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Recycled concrete aggregates in the circular economy: technological, environmental, and regulatory perspectives from Poland and Europe

Introduction

The construction sector is one of the most resource-intensive and environmentally impactful industries, contributing significantly to global greenhouse gas emissions and the use of natural resources. In response to growing environmental pressures and increasingly

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stringent climate regulations, reducing greenhouse gas emissions – particularly carbon dioxide (CO_2) – has become a major challenge. According to UNEP (2023), the sector accounts for approximately 37% of global energy-related CO_2 emissions, including around 10% embodied in construction materials and processes. Additionally, the production of key materials such as cement and steel contributes a further 5–7% of global emissions (EEA 2023).

Construction and demolition waste (CDW) is one of the largest waste streams in the European Union, representing about 40% of total waste (CINEA 2024). At the same time, the sector consumes nearly 50% of primary raw materials, highlighting the need for more sustainable resource management. In this context, recycled concrete aggregates (RCA) have emerged as an important element of circular construction, offering potential to reduce the use of natural aggregates and related environmental impacts (BPIE 2024).

Recent regulatory developments have accelerated this transition. The revised Construction Products Regulation (European Parliament and Council 2024) introduces stricter requirements, while the European Union promotes a circular economy focused on resource efficiency, waste reduction, and material reuse. Environmental performance, lifecycle assessment, and digitalization are becoming integral to construction practices, alongside tighter CDW management rules. These changes reflect a shift from a linear "take–make–use–dispose" model to a circular approach, where materials remain in use as long as possible (Figures 1–2). Recycling, especially through the recovery of materials from demolition and renovation, plays a key role in this process.

Despite relatively high recovery rates in some European countries, much of CDW is still used in low-value applications such as backfilling, limiting its potential. Although advanced technologies enable the production of high-quality recycled aggregates comparable to natural materials, their wider adoption is hindered by technological, regulatory, and market barriers.

The implementation of circular solutions varies across Europe. Countries such as the Netherlands and Germany have achieved high levels of recycled aggregate use, while others, including Poland, remain in transition, with evolving regulations, technologies, and market acceptance.

Therefore, this study aims to provide a comprehensive analysis of the role of recycled aggregates within the Polish construction sector, situating it in the broader context of ongoing transformations in the European construction industry. The research focuses on the increasing importance of secondary raw materials as a response to environmental pressures, resource scarcity, and the need to reduce greenhouse gas emissions associated with construction activities.

Particular attention is given to the contribution of recycled aggregates to the implementation of circular economy principles, especially in terms of resource efficiency, waste minimization, and the substitution of natural aggregates with materials derived from construction and demolition waste. The study also examines how European Union policies – especially those related to the Circular Economy Action Plan and the Construction Products

Fig. 1. Linear model in the construction sector

Rys. 1. Model liniowy w sektorze budowlanym

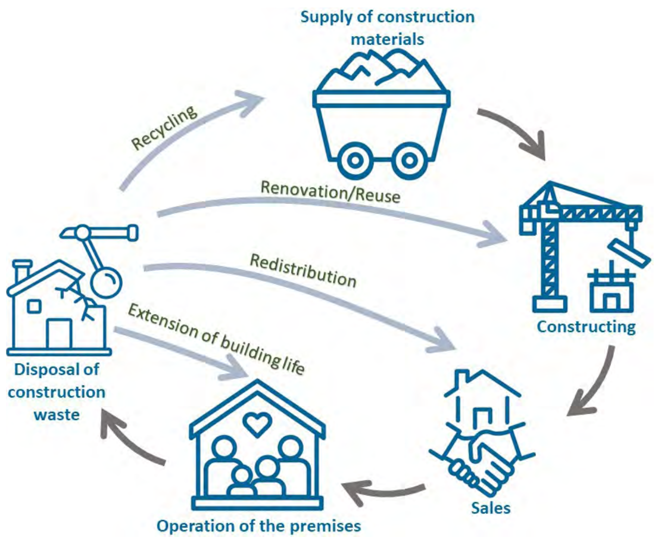

Fig. 2. Circular model in the construction sector

Rys. 2. Model cyrkularny w sektorze budowlanym

Regulation (European Parliament and Council 2024) – are shaping national practices and influencing material flows within the construction sector.

A key objective is to evaluate recent technological advancements in recycling processes, including multi-stage crushing, advanced separation techniques, and the recovery of fine fractions, which enable the production of high-quality recycled aggregates with properties increasingly comparable to natural materials. The study also considers innovations related to process water recovery and the utilization of by-products such as recycled cement powder, which further enhance the environmental performance of recycling systems.

In addition, the analysis addresses the regulatory framework governing the use of recycled aggregates, including harmonized European standards, national implementation documents, and technical guidelines applied in infrastructure projects. The role of new regulatory instruments, such as lifecycle-based assessment requirements and digital tools like the Digital Product Passport, is also considered in terms of their potential to improve transparency, traceability, and market acceptance of secondary materials (European Parliament and Council 2024a).

Finally, the study identifies and critically evaluates key barriers limiting the wider adoption of recycled aggregates in Poland. These include technological constraints related to material variability and processing efficiency, economic factors such as cost competitiveness with natural aggregates, regulatory and standardization issues, and limited market confidence in recycled materials, particularly in structural applications.

By integrating these perspectives, the study aims to assess both the current state and future potential of recycled aggregates in Poland, highlighting the conditions necessary for their broader implementation in line with European sustainability objectives and the transition toward a circular construction economy.

1. Materials and methods

This study adopts a qualitative and analytical approach to identify determinants of the recycled aggregates market in Poland within the broader European Union context, with emphasis on circular economy (CE) policies and recent legislation, including the Construction Products Regulation (CPR) (European Parliament and Council 2024).

The primary method is a systematic literature review of national and international sources covering circular economy strategies and EU regulations, recycling technologies for construction and demolition waste (CDW), performance and applications of recycled aggregates, and environmental assessment methods such as life cycle assessment (LCA).

The review is complemented by an analysis of strategic and regulatory documents, including EU legislation, European Commission guidelines, and reports from public and industry institutions. This stage aims to identify key policy directions and assess their impact on the recycled aggregates market.

Additionally, selected industrial case studies were examined to provide practical insight into current technologies, including multi-stage crushing, separation and classification processes, process water recovery using pressure filtration, and applications of recycled aggregates in concrete and cement-bound granular mixtures (CBGM).

A comparative analysis of selected EU countries with advanced CDW management systems was also conducted, focusing on recycling rates, regulatory approaches, support mechanisms, and the integration of circular economy principles in construction. The aim is to identify differences and similarities between Poland and leading EU countries and highlight transferable best practices.

The collected data were analyzed qualitatively to identify key trends, barriers, and drivers of market development. A synthetic approach was then used to generalize findings and formulate conclusions on regulatory impacts, technological progress, and market constraints.

The study is based exclusively on secondary data and does not include primary experimental research. Therefore, while limited in quantitative validation, it provides a coherent overview of the research problem.

2. Results and discussion

2.1. Technological advancements in concrete recycling

Advanced recycling technologies have improved the quality and applicability of recycled concrete aggregates (RCA). Multi-stage processes – crushing, screening, and advanced separation – enable the production of high-quality RCA+ comparable to natural aggregates. Recovery of fine fractions, such as recycled cement powder (RCP), and secondary carbonation further enhance reuse potential and CO_2 reduction (UNEP 2023; European Demolition Association 2024).

In Europe, recycled aggregates are gaining importance as part of the transition to a circular economy, driven by EU regulations and the need to reduce primary raw material consumption (European Commission 2020). CDW remains a major waste stream, regulated by the Waste Framework Directive and Circular Economy Package, promoting recycling and limiting landfilling (European Parliament and Council 2008). Concepts such as urban mining support selective demolition and high-quality material recovery (Arora et al. 2021).

Technological progress enables a shift from downcycling to high-value recycling (Silva et al. 2014), supported by decentralized processing that reduces transport impacts (Pomponi and Moncaster 2017). LCA studies confirm environmental benefits, though dependent on logistics and processing intensity (Chen et al. 2025). However, barriers persist, including quality variability, contamination, lack of standardization, and economic competitiveness of natural aggregates (Gebremariam et al. 2025). Countries like the Netherlands and Germany lead in RCA use, while others lag (Eurostat 2022).

Modern CDW processing should be understood as an integrated technological chain rather than only a crushing operation. The process begins before demolition, through pre-demolition audits, selective dismantling, and documented waste logistics. These measures reduce contamination by gypsum, wood, plastics, metals, glass, and other impurities, thereby improving the quality and market acceptance of recycled aggregates (European Commission 2024).

The processing stage may include primary and secondary crushing, screening, magnetic separation, eddy-current separation, air classification, washing, attrition treatment, density-based separation, jigging, and sensor-based sorting. Such technologies make it possible to separate concrete-rich fractions from mixed CDW and to produce more homogeneous

RCA with improved particle size distribution, lower impurity content, and better mechanical properties. Advanced systems may also separate concrete waste into coarse aggregates, sand, and fine cement-rich fractions, while accelerated carbonation can improve RCA quality by densifying adhered mortar and contribute to CO_2 binding (Pacheco, de Brito, Lamperti Tornaghi, 2023).

For Polish market conditions, the most realistic development pathway is a combination of selective demolition, stationary or mobile crushing and screening plants, advanced separation for higher-grade concrete fractions, and water/fine-fraction recovery systems. This technological configuration can support both large infrastructure projects and local circular construction models, provided that quality control and certification systems are strengthened (European Commission, 2024; Pacheco et al. 2023).

2.2. Material performance of recycled aggregates

Studies show that moderate RCA use (~30%) does not significantly affect concrete properties such as strength, workability, carbonation resistance, or pumpability. Proper pre-treatment, especially pre-wetting, is essential to control water absorption.

In Poland, CDW management has evolved through EU legislation and national regulations, including the Waste Act (2012) and the BDO system, improving transparency and monitoring (GUS 2024; MKiŚ 2024; PIPHB 2024; UMWM 2024). Despite this progress, recycling rates (39–65%) remain below EU targets (EEA 2020; Eurostat 2022; EEA 2023). Infrastructure development is ongoing but uneven (Kaza et al. 2018).

Recycled aggregates are mainly used in road construction, with limited application in structural concrete due to quality variability and standards (Silva et al. 2014). Economic barriers persist, as natural aggregates remain cheaper (Xiao et al. 2026). At the same time, environmental, social, and governance (ESG) and LCA approaches increase interest in low-carbon materials (European Commission 2020).

Market growth is constrained by limited selective demolition, a lack of standards, and low market trust (EEA 2022). Nevertheless, eco-innovations and EU regulations (e.g., CPR 305/2011, EPD) support development (Wysocki and Michalak 2023). High-quality RCA can replace natural aggregates in some applications (Abdulmajed et al. 2025), though structural use remains limited.

2.3. Material flows and market balance: CDW/RCA versus natural aggregates

The material-flow context is crucial for evaluating the real substitution potential of recycled concrete aggregates. At the EU level, aggregate extraction in the EU-27 amounted to approximately 2,550 million tonnes in 2019, whereas construction and demolition waste generation reached approximately 840 million tonnes in 2021, representing about 36% of all waste generated in the EU (Pacheco et al. 2023). These figures indicate that CDW is an important secondary raw material stream, but it cannot fully replace primary aggregates. Therefore, RCA should be considered a strategic supplementary material supporting circular construction rather than a complete substitute for natural aggregates.

In Poland, the imbalance between CDW flows and natural aggregate production is also visible. Recent data indicate that domestic output of sand and gravel amounted to 171.2 million tonnes in 2025, while the output of dimension and crushed stones reached 82.47 million tonnes in the same year, giving a combined natural aggregate output of approximately 253.67 million tonnes (PGI-NRI 2026a, 2026b). For comparison, Statistics Poland reported that the construction sector generated approximately 10.7 million tonnes of waste in 2023 (Statistics Poland 2024). Even if this entire amount were hypothetically treated as a potential source of recycled aggregates, it would represent only a small share of the natural aggregate market. In practice, the actual substitution potential is lower, as only selected mineral and concrete-rich fractions can be processed into certified, high-quality RCA suitable for concrete applications.

It should also be emphasized that official statistics usually report CDW generation, recovery or recycling, but do not always distinguish between backfilling, low-grade aggregate use, and certified product-grade RCA suitable for concrete. This creates uncertainty in assessing the actual market volume of high-quality RCA. For this reason, future monitoring systems should separately report recycled aggregate production by quality class and application, including road construction, cement-bound granular mixtures, non-structural concrete, and structural concrete (Pacheco et al. 2023).

2.4. Process water recovery and fine fraction management

Modern recycling includes water recovery and fine fraction management. Pressure filtration enables water reuse compliant with EN 1008, with no negative impact on concrete properties. Fine fractions (filter cake) can be used in CBGM, though they may reduce strength by 20–25%, requiring mix optimization.

EU regulation CPR 2024 expands requirements to environmental performance, lifecycle assessment, and digitalization (European Parliament and Council 2024). The Digital Product Passport improves transparency and supports circularity. Harmonized standards (e.g., PN-EN 12620, PN-EN 206, PN-EN 13242, PN-EN 13043) define requirements for aggregates and enable the use of recycled materials under quality conditions (CEN 2002, 2003, 2013).

PN-EN 12620 specifies key properties such as grading, density, water absorption, and contaminants, and introduces quality classes (e.g., A, A+, B), determining applications. Higher-quality aggregates can be used in structural concrete, while lower classes are limited to less demanding uses. These standards provide a consistent framework ensuring safe and effective use of recycled aggregates in construction (Tables 1 and 2).

Table 1. Recommendations for the properties of fine recycled aggregates according to PN-EN 12620 (based on PN-EN 12620+A1:2010 Aggregates for concrete)

Tabela 1. Zalecenia dotyczące właściwości drobnych kruszyw pochodzących z recyklingu zgodnie z normą PN-EN 12620 (na podstawie normy PN-EN 12620+A1:2010 „Kruszywa do betonu")

Property	Reference in PN-EN 12620	Category	Requirement / Value
Fines content	4.6	A	Category or declared value
Fines quality (methylene blue value)	Annex D	A	≤ 1.2 g/100 g
Oven-dry particle density (ρrd)	5.5	A	≥ 2,100 kg/m^3
Water absorption	5.5	A	Declared value
Constituents	5.8	A	Rc90, Rcu95, Rb10, Ra1, FL2, XRg1
Water-soluble sulfate content	6.3.3	A	SS0.2
Acid-soluble chloride ion content	6.2	A	Declared value
Effect on initial setting time	6.4.1	A	≤ A40

The NR category (no requirement) may be applied to properties not listed in the table, in accordance with PN-EN 12620. For applications requiring high surface quality, it is recommended to limit the flakiness index to category FL0.2. The classification of constituents refers to the fraction above 4 mm of aggregates from the same source.

Under national conditions, the standardization system for concrete and aggregates in Poland is based on European standards, complemented by national documents adapting them to local conditions. A key role is played by PN-B-06265:2022-08, the national annex to PN-EN 206, which specifies requirements for concrete design, production, and quality control, including the use of recycled aggregates (CEN 2013; PKN 2022).

Technical guidelines issued by the General Directorate for National Roads and Motorways (GDDKiA), such as WT-4 and OST, are also important. Although not formal standards, they define material requirements for infrastructure projects, allowing the use of recycled aggregates if quality criteria are met (GDDKiA 2010).

Additionally, European testing standards for aggregates – covering grading, fragmentation resistance, shape, and chemical properties – are widely applied in Poland and form the basis for material assessment (CEN 2002, 2003, 2010).

Together, European standards (e.g., PN-EN 12620, PN-EN 206), national annexes, and technical guidelines create a coherent system enabling the safe use of recycled aggregates. This framework supports circular economy principles while ensuring quality, durability, and structural safety (European Union 2024; CEN 2013) (Table 3).

Table 2. Recommendations for the properties of coarse recycled aggregates according to PN-EN 12620 (based on PN-EN 12620+A1:2010 Aggregates for concrete)

Tabela 2. Zalecenia dotyczące właściwości gruboziarnistych kruszyw pochodzących z recyklingu zgodnie z normą PN-EN 12620 (na podstawie normy PN-EN 12620+A1:2010 „Kruszywa do betonu”)

Property	Clause in PN-EN 12620	Aggregate type	Category according to PN-EN 12620 / Requirement
Fines content	4.6	A+, A, B	Category or value to be declared (% by mass passing the 0.063 mm sieve)
Flakiness index	4.4	A+, A, B	≤ FI50 or ≤ SI55
Resistance to fragmentation	5.2	A+	≤ LA35
Resistance to fragmentation	5.2	A, B	≤ LA50 or ≤ SZ32
Oven-dry particle density (ρrd)	5.5	A+	≥ 2,300 kg/m^3
Oven-dry particle density (ρrd)	5.5	A, B	≥ 2,150 kg/m^3
Water absorption	5.5	A+	Declared value
Constituents	5.8	A	Rc90, Rcu95, Rb10, Ra1, FL2, XRg1
Constituents	5.8	B	Rc50, Rcu70, Rb30, Ra5, FL2, XRg2
Water-soluble sulfate content	6.3.3	A+, A, B	SS0.2
Acid-soluble chloride ion content	6.2	A+, A, B	Declared value
Effect on initial setting time	6.4.1	A+, A, B	≤ A40

The “NR” category (no requirement) may be applied to properties not listed in the table, in accordance with PN-EN 12620. For applications requiring high-quality surface finishing, it is recommended to limit the flakiness index of constituents to category FL0.2 or lower. The classification of constituents is based on the fraction above 4 mm of aggregates originating from the same source.

2.5. Application in infrastructure and construction

In Poland, recycled aggregates are mainly used in road subbase layers, embankments, railway infrastructure, and selected concrete applications. Case studies confirm improved load-bearing capacity and cost reduction, although structural use remains limited.

An important technological direction is the development of advanced multi-stage processing systems for concrete waste, enabling the production of aggregates comparable to natural materials. An example is the ReConcrete technology used at the Heidelberg Materials Polska recycling plant in Dąbrowa Górnicza, which allows separation and recovery of fractions such as recycled coarse aggregate (RCA), recycled sand (RCS), and recycled cement powder (RCP), reused, for example, in cement production (Synowiec et al. 2025).

Table 3. Selected Polish standards and guidelines for aggregates and concrete – scope and practical relevance

Tabela 3. Wybrane polskie normy i wytyczne dotyczące kruszyw i betonu – zakres i znaczenie praktyczne

Document	Type	Scope of regulation	Relevance for recycled aggregates	Relation to EN standards
PN-B-06265:2022-08	National standard (supplementary)	Design, production, and quality control of concrete	Specifies conditions for the use of components, including recycled aggregates; refines durability and exposure requirements	Supplement to PN-EN 206
PN-EN 206 (with national annex)	Harmonized standard	Concrete – requirements, properties, production, and conformity	Defines principles for aggregate selection and limitations depending on exposure class	Core framework
PN-EN 12620	Harmonized standard	Aggregates for concrete	Defines quality requirements for aggregates, including recycled ones (composition, physical and chemical properties)	Direct
WT-4 (GDDKiA)	Technical guideline	Aggregates and unbound mixtures in road construction	Specifies acceptance criteria and requirements for aggregates (including secondary materials) in road works	Supplement to EN standards
OST (General Technical Specifications)	Industry documents	Execution and acceptance requirements	Provide practical quality criteria for materials used in infrastructure projects	Based on PN-EN

These findings highlight that water recovery is technologically mature and widely applicable. Fine fraction utilization still requires further research and optimization.

Multi-stage processing – crushing, screening, and air separation – improves aggregate quality by reducing contaminants and controlling particle size. This results in more homogeneous material with lower water absorption and better mechanical properties.

The ReConcrete process includes removal of light and organic impurities, metal separation, and granulometric classification, enabling production of aggregates with tailored properties. As a result, recycled materials can meet normative requirements and be used both in structural concrete and in less demanding infrastructure applications (Synowiec et al. 2025). Figure 3 presents the schematic flow diagram of the ReConcrete process, including the stages of waste concrete treatment such as removal of light and organic impurities, metal separation, and granulometric classification, leading to the production of recycled aggregates with tailored material properties.

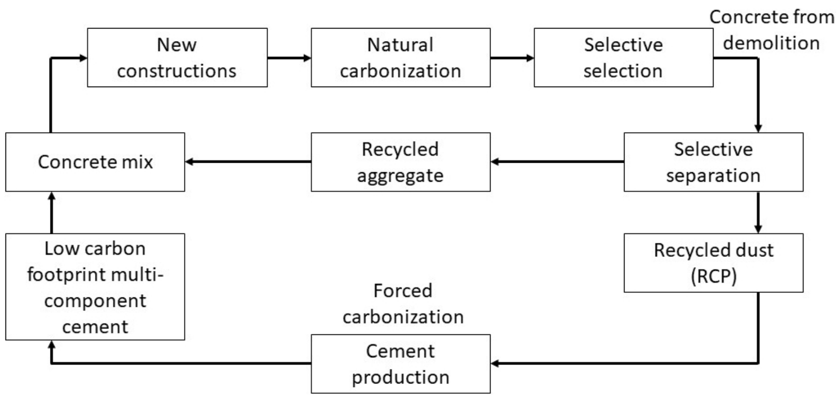

Fig. 3. ReConcrete process flow diagram

Rys. 3. Schemat przebiegu procesu ReConcrete

Research shows that RCA produced through advanced recycling can achieve properties comparable to natural aggregates, particularly in bulk density (about 2200–2500 kg/m for coarse RCA A+), fragmentation resistance, and particle shape. The key quality factor is the degree of cement mortar removal, which influences water absorption (typically higher than in natural aggregates) and porosity.

Reducing mortar-coated fractions improves concrete stability and lowers demand for mixing water and admixtures. High-quality recycled aggregates also enhance workability, rheology, transportability, and pumpability of concrete mixes (Synowiec et al. 2025).

Experimental results show that replacing up to 30% of natural aggregates with RCA+ does not significantly affect key concrete properties, including compressive strength, carbonation resistance, and rheology. Tests with constant cement content (300 kg/m^3) and water (165 kg/m^3) confirmed that RCA was the only variable (Synowiec et al. 2025).

Table 4. Mix designs of the investigated concretes (Synowiec et al. 2025)

Tabela 4. Składy mieszanek badanych betonów (Synowiec i in. 2025)

Component	Content (kg/m^3)	Reference concrete	Concrete with 30% RCA+
Cement CEM II/B-M (S-LL) 42.5N	300	300	300
Natural aggregate 0–2 mm	703	705	705
Natural gravel aggregate 2–8 mm	477	320	320
Natural gravel aggregate 8–16 mm	663	444	444
RCA A+ aggregate 4–16 mm	–	353	353
Polycarboxylate superplasticizer (PCE)	2.40	2.40	2.40
Effective water	165	165	165

Proper pre-treatment, especially pre-wetting, stabilizes mix consistency and reduces the impact of higher water absorption. Concrete with RCA also shows comparable pumpability to reference mixes, confirming its suitability for practical applications (Synowiec et al. 2025).

Table 5. Carbonation depth of the investigated concretes (Synowiec et al. 2025)

Tabela 5. Głębokość karbonatyzacji badanych betonów (Synowiec i in. 2025)

CO_2 exposure time	Average carbonation depth (mm)	Reference concrete	Concrete with 30% RCA+
28 days	6.5	6.5	4.0
70 days	11.5	11.5	10.0

Results show that concrete with 30% RCA+ has comparable or even lower carbonation depth after 28 days compared to reference concrete. This is likely due to pore refinement from fine recycled particles and residual cement paste, which enhances hydration and densifies the interfacial transition zone (ITZ).

After 70 days of CO_2 exposure, differences decrease, although RCA concrete still shows slightly lower carbonation depth, indicating that the initial beneficial effect diminishes over time.

These findings align with the literature, confirming that moderate RCA+ replacement does not reduce carbonation resistance and may improve early performance due to filler and internal curing effects (Synowiec et al. 2025).

Table 6. Maximum replacement levels of coarse aggregates in concrete depending on exposure class (Synowiec et al. 2025)

Tabela 6. Maksymalne poziomy zastąpienia kruszyw gruboziarnistych w betonie w zależności od klasy ekspozycji (Synowiec i in. 2025)

Recycled aggregate type	X0	XC1, XC2	XC3	XC4	XF1, XA1, XD1	Other exposure classes
Fine aggregate (Rc90, Rcu95, Rb10, Ra1, FL2, XRg1)	50%	30%	20%	0%	0%	0%
Coarse aggregate Type A+ (Rc90, Rcu95, Rb10, Ra1, FL2, XRg1)	100%	100%	100%	100%	100%	0%
Coarse aggregate Type A (Rc90, Rcu95, Rb10, Ra1, FL2, XRg1)	100%	70%	50%	30%	30%	0%
Coarse aggregate Type B (Rc50, Rcu70, Rb30, Ra5, FL2, XRg2)	50%	20%	0%	0%	0%	0%

Overall, using up to 30% RCA+ is technically safe for durability applications, provided the material is properly processed and characterized.

The data show a strong relationship between recycled aggregate quality and allowable substitution levels, which varies with exposure conditions. High-quality RCA+ (Type A+) can replace natural aggregates by up to 100% in non- and moderately aggressive environments (X0–XC4) and in selected XF1, XA1, and XD1 classes, achieving performance comparable to natural aggregates. Lower classes (Type A, B) require stricter limits, especially in aggressive conditions, with Type B often unsuitable beyond XC3 due to durability concerns. Fine recycled aggregates are the most limited, with up to 50% substitution only in non-aggressive conditions (X0). These findings highlight the need for strict quality control and classification.

Advanced recycling also enables recovery of fine fractions such as recycled cement powder (RCP), which can be reused in clinker and cement production. Secondary carbonation supports CO_2 binding, contributing to decarbonization strategies. RCA+ shows comparable density, strength, and particle geometry to natural aggregates, and its use at ~30% does not significantly affect rheology, strength, pumpability, or carbonation resistance. Proper pre-treatment (e.g., pre-wetting) stabilizes mix properties. Technologies like ReConcrete support circular economy goals and emission reduction.

Water and fine fraction recovery systems are also well developed. Traditional systems reuse both aggregates and slurry, though fine particles can limit structural applications (Rogucki et al. 2025). Filter press solutions (e.g., WATERWASH) enable separation into clean water and solid residue. Recovered water (pH ~12–13) meets PN-EN 1008 requirements and can be reused in concrete production.

Experimental results (Table 7) confirm that recycled water does not adversely affect concrete properties; workability, air content, and compressive strength (about 40–42 MPa

Table 7. Properties of fresh concrete mix and hardened concrete (Rogucki et al. 2025)

Tabela 7. Właściwości świeżej mieszanki betonowej i betonu stwardniałego (Rogucki i in. 2025)

Parameter	1	2	3	4
Slump at 5 min (mm)	185	195	210	205
Slump at 60 min (mm)	155	155	170	170
Slump at 90 min (mm)	120	120	165	160
Air content (%)	3.0	2.7	2.9	2.5
Compressive strength at 2 days (MPa)	14.8	14.2	13.3	13.5
Compressive strength at 7 days (MPa)	24.6	25.1	25.0	24.8
Compressive strength at 28 days (MPa)	41.2	42.0	40.3	40.5
Compressive strength at 56 days (MPa)	45.1	46.2	–	–
Density (kg/m^3)	2,325	2,340	2,330	2,335

after 28 days) remain comparable to conventional mixes, supporting its full-value use (Rogucki et al. 2025).

The dewatered filter cake can also be used in cement-bound granular mixtures (CBGM) due to its high content of fine particles (<0.063 mm), which can improve particle grading in mixes with low cement and water demand. However, studies show that partial replacement of cement and aggregates with this material may reduce compressive strength by about 20–25%, indicating the need for further optimization of dosage and processing (Rogucki et al. 2025).

From an engineering point of view, this material is mainly suitable for non-structural or lower-performance CBGM applications, where reduced strength can be offset by improved workability and grading. Its use in higher-performance bound layers should be limited unless additional treatment (e.g., improved dewatering or fraction refinement) is applied to reduce strength loss (Table 8).

Table 8. Properties of CBGM mixtures (Rogucki et al. 2025)

Tabela 8. Właściwości mieszanin CBGM (Rogucki i in. 2025)

Parameter	A	B	C
Density (kg/m^3)	~2,100	2,130	2,140
Compressive strength at 7 days (MPa)	3.7	–	–
Compressive strength at 28 days (MPa)	2.8	5.1	4.8

The results show that CBGM mixtures have similar bulk density (approx. 2,100–2,140 kg/m^3), indicating comparable compaction and particle packing. However, their mechanical performance differs significantly.

Mixture A shows the lowest compressive strength after 28 days (2.8 MPa), likely due to an imbalance between fines content and binder efficiency, resulting in a weaker cementitious matrix. In contrast, mixtures B and C achieve higher strengths (5.1 MPa and 4.8 MPa), indicating better grading and improved binder–aggregate interaction. The lack of 7-day data for B and C limits early-age comparison, but overall results show that strength depends more on mix composition than density, particularly on the effective use of fine recycled slurry fractions.

From an engineering perspective, mixtures B and C are more suitable for CBGM applications with moderate strength requirements, while mixture A requires optimization of fines and binder distribution. This confirms that performance in CBGM systems with recycled fines is governed primarily by mix design rather than density alone.

Pressure filtration systems complement recycling processes by enabling water recovery and better management of fine fractions, supporting circular economy goals and improving environmental efficiency.

Recycled aggregates are increasingly used in Polish road construction, including concrete blocks, slabs, and insulation elements (Jasek et al. 2025), offering good strength, low cost, and improved load-bearing performance (Xie et al. 2024). They have been applied in projects such as the A1 motorway, urban works in Kraków, railway line E30, and the Grota-Rowecki Bridge in Warsaw, mainly in subbases and embankments.

Despite successful applications, structural use remains limited. Its development is supported by European standards (EN 12620, EN 206), national annexes (PN-B-06265), and technical guidelines (GDDKiA), while CPR 2024 introduces lifecycle assessment, environmental requirements, and the Digital Product Passport (DPP), improving transparency and standardization.

Growing demand for sustainable materials and advances in recycling technology support further development of the recycled aggregate sector within the circular economy

The quality assessment of recycled aggregates is a multi-stage process involving documentation analysis, TLS scanning for geometric mapping, core sampling, and laboratory testing of strength, composition, carbonation depth, and contaminants. This is followed by selective demolition, crushing, screening, and optional washing.

Final evaluation includes physical, mechanical, and chemical tests (density, absorption, frost resistance, fragmentation resistance) and microstructural analysis (SEM, XRD), as well as performance testing in concrete mixes to determine suitability for substitution of natural aggregates in specific applications (Kępniak et al. 2025).

2.7. Barriers and market limitations

Despite increasing interest and technological progress, several barriers limit the development of the recycled aggregates market: variability and heterogeneity of input materials, insufficient standardization and certification systems, economic competitiveness of natural aggregates, limited market trust, especially in structural applications, uneven development of recycling infrastructure, and insufficient levels of selective demolition.

Additionally, there is a noticeable gap between declared sustainability goals and actual implementation in the construction sector.

2.8. Economic competitiveness of RCA

The economic competitiveness of recycled concrete aggregates depends on both production costs and local market conditions. For comparison purposes, the functional unit should be defined as one tonne of aggregate ready for use. The unit cost of RCA production includes selective demolition or pre-treatment, crushing, screening, separation, washing, energy consumption, water use, labor, equipment amortization, quality testing, certification, internal logistics, and transport to the final user. This cost may be reduced by avoiding landfill or disposal fees and by lower demand for natural aggregate extraction (Dias et al. 2022).

Literature indicates that recycled aggregates may be cost-competitive compared with natural aggregates, especially when demolition sites, recycling plants, and construction projects are located within short transport distances. However, this advantage can decrease or disappear when transport distances are long, the input material is highly contaminated, or additional processing is required to meet concrete-grade quality standards. Therefore, RCA is most economically attractive in urban areas with high CDW generation, high demand for aggregates, limited landfill capacity, and well-developed recycling infrastructure (Ohemeng and Ekolu 2020; Dias et al. 2022).

Available international studies show that the production cost of coarse RCA may be significantly lower than that of comparable natural aggregates. For example, Ohemeng and Ekolu (2020) indicated that the long-term cost of producing one tonne of coarse recycled concrete aggregate was approximately 40% lower than that of coarse natural aggregate. However, because standardized Polish plant-level cost data are limited, these values should be treated as indicative benchmarks rather than direct market prices for Poland. Further research should include life cycle costing and sensitivity analysis, considering transport distance, landfill fees, selective demolition costs, certification requirements, and plant capacity.

2.9. European context and comparative analysis

A comparative analysis across Europe indicates significant regional differences in the adoption of recycled aggregates.

Countries such as the Netherlands, Germany, and Belgium achieve high recycling rates due to:

- strict regulatory enforcement, mandatory recycling targets, green public procurement policies,
- well-developed certification systems.

In contrast, Poland represents a transitional market characterized by growing regulatory alignment with EU policies, expanding recycling infrastructure, increasing environmental awareness, but still limited market penetration of recycled aggregates.

At the EU level, recycled aggregates play a key role in achieving circular economy objectives, including: reduction of primary raw material consumption, diversion of waste from landfills, reduction of CO_2 emissions.

However, the overall circularity level remains relatively low, indicating significant untapped potential.

The circularity of aggregates in Poland is expected to increase gradually, although from a relatively low base. Poland remains a transitional market, where the use of recycled aggregates is still concentrated mainly in road construction, subbases, embankments, and selected non-structural applications. This is consistent with the relatively low circular material use rate in Poland, which reached 7.5% in 2023 (EEA 2025). Broader use in concrete, especially structural concrete, will require stable quality assurance, certification, selective demolition, and stronger market confidence.

Several factors may accelerate this transition. These include the obligation to separate construction and demolition waste into specific material fractions, including wood, metals, glass, plastics, gypsum, and mineral waste such as concrete, bricks, tiles, ceramics, and stones (Ustawa z dnia 14 grudnia 2012 r. o odpadach, as amended). Additional drivers include the revised Construction Products Regulation, the development of the Digital Product Passport, green public procurement, and increasing ESG and LCA requirements in construction (European Parliament and Council 2024; European Commission 2024).

In the short and medium term, the highest growth potential for RCA in Poland is expected in road infrastructure, cement-bound granular mixtures, concrete blocks, prefabricated non-structural elements, and low-risk concrete applications. In the longer term, advanced recycling technologies, improved standards, and wider certification may enable greater use of high-quality RCA in structural concrete. Nevertheless, due to the very large scale of natural aggregate production in Poland, RCA should be regarded as an important complementary resource supporting circular economy objectives rather than a full replacement for natural aggregates (Pacheco et al. 2023).

Conclusions

This study provides a comprehensive analysis of the development of recycled concrete aggregates (RCA) within the Polish construction sector in the broader context of the European circular economy transition. The findings confirm that technological advancements, regulatory evolution, and environmental pressures are key drivers shaping this market.

The results demonstrate that advanced recycling technologies, particularly multi-stage crushing, separation, and classification, enable the production of high-quality recycled aggregates (RCA+) with properties comparable to natural aggregates. The recovery of fine fractions, including recycled cement powder (RCP), and the implementation of secondary carbonation processes further enhance the environmental performance of recycling systems by enabling resource recovery and CO_2 sequestration.

From a material perspective, the incorporation of RCA at replacement levels of up to approximately 30% does not significantly affect key concrete properties, including compressive strength, workability, pumpability, and carbonation resistance. In some cases, beneficial effects related to internal curing and microfiller action are observed. However, the performance of recycled aggregates remains strongly dependent on their quality class and proper pre-treatment, particularly pre-wetting.

The study also confirms the growing importance of integrated recycling systems, including process water recovery technologies. Pressure filtration systems enable the reuse of water in compliance with relevant standards without compromising concrete performance. At the same time, the utilization of fine fractions in cement-bound mixtures remains limited due to potential reductions in mechanical strength, indicating the need for further optimization.

Despite technological progress, the development of the recycled aggregates market in Poland is still constrained by several barriers, including material variability, insufficient standardization, economic competitiveness of natural aggregates, and limited market acceptance, particularly in structural applications. These challenges are further compounded by uneven infrastructure development and insufficient levels of selective demolition.

The material-flow analysis also shows that RCA should be regarded as an important complementary resource rather than a full substitute for natural aggregates. Although construction and demolition waste represents a significant secondary material stream, the scale of natural aggregate production remains substantially higher than the currently available volume of high-quality recycled aggregates. This indicates that the greatest short- and medium-term potential for RCA in Poland lies in targeted applications, such as road construction, cement-bound granular mixtures, non-structural concrete elements and selected concrete applications where quality requirements can be reliably met.

The comparative analysis highlights that those countries with well-established circular economy systems achieve significantly higher levels of recycled aggregate utilization due to strong regulatory frameworks, effective enforcement mechanisms, and the implementation of green public procurement and certification systems. In this context, Poland represents a transitional market with considerable growth potential, requiring further alignment of regulatory, technological, and economic instruments.

Recent regulatory developments at the European level, including the revised Construction Products Regulation (CPR 2024), are expected to play a crucial role in accelerating the adoption of recycled materials by integrating lifecycle assessment, environmental performance indicators, and digital tools such as the Digital Product Passport.

The future circularity of aggregates in Poland will therefore depend not only on technological progress but also on the development of reliable material-flow monitoring, selective demolition practices, certification systems, green public procurement, and economic incentives. The economic analysis indicates that RCA may become cost-competitive under favorable conditions, particularly where transport distances are short, landfill or disposal costs are avoided, and recycling facilities are located close to both demolition sites and construction projects. However, the competitiveness of RCA remains strongly site-specific and requires further verification under Polish market conditions.

Overall, recycled aggregates constitute a key component of the transition toward a low-carbon and resource-efficient construction sector. Their broader implementation will depend on the integration of circular economy principles into engineering practice, further development of processing technologies, strengthening of quality assurance systems, and increased collaboration between industry, policymakers, and research institutions.

Future research should focus on quantitative environmental and economic assessments, particularly Life Cycle Assessment and Life Cycle Costing, as well as on detailed material-flow analyses comparing CDW generation, RCA production, and natural aggregate demand. Further studies should also address the optimization of fine recycled fractions, the cost structure of RCA production under Polish conditions, and the technical and regulatory requirements for expanding the applicability of recycled aggregates in structural concrete.

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RECYCLED CONCRETE AGGREGATES IN THE CIRCULAR ECONOMY: TECHNOLOGICAL, ENVIRONMENTAL, AND REGULATORY PERSPECTIVES FROM POLAND AND EUROPE

Keywords

recycled concrete aggregates, circular economy, concrete recycling, advanced recycling technologies, life cycle assessment (LCA)

Abstract

The construction sector is a major contributor to resource consumption and greenhouse gas emissions, requiring sustainable and circular material management. Recycled concrete aggregates (RCA) from construction and demolition waste are a key element of this transition. This study examines the development of the RCA market in Poland within EU circular economy policy, focusing on technology, regulation, and implementation barriers.

A qualitative approach based on literature, regulatory analysis, and case studies was applied. The scope includes recycling technologies, RCA properties, water recovery systems, and a comparison of selected European countries.

Results indicate that multi-stage processing enables high-quality RCA+ with properties comparable to natural aggregates. Up to 30% RCA does not significantly affect compressive strength, workability, or carbonation resistance. Pressure filtration systems allow water reuse without performance loss, while fine fraction utilization remains challenging.

Despite progress, adoption in Poland is limited by variability, weak standardization, economic constraints, and low acceptance in structural applications. More advanced EU countries achieve higher recycling rates due to stronger regulatory and policy instruments.

The study concludes that RCA supports decarbonization and resource efficiency in construction, but broader implementation requires technological improvement, regulatory alignment, and better-quality assurance. Future research should include Life Cycle Assessment (LCA) for environmental and economic evaluation.

KRUSZYWA Z RECYKLINGU BETONU W GOSPODARCE O OBIEGU ZAMKNIĘTYM: PERSPEKTYWY TECHNOLOGICZNE, ŚRODOWISKOWE I REGULACYJNE Z POLSKI I EUROPY

Słowa kluczowe

kruszywa z recyklingu betonu, gospodarka o obiegu zamkniętym, recykling betonu, zaawansowane technologie recyklingu, ocena cyklu życia (LCA)

Streszczenie

Budownictwo jest jednym z głównych sektorów odpowiadających za zużycie zasobów oraz emisje gazów cieplarnianych, co wymaga wdrażania zrównoważonych i cyrkularnych modeli gospodarowania materiałami. Kruszywa z recyklingu betonu (RCA), pozyskiwane z odpadów budowlanych i rozbiórkowych, stanowią istotny element tej transformacji. Celem pracy jest analiza rozwoju rynku RCA w Polsce w kontekście polityk gospodarki o obiegu zamkniętym UE, ze szczególnym uwzględnieniem technologii, regulacji i barier wdrożeniowych.

Zastosowano podejście jakościowe oparte na analizie literatury, dokumentów oraz studiów przypadków. Obejmuje ono technologie recyklingu, właściwości RCA, odzysk wody technologicznej oraz porównanie wybranych krajów europejskich.

Wyniki wskazują, że wieloetapowe procesy umożliwiają uzyskanie RCA+ o parametrach zbliżonych do kruszyw naturalnych. Dodatek do 30% RCA nie wpływa istotnie na wytrzymałość, urabialność ani odporność na karbonatyzację. Systemy odzysku wody pozwalają na jej ponowne wykorzystanie bez pogorszenia jakości betonu, natomiast zagospodarowanie frakcji drobnych pozostaje wyzwaniem.

Pomimo postępu technologicznego wdrożenie RCA w Polsce ograniczają zmienność surowca, brak standaryzacji, bariery ekonomiczne oraz niska akceptacja rynku. Kraje UE o bardziej rozwiniętej gospodarce cyrkularnej osiągają wyższe poziomy recyklingu dzięki silniejszym regulacjom.

Wnioski wskazują, że RCA ma istotny potencjał w zakresie dekarbonizacji i efektywności zasobowej budownictwa, jednak jego szersze wdrożenie wymaga dalszego rozwoju technologii, harmonizacji regulacyjnej oraz analiz cyklu życia (LCA).