produce RCA with a slightly lower density for coarser fractions (4–22 mm), as observed in both Urban Mine and Twee R Mangeler samples processed via the rotor crusher (densities around 2480 kg/m^3), due to partial comminution of the adhered mortar.

The Smart Liberator applies controlled compressive and shear stresses to selectively liberate the natural aggregates from the adhered mortar while minimizing fracture of the gravel. As a result, RCA produced with the Smart Liberator exhibited the highest densities among all methods (2580–2610 kg/m^3), particularly for the 0.125–4 mm and 4–22 mm fractions, due to the preservation of natural aggregate integrity and retention of denser, stronger mortar.

The Mangeler uses alternating compression and shear to remove adhered cementitious material without subjecting aggregates to high-stress crushing. RCA produced with the Mangeler showed intermediate density values (2490–2530 kg/m^3), reflecting partial removal of weak mortar while maintaining the integrity of the natural aggregates.

For fine RCA fractions (<0.125 mm), density differences across methods were less pronounced. This is because the fine powders largely consist of adhered mortar, whose density is governed more by the intrinsic mortar properties than by the liberation technique.

An increase in the adhered mortar content of RCA did not significantly affect its density because the negative effect of additional mortar is partially offset by the higher strength and density of the mortar itself, as well as the improved bond between natural aggregates and mortar in high-strength concretes [103], such as those in the viaduct T-beams and columns studied. These observations align with the fundamental principles of RCA production. Techniques that preserve aggregate integrity and promote a strong mortar-aggregate bond, such as selective separation devices, tend to yield RCA with higher density. In contrast, high-energy crushing methods that fragment aggregates or weaken the adhered mortar may lead to a slight reduction in density. The combined effect of stronger mortar and well-preserved aggregates explains why density variations remain limited even with increased mortar content.

6.2.4. Water absorption

The rotor crusher produces higher variability in absorption values. As Smart Liberator and Mangeler are used, this variability decreases and water absorption becomes independent of parent concrete. Smart Liberator led to reduced absorption because this technique has a polishing effect that separates the adhered cement mortar from the coarse aggregates. The Mangeler RCA exhibited higher absorption values than Smart Liberator RCA, which is logical as the content of fine particles smaller than 0.125 mm are increased and tend to absorb more water. The sieving could be improved for Mangeler technique in the future. In general, it can be concluded that by utilizing advanced techniques with more of an abrasion effect, it is possible to reduce water absorption of coarse RCA to 1.2% (columns RCA, Smart Liberator), and of fine RCA to 2.1% (columns RCA, Smart Liberator).

Overall, literature reviews consistently highlight that mechanical treatment methods can improve RCA quality by adhered cement mortar, which in turn positively influences water absorption, density, and mechanical performance of concrete incorporating treated RCA [24,31,106].

6.2.5. Chemical composition

The chemical characterization of advanced and traditional RCA highlights the critical influence of particle size and origin on their potential valorization. Fine fraction (<0.125 mm) in this study exhibit elevated CaO contents (16–28 wt%), reflecting substantial residual cement paste content with high CaO/SiO$_2$ ratios, whereas coarser fractions (0.125–4 mm) are predominantly siliceous with lower CaO (6–13 wt%). These oxide distributions are consistent with previous work on field-sampled RCA, where fine fraction (<0.125 mm) similarly exhibited CaO concentrations in the range of ~18–28 wt% accompanied by lower SiO$_2$, indicative of adhered mortar dominance compared to natural sands [53]. The high CaO/SiO$_2$ ratio indicates the advantage of targeted fine separation for applications such as cement production, supplementary cementitious materials, or accelerated carbonation for CO$_2$ sequestration.

In conclusion, the findings highlight that selective recycling and appropriate comminution techniques are key to producing high-quality RCA with predictable density, water absorption, particle morphology and chemistry. Such RCA is better suited for structural concrete applications, offering improved packing, workability, and durability compared with RCA obtained through conventional crushing. The results emphasize the importance of tailoring recycling processes to both the characteristics of the parent concrete and the desired properties of the RCA.

7. Future demolition practice

This paper presents one of the few detailed workflow for implementing selective demolition in infrastructure, aimed at obtaining high-quality RCA. It includes a practical application for a viaduct in the Netherlands. The deployment of selective demolition relies on parent concrete identification and adequate accessibility. Adequate operational accessibility of the demolition site facilitates selective recovery of high-quality concrete structural members. The workflow begins with contractual agreement and project definition, followed by a technical assessment and planning phase conducted by qualified engineering personnel.

7.1. Parent concrete characterization

A thorough understanding of the parent concrete's properties is critical to producing homogeneous RCA. When the source concrete exhibits a relatively uniform water-to-cement ratio and strength class, the adhered mortar quality and pore structure are more consistent, leading to reduced variability in RCA porosity and related properties such as water absorption and density [9].

The information about the composition (cement, aggregates, fibres, coating) of each concrete member type (strength class, with/without reinforcement, type of reinforcement), and material degradation are essential information for RCA quality prediction.

The three steps (shown in Fig. 22) in assessment of bridge concrete members quality provide the prediction components in a joined-up way [8]. The steps themselves are further described in the remainder of this section. The framework is applied to the case study of the Sluinerweg viaduct [13], a twin to Ardeweg viaduct and will be applied for future demonstration studies.

1) *Visual and imaging scans.* The first step consists of an enquiry into the 'real' structure using visual inspection. It generates information into the actual state of the structure, clearly identifying the objectives and decisions that the quality assessment will support. It outlines different surface states and representative testing zones.
2) *Chemical composition data acquisition.* The collection of chemical scans data with handheld XRF for each structural member can be done following framework developed by Nedeljkovic et al. [92]. The necessary data quality (e.g. resolution and measurement frequency) is addressed by Gomez et al. [107]. The adoption of handheld XRF, both in technology and process, is also advised as this will reduce assessment time in a non-destructive way. A hXRF measurement informs operational decisions, i.e. essentially about choosing which option for action is the best upon available information. Information includes data such as concrete composition in two layers (cement, aggregate, fibres), surface treatments (coatings), site exposures (contamination) and possible internal processes (material degradation). For many structures, these data also exist in drawings, specifications, surveys, photographs originally used in design and construction and can be used as verification of hXRF measurements.
3) *Data acquisition for mechanical and physical properties.* Set of Schmidt hammer and ultrasonic pulse velocity measurements for each structural member are used for further analysis and decision upon demolition methodology. Optimal data acquisition deals with the measurements on number of representative regions per structural member which can be chosen based on step 1).

Proposed assessment and decision-making approach for selective

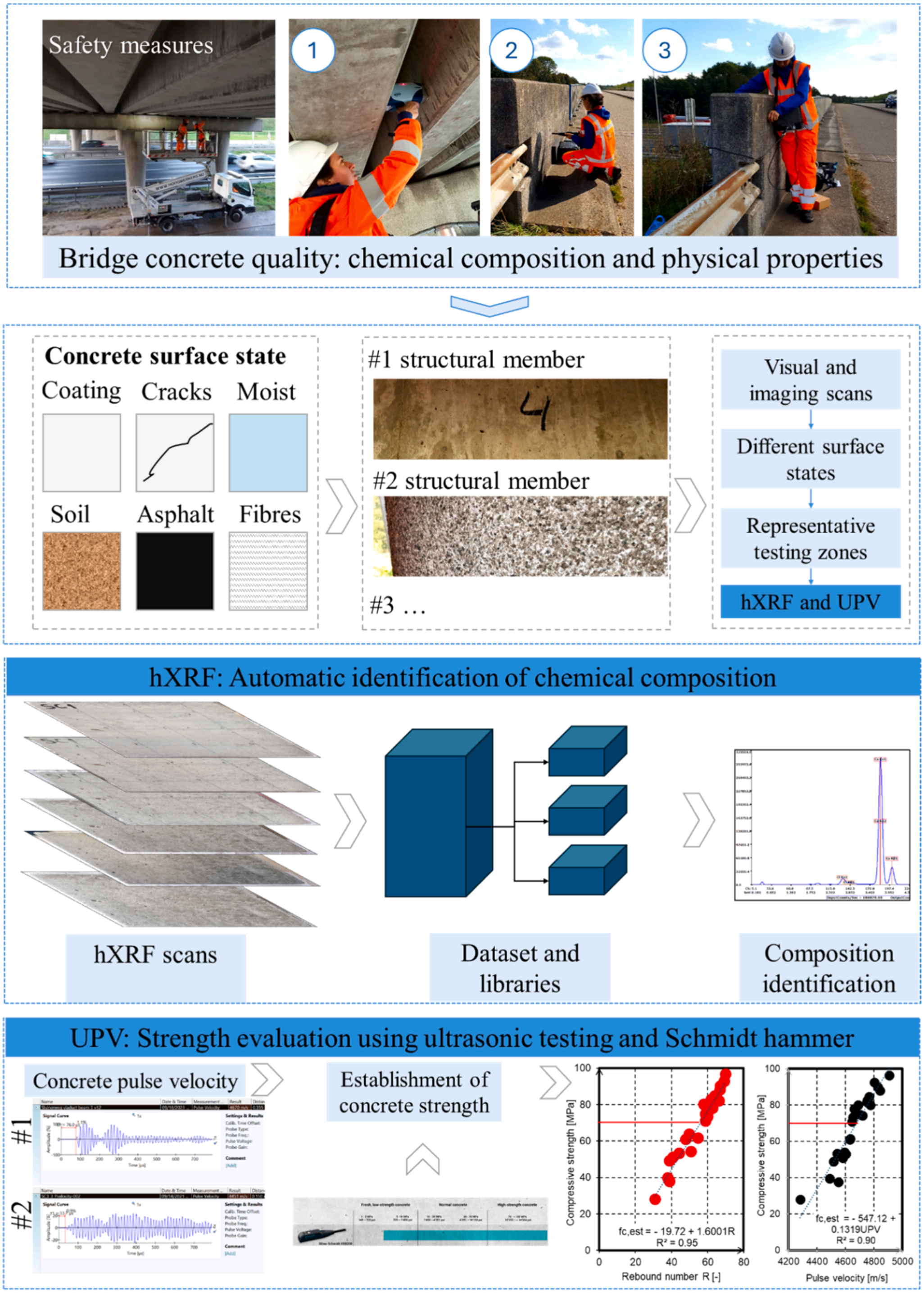


Fig. 22. Layout of parent concrete quality evaluation.

demolition of structural members in concrete structures is outlined in Fig. 23. The assessment is supported by previous 3-step concrete quality evaluation. To systematically guide decision-making, a multi-criteria assessment framework is proposed, considering the characteristics of the parent concrete and the expected quality of RCA. The proposed approach evaluates each structural member according to three primary criteria:

Criterion 1 (C1): Material degradation

- **Type:** Identification of the type of degradation present, whether physical (e.g., freeze-thaw damage, microcracking) and/or chemical (e.g., ASR, sulfate attack).
- **Severity:** Assessment of degradation severity, which influences the degree of deterioration in the resulting RCA.

Criterion 2 (C2): Chemical composition

- **Cement type:** Parent concretes with high clinker content (CEM I) or CaO concentrations exceeding 60 wt% suggest that the resulting fine RCA and recycled powders could be utilized as mineral additions in

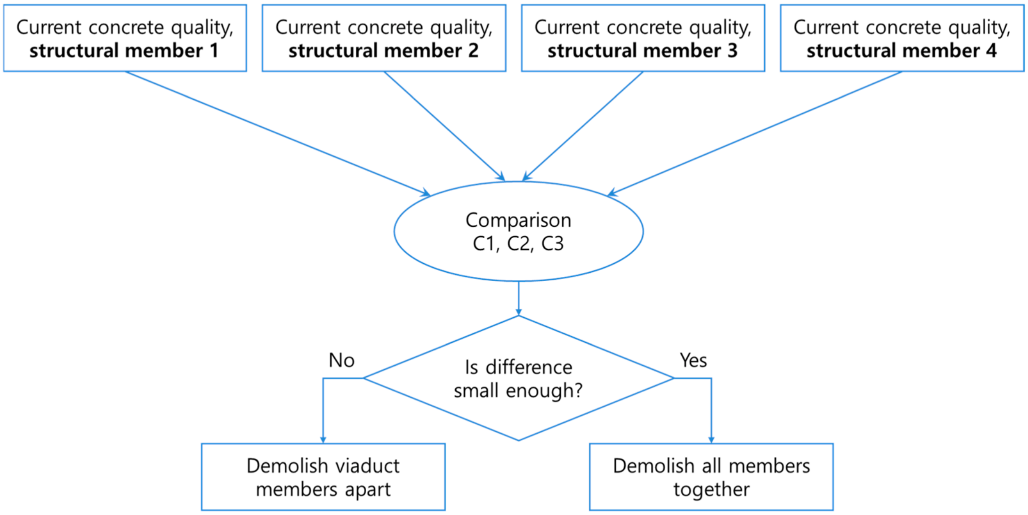


Fig. 23. Decision-making framework for selective demolition of concrete structures based on parent concrete quality.

clinker manufacturing or for CO_2 sequestration. Portland cement is the preferred cement type in the adhered mortar, as its high CaO and $Ca(OH)_2$ content enables effective carbonation reactions.

- **Aggregate type:** Differentiation between SiO_2-rich or CaO-rich aggregates, as aggregate composition affects mechanical performance, abrasion resistance, and durability of the RCA.

Criterion 3 (C3): Strength class

- Assessment of the original/current strength class allows prioritization of structural members that produce high-quality RCA for reuse in structural applications.

Each structural member within the bridge is evaluated against these criteria to assign a suitability score. Members exhibiting minimal degradation, favorable chemical composition, and high parent concrete strength are prioritized for selective demolition. Structural members exhibiting severe degradation, such as those affected by internal mechanisms like sulfate attack, should be rejected from selective demolition and handled via traditional processing (standard stockpiling). Members meeting favorable conditions may be allocated to selective demolition stockpiles, serving as feedstock for the production of high-quality RCA.

7.2. Selective demolition

Finally, the demolition stage is crucial for the success of quality improvement of RCA. Infrastructure operators are scheduling demolition activities as a matter of course. The results of this study provide information to asset owners for improving the operational efficiency of demolition activities and equipment utilization. For example, these findings can support demolition optimization, enabling scheduled operations that anticipate and minimize contamination of the resulting concrete rubble. To support practical implementation of selective demolition, decision-support frameworks have also been developed to assist demolition practitioners in selecting appropriate waste management strategies by systematically comparing technical, environmental, economic, and social factors [108].

In addition to the realisation of the added value (i.e. improving quality of RCA), operators and owners also have to gain confidence in selective demolition, when moving away from standard practice. This can be achieved by developing a track record of successful demonstrations, as is currently being carried out by Proeftuin Recyclaat for the Dutch infrastructure agency Rijkswaterstaat.

8. Quality assurance of RCA for structural applications

The quality requirements for RCA intended for structural concrete should be equivalent to those specified for natural aggregates for the same application. In this study, the main factors affecting the quality of RCA are investigated, including the quality of the parent concrete, the influence of the industrial-scale production process, and the type of advanced treatments applied.

National standards define classification systems for structural RCA, although limit values vary according to intended use. Among the governing parameters, water absorption remains the most widely applied acceptance criterion. For coarse RCA, typical limits for structural applications include 7% in the Netherlands [42], 10% in Germany [108], and 3–5% in Japan under JIS A 5021 [109] and JIS A 5022 [110]. The Japanese system distinguishes Class H RCA produced through advanced processing methods that largely remove adhered mortar [111]. The stricter Japanese limits reflect high seismic performance demands and durability requirements (e.g., freeze-thaw resistance). In the Netherlands, in particular, the durable concrete must withstand chloride-rich environments and frost, highlighting the critical role of careful selection and processing of the parent concrete.

Selective demolition significantly enhances quality assurance by enabling identification of parent concrete properties prior to recycling, thereby reducing uncertainty in the resulting RCA characteristics. When high-strength parent concrete ($\geq$ C40/50) is selectively processed, RCA densities approaching 2600 kg/m^3 can be achieved, comparable to natural aggregates. For fine RCA, densities around 2500 kg/m^3 are realistic, as demonstrated in this study. Such physical indicators directly influence mixture design and structural performance considerations for recycled aggregate concrete.

The forthcoming revision of Eurocode 2 (prEN 1992–1–1) introduces Annex N with provisions for structural design using RCA [46]. Similarly, the fib Model Code 2020 provides modifications to mechanical properties and resistance models for recycled aggregate concrete [112–114]. These developments strengthen the regulatory basis for structural implementation of RCA. However, further research remains necessary, particularly regarding the combined use of fine and coarse RCA and their influence on mechanical performance and long-term behavior [115].

Within the European framework, EN 206 regulates maximum substitution ratios of coarse RCA according to environmental exposure classes, although without explicit mechanical performance adjustments. In the Netherlands, guidance documents such as RTD 1033, CUR 127, and revisions of NEN 8005 recommend a maximum total water absorption of 18 kg/m^3 and replacement limits of approximately 20% for fine and 50% for coarse RCA under typical exposure conditions [116]. Advanced processing technologies enable RCA to satisfy Eurocode 2 indicators, including density, water absorption, and Los Angeles abrasion resistance. The high-quality RCA derived from selectively demolished viaduct concrete in this study complies with these structural performance requirements.

International experience confirms that structural application of RCA is technically feasible when production processes and quality control are rigorously managed [117]. The integration of long-term properties, shrinkage and creep, durability testing and life-cycle assessment into qualification procedures would further support harmonization of standards and accelerate the transition toward circular structural concrete.

9. Conclusions

In this study, the effects of demolition strategy and recycling process on the properties of powder, fine, and coarse RCA fractions obtained from a 60-year-old concrete viaduct were evaluated. The key conclusions are:

- **Understanding RCA quality as a function of demolition and recycling strategy.** Selective demolition combined with advanced recycling consistently improves the quality of powder, fine, and coarse RCA compared to unknown-origin concrete rubble.
  - Coarse RCA achieved high mechanical performance, with water absorption as low as 1.5–4%, Los Angeles abrasion values down to approximately LA15 (Smart Liberator), and SSD particle density up to 2610 kg/m^3 . These results demonstrate that sorting concrete by structural member prior to recycling enables direct control over adhered mortar content and substantially enhances RCA quality for high-performance structural applications.
  - Fine RCA (0–4 mm) obtained from selectively demolished structural members exhibit favorable density and water absorption characteristics. Their density is lower than pure quartz (2650 kg/m^3) due to adhered mortar, yet significantly higher than fine RCA from unknown-origin concrete rubble (2380 kg/m^3), reflecting a denser and less porous microstructure. Importantly, the liberation of adhered mortar is strongly influenced by parent concrete characteristics. Fine RCA from T-beam concrete processed with the Smart Liberator exhibited substantially lower adhered mortar content (11.6%) compared to rotor-crushed RCA (20.9%), whereas RCA from foundation concrete showed similar adhered mortar content regardless of the processing method (Smart Liberator: 12.2%; rotor crusher: 13.9%). These results demonstrate that the effectiveness of advanced recycling is strongly governed by parent concrete properties, with direct implications for fine RCA performance and water absorption.
- **Foundation-derived fine RCA: performance and critical quality controls.**
  Fine RCA from foundations showed lower water absorption than RCA from T-beams and columns, with a distinctive particle size distribution. However, critical quality parameters must be monitored: methylene blue (MB) values indicate potential clayey constituents; powder fractions exhibited elevated total organic carbon (TOC = 0.89%), exceeding EN 197–6:2023 limits; and elevated Ra and Rb values reflect bituminous coatings and masonry residues. These findings demonstrate that high-performing foundation-derived fine RCA still require controlled removal of contaminants to ensure that the full potential of selective demolition is realized.
- **Powder fractions: chemical constraints and applicability.**
  Recycled powders (<0.125 mm) produced with the Smart Liberator contained sulfate above recommended limits (>0.20%), and powders from foundations processed with the Mangeler exceeded critical TOC thresholds (>0.80%). Although these fractions may not fully comply with current concrete production standards, targeted application or blending strategies can enable their safe and effective use.
- **Performance-based quality indicators for RCA**
  Water absorption at 60 min and 24 h differed only marginally, with approximately 90–100% of total 24-hour uptake occurring within the first hour, varying by particle size fraction. Water absorption measured at 60 min proved to be a reliable indicator of 24-hour uptake across fine and coarse RCA, providing a practical measurable parameter for quality control. Complementary evaluation of particle size distribution and water absorption kinetics is essential for understanding RCA performance and guiding further testing when targeting higher replacement levels in new concrete mixes.
- **Mechanistic insights into advanced versus conventional recycling.**
  Unlike conventional high-energy impact crushing, which fractures the concrete matrix while generating excessive fines, advanced recycling techniques based on controlled friction, shearing, and selective abrasion enable efficient liberation and removal of adhered mortar while preserving aggregate integrity. This results in RCA with reduced fines, lower water absorption, and mechanical performance comparable to natural aggregates, indicating compliance with Eurocode 2 requirements.

CRediT authorship contribution statement

Nedeljkovic Marija: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wim Ekkelenkamp:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Burcu Aytekin:** Writing – review & editing, Formal analysis, Conceptualization. **Penny Pipilikaki:** Writing – review & editing, Resources, Investigation, Formal analysis. **Sonja Fennis:** Writing – review & editing, Resources, Funding acquisition. **Jeannette van den Bos:** Writing – review & editing, Resources, Project administration, Conceptualization.

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.

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Data availability

Data will be made available on request.

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