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Potential Future Direction of The Sustainable Production of Precast Concrete with Recycled Concrete Aggregate: A Critical Review

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Abstract

This critical review explores the incorporation of recycled concrete aggregate (RCA) in precast concrete within the context of sustainable construction. Amid the construction industry's quest for eco-friendly alternatives, the integration of RCA in precast concrete has the potential to revolutionize it. This review highlights the many benefits of using precast concrete with RCA, such as faster construction, enhanced quality control, and reduced on-site disruptions. Examining the current applications of RCA in precast concrete, this paper critically evaluates its merits and drawbacks, shedding light on the complexities of this environment-friendly construction method. Further, this paper delves into how RCA contributes to sustainable energy and cleaner construction. It not only scrutinizes the existing practices but also proposes innovative ways to implement them, thereby fostering a more sustainable and environment-friendly construction industry. By examining new precast concrete technology, modeling, and sustainability, this review describes the transformative trends shaping both precast concrete and the construction sector. Advocating for the widespread adoption of RCA in precast concrete for sustainable construction, this review challenges established paradigms. It emphasizes the importance of adhering to industry standards and considering environmental and financial factors in achieving a more sustainable construction industry.

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1. Introduction

Concrete is the second most widely utilized material globally, following water, and it has been instrumental in the construction industry's contribution to global economic development.[1-4] Depending on the source, the global annual production of concrete ranges from 13 billion to 21 billion tons.[2] However, it has also earned notoriety as one of the most environmentally unsustainable materials[1-2] due to the substantial emissions of carbon dioxide (CO_2) from the manufacturing of cement and the extensive use of resources (approximately 7–14%).[3,4] As a composite material, concrete is the cornerstone of construction, as it is the primary material for building foundations, walls, and floors. Yet, the production of concrete comes at a steep environmental cost, demanding substantial quantities of natural resources, including aggregates, cement, and water.[4,5] Aggregates, making up 60–75% of concrete's volume, are particularly significant.[6,7] Unfortunately, the overconsumption of these natural resources has resulted in landscape degradation and environmental pollution.[8] The current environmental crisis has prompted a global call for adopting zero-waste strategies in the construction industry – an immensely challenging but essential objective.[9] Infrastructure development is pivotal to a nation's economy, as evidenced by the anticipated 3.6% growth in the construction industry, which strongly mirrors global economic growth rates. However, such growth often comes at the cost of substantial, extensive resource

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extraction.[10] Furthermore, the construction industry has been observed to generate significant waste during the construction of new structures and the dismantling of existing ones.[11] Construction and demolition waste (CDW) emerges from a wide range of sources, including demolition, refurbishment, new construction, public works, and other construction-related activities.[9,12] CDW comprises materials such as concrete, asphalt concrete, steel, wood, wallboard, mortar, masonry, and clay tie, which are commonly used in the construction of buildings, roads, and bridges, as well as in various industries.[8,13] Specifically, CDW includes waste originating from excavation, land formation, road construction, demolition, site clearance, and civil and building construction.[14]

CDW has a highly diverse composition, with inert material, excluding excavation soils, typically accounting for 40–85% of the waste volume.[15] Globally, CDW constitutes around 35% of the total waste produced,[16] the majority of it coming from countries including China, the United States, and India.[17-20] For instance, the United States produced 600 million tons of CDW in 2018, exceeding the volume of municipal solid waste by more than twofold. Table 1 presents the annual generation of CDW in major countries.

Table 1. Annual generation of CDW in major countries (million tons).

Country	Akhtar *et al.*[17]	Neupane *et al.*[18]	Trivedi *et al.*[19]	Joseph *et al.*[20]
China	1020	1130	2360	2600
USA	519	500	600	600
India	530	530	100–400	150
Australia	19	19.3	20.4	25.2
England	100.23	114.2	55.42	187.3
France	246.7	342.6	72.11	46
Italy	39.65	46.3	39.94	68.3
Germany	210.3	92.3	90.0	-
Japan	75.4	75	-	-
South Korea	68	68	67.68	-

The Asian continent accounts for 53.2% of the worldwide waste production. This can be ascribed to growing urbanization, construction projects, and infrastructural development. European countries produce over 26.9% of global CDW. North America generates around 14.6% of worldwide CDW, while Africa, South America, and Oceania generate approximately 2.8%, 2.0%, and 0.5% respectively.[18] Demolition activities accounted for over 90% of CDW generation, while construction activities contributed to less than 10%. Of the total CDW generated, approximately 455 million tons were directed toward reuse or recycling, and under 145 million tons ended up in landfills.[21] The uncontrolled dumping of untreated CDW in illegal landfills and along roadsides has spawned environmental and economic challenges. Several strategies, including waste reduction, reuse, recycling, and proper landfill disposal, have been proposed to mitigate CDW pollution.[22] Developing countries have often turned to the reuse and recycling of CDW as a means to reduce construction expenses.[8] China has a recycling and reprocessing rate of less than 5% for CDW, which accounts for 30–40% of the country's total municipal waste. Developed countries including Germany, Denmark, Singapore, Japan, South Korea, and the United States have greatly varying rates of CDW recycling and reuse, achieving rates as high as 70% to 95%.[23]

Just 13 countries—out of the 61 that have published research articles—have contributed more than 10 research papers on the management of building waste. China, Australia, and Hong Kong were the top three contributors, with 75, 43, and 38 research papers respectively.[16] The absence of an appropriate infrastructure for managing construction waste, both in terms of physical facilities and legislation, was identified as the main obstacle.[24] CDW represents a significant potential for resource conservation and the adoption of circular economy practices. Efforts to recover valuable materials from CDW for reuse or repurposing are central to sustainable construction practices.[8] By 2026, the CDW market is expected to be worth $34.4 billion, expanding at a compound yearly growth rate of 5.3% between 2021 and 2026.[9] Establishing an efficient circular economy model for CDW is pivotal, as it has applications beyond the building industry. Fig. 1 emphasizes the importance of professional and stakeholder participation in building design and construction to reduce and reuse CDW.

Precast construction technology has progressively supplanted traditional cast-in-situ techniques in multiple construction sectors in recent years.[27] Compared to concreting, which has been increasingly acknowledged in the construction industry as a method of assembling structures or bridges using precast components, it involves much simpler, faster, and more affordable construction procedures.[28] The size of the global precast concrete market was 146.38 million USD in 2022 and is projected to reach 229.87 million USD in 2030, growing at an annual rate of 49.09%.[29] As Fig. 2 illustrates, the market is expanding due to the growing demand for precast concrete structures in the industrial, commercial, and residential sectors.

Precast construction is widely acknowledged for its commendable sustainability and efficiency attributes.[23,27] Against the backdrop of depleting resources, growing

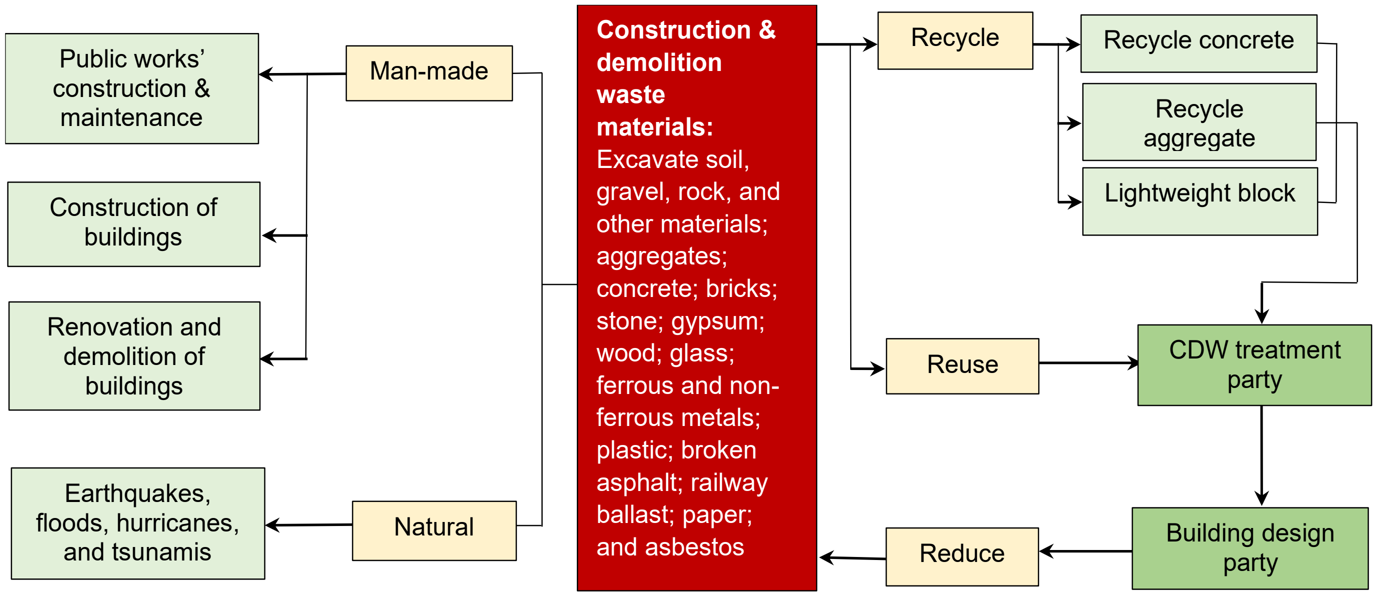

Fig. 1 Toward a method of circular economy for CDW. Reproduced with the permission from [25,26], Copyright 2018 Elsevier B.V. and 2020 Elsevier Inc.

environmental concerns, and the substantial impact of CDW, the incorporation of recycled concrete aggregate (RCA)emerges as a pivotal and sustainable practice.[9,18,30] The assimilation of RCA into precast concrete presents an attractive solution to address the environmental challenges entrenched in conventional concrete production. Furthermore, the procurement of RCA from CDW is fundamentally straightforward, as this alternative aggregate can be readily sourced from construction sites.[20,28] It is imperative to investigate the feasibility of utilizing concrete containing RCA to actively promote the adoption of this sustainable material in the precast concrete industry, thereby advancing the cause of a more environmentally conscious construction sector.[28] Since it is repurposed from concrete waste, RCA serves the dual purpose of reducing waste and contributing to a more environmentally responsible construction paradigm. Although RCA does not represent a novel concept, this paper delves deeper into the specific applications and implications of incorporating RCA into precast concrete, with a primary emphasis on sustainability. This comprehensive review contributes to the existing body of research by uniquely exploring the integration of RCA into precast concrete, focusing on the potential future direction of sustainable production. Unlike prior studies that touched on the performance properties, treatment method, or life cycle assessment of conventional concrete and RCA use, this review

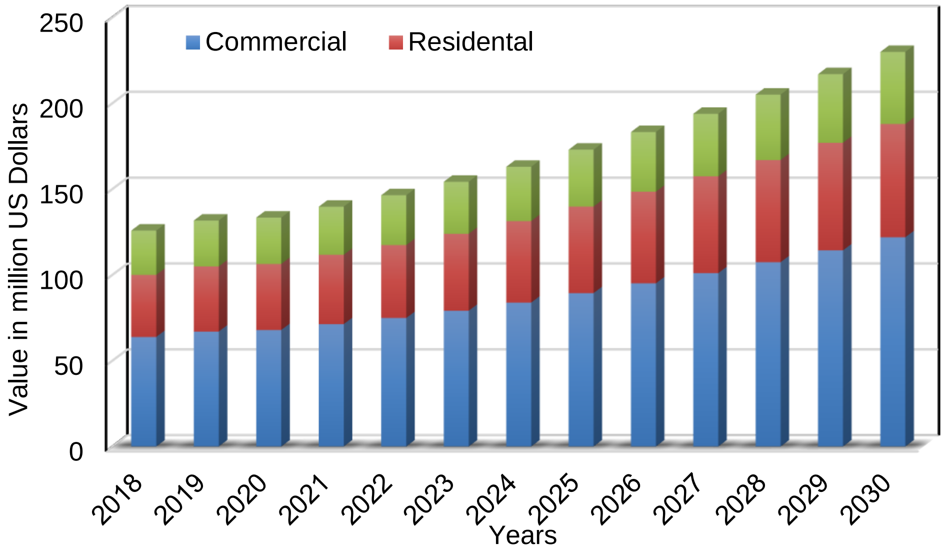

Fig. 2 Size of the global precast concrete market with projections through 2030 by building type. Reproduced with the permission from [29].

provides a more detailed and current perspective. It stands out by specifically examining the applications and implications of RCA in precast concrete, offering insights into the opportunities and challenges associated with this approach. This work serves as a focused bridge between RCA, precast concrete, and sustainable construction practices, distinguishing itself through a comparative exploration of the subject.

2. Recycled concrete aggregate (RCA)

Recycling concrete waste from CDW into recycled aggregate is the most optimal and promising approach to maximize environmental and economic benefits.[11,31,32] Fig. 3 shows the material flow cycle for aggregates. Recycled aggregate is an alternative to natural concrete aggregate.[9] RCA refers to aggregates made by recycling CDW,[15] which is one of the main strategies to produce more eco-friendly concrete.[33] Hence, recent years have seen several studies assessing the use of CDW in concrete. The current study aimed to analyze the characteristics of concrete produced using RCA to comprehend its capabilities and constraints comprehensively.

2.1 Definition of RCA

RCA is a sustainable material obtained by crushing parent or old concrete from demolished structures or other origins[6] Recycled concrete could be a sustainable alternative to natural aggregate in fresh concrete mixes, either partially or entirely, as reported by Liu *et al*.[35] and Behera *et al*..[6] The cost of RCA limits its widespread use, particularly given the continued availability of natural resources for concrete production.[36] RCA exhibits several properties that distinguish it from natural aggregates. First, RCA is highly sustainable, as it is derived by recycling concrete waste.[1,6,9-11] RCA also has favorable mechanical properties, demonstrating adequate strength and durability.[19-20,37] making it a viable option for various construction applications.[38] However, it is essential to acknowledge that the quality and characteristics of RCA can vary depending on the source material and the recycling process,[39] necessitating stringent quality control measures to ensure consistent and reliable performance in concrete applications.[40,41] RCA is categorized as coarse or fine, determined by its particle size distribution[42-45] Its properties are contingent upon the origin of the concrete,[11] the method of crushing,[46,47] and the treatment of the material[20,37,48] RCA derived from reinforced concrete may contain steel reinforcement, which has to be removed through additional processing before use in concrete production. The three phases of RCA are adherent mortar, which acts as an additional matrix, interfacial transition zones between coarse aggregate and matrix, and the aggregate and mortar phases.[6,49] The matrix differences between RCA and natural aggregate concrete are illustrated schematically in Fig. 4.

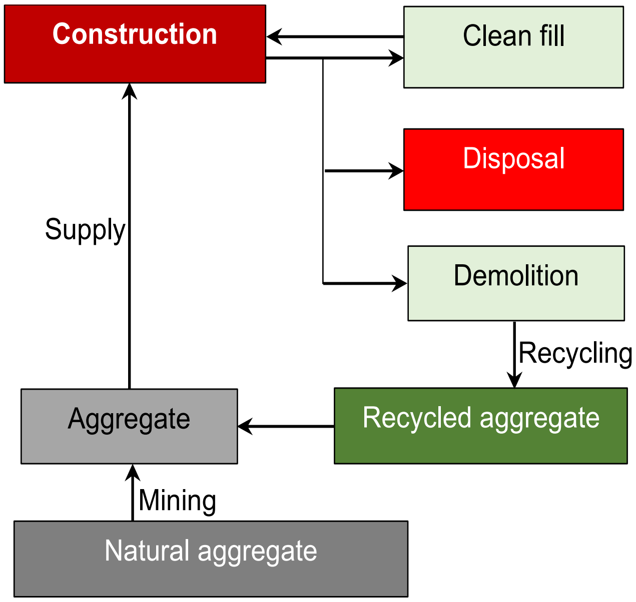

Fig. 3 Material flow cycle for aggregates. Reproduced with the permission from [34].

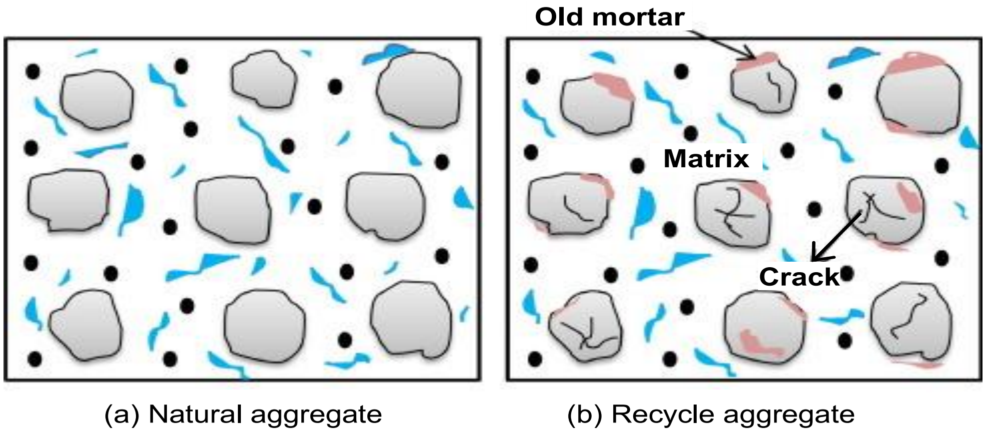

Fig. 4 Comparison of natural aggregate and recycled aggregate concrete matrices. Reproduced with the permission from [6], Copyright 2014 Elsevier Ltd.

RCA utilization in civil engineering has gained interest due to its potential sustainability advantages. Consequently, assessments have been conducted to compare its environmental impact with concrete containing natural aggregate.[2] Concrete incorporating RCA has been observed to exhibit inferior properties compared to natural concrete aggregate, including decreased mechanical strength, elasticity modulus, density, and permeability, as well as increased drying shrinkage, bleeding, and creep deformation. These property changes have been primarily attributed to adhered mortar in RCA.[3,50] Efforts have been made to improve the quality of RCA by enhancing its mechanical strength and durability by removing or reinforcing adhered mortar. Researchers have discovered the potential ecological and economic benefits of adding recycled materials, supplemental cementitious materials, and recycled water into RCA. However, the composition of concrete varies greatly from one location to the next.[1,51] RCA-incorporated concrete can have diminished mechanical and durability characteristics compared to concrete exclusively composed of natural aggregates. The reduction is usually tackled by augmenting the binder content, but this results in elevated emissions linked with the usage of RCA. According to Bennett *et al*.,[52] substituting low-emitting supplemental cementitious materials for high-emitting ordinary Portland cement binders is advised to create a sustainable RCA mix design.

2.2 Types of RCA

The utilization of natural aggregate in the concrete manufacturing process is highly significant. RCA in concrete has grown in popularity as a substitute for natural aggregate. This is mainly due to its capacity to mitigate the environmental consequences of manufacturing fresh concrete. RCA is produced by crushing, cleaning, and grading discarded concrete. It can be categorized into two types based on particle size: coarse (CRCA) and fine (FRCA).[42-45] Additionally, RCA can be classified into two types based on the degree of adhered mortar: "mortar-attached aggregate" and "mortar-covered aggregate",[51] as shown in Fig. 5, using an optical microscope to calculate the percentage of mortar attached to RCA surfaces. According to Verian *et al.*,[41] the chance of discovering old mortars adhered to RCA surfaces is 28.9%. Furthermore, Afroughsabet *et al*.[53] found that, on two parent concrete samples, the attached mortar content of RCA ranged from 24% to 38% while utilizing the hydrochloric acid dissolving method. According to McNeil and Kang,[54] residual adhered mortar on aggregates significantly affects RCA's density, porosity, and water absorption characteristics. Reducing mortar adhering to RCA has been noted to increase the end product's quality.[9] By crushing RCA into smaller pieces and then washing the aggregates with water, the mortar content of RCA can be reduced.[41] The number of processing steps affects the amount of mortar applied to the aggregates because it causes the gradual fragmentation of cement paste applied to the RCA's surface.[6,55] Chemical treatments, such as acid washing, can effectively loosen and remove adhered mortar. However, it is essential to exercise caution when managing chemical treatments to prevent any harm to the aggregate.[33,56]

Natural coarse aggregate can be replaced with aggregates ranging from 5 to 12 mm and 12 to 20 mm to create CRCA.[57] Depending on the quality of the initial concrete, the content of particles finer than 88 µm in the RCA, with a maximum size of 25 mm, ranges from 1.3% to 1.7%,[46] FRCA accounts for 30–60% of the overall concrete waste produced when crushing for the coarse portion.[58] Therefore, exploring methods for incorporating CRCA and FRCA in manufacturing fresh concrete is essential. Researchers have employed different concentrations of RCA in their concrete compositions. Table 2 summarizes previous research on the percentage of natural aggregate replaced by RCA. As per the reported study results, CRCA, FRCA, and the combination of CRCA and FRCA have the potential to be utilized as aggregates in concrete

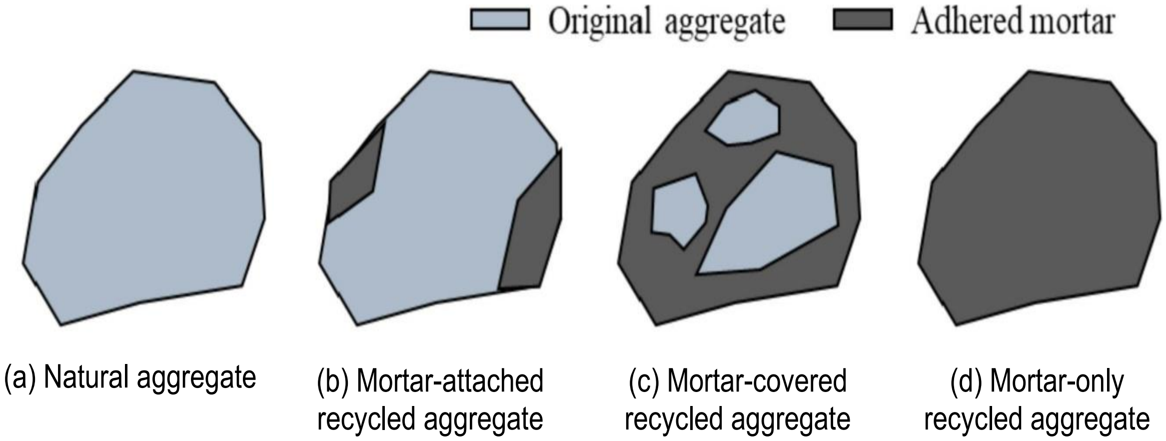

Fig. 5 Aggregate types based on mortar adhesion. Reproduced with the permission from [52], Copyright 2022 Elsevier Ltd.

Table 2. Summary of previous research on the natural aggregate replacement percentage by RCA.

No.	Natural aggregate replacement (%)			Maximum compressive strength at 28 days ($f'_{c,28}$) (MPa)	References
	CRCA	FRCA	CRCA+FRCA		
1	40			27	[45]
2	60			33	[3]
3	100			65	[28]
4	30, 50			33.1 (50%)	[7]
5	30, 70			70.7 (70%)	[59]
6	25, 100			70 (100%)	[60]
7	50, 100			53 (50%)	[35]
8	15, 30, 45			42.4 (15%)	[57]
9	20, 50, 100			72.81 (100%)	[61]
10	20, 50, 100			72.81 (100%)	[62]
11	15, 30, 60, 100			38.1 (15%)	[63]
12	25, 50, 75, 100			34 (25%)	[64]
13	25, 50, 75, 100			37 (25%)	[65]
14	25, 50, 75, 100			39.7 (50%)	[66]
15	10, 25, 50, 100	10, 25, 50, 100		54.1 (C10%), 51.6 (F10%)	[15]
16		25, 50, 100		49 (25%)	[42]
17		25, 50, 75, 100		8.5 (50%)	[67]
18		10, 20, 30, 50,100		62.2 (10%)	[68]
19	100	100	100 + 100	64.6 (C100%)	[69]
20			30 + 30	40.4 (50%)	[58]
21			100 + 100, 100 + 85, 100 + 70	42 (C100%+F70%)	[44]

applications.

CRCA is a feasible substitute for coarse natural aggregate, as evidenced by the studies mentioned in Table 2. The substitution ratio for CRCA can often reach 100%. According to Fiol *et al*.,[61] using 100% CRCA for all mix designs resulted in compressive strength values between 56.75 and 72.81 MPa. This effect is caused by the introduction of a dry RCA with increased absorption, which effectively reduces the water-to-cement ratio. The density of SCC decreases as the percentage of CRCA rises. These outcomes, which help reduce the self-weight of concrete, are produced by the recycled aggregate's reduced particle density.[69] Conversely, concrete with 100% RCA and a water-to-cement ratio of 0.60 had a compressive strength that was 60.60% less than the reference, while concrete with 25% RCA and a water-to-cement ratio of 0.50 suffered a compressive strength loss of 8.7%.[65] Although the incorporation ratio of CRCA is inversely related to its environmental impacts, these impacts seem small in comparison to the contributions of the transportation and cement production sectors.[1] The maximum nominal size of RCA affects the mortar content adhering to recycled aggregate, as smaller aggregates tend to have a higher amount of attached mortar.[70] The correlation between the replacement ratio of RCA and the total volume and pore size has been observed, with a greater impact for newer concrete, which diminishes with aggregate.[63]

Alternative approaches for utilizing FRCA have been suggested, but there is disagreement. Some researchers have identified the high water absorption rate of FRCA as the primary reason to avoid its use in concrete, as it can result in less effective concrete.[15] The mechanical properties decrease as the replacement ratio rises, but the results are still respectable, particularly when the replacement ratio of FRCA is reasonable and below 30%.[68] Furthermore, FRCA has demonstrated satisfactory physical and mechanical behavior, making it applicable for replacement levels of up to 50%.[67]

FRCA's application in structural concrete is restricted due to its high porosity and water absorption rate, which can compromise the end product's quality.[1,71] Alternative applications of FRCA have been suggested, such as its use as a raw material in the production of Portland clinker, a supplementary material in Portland cement production (excluding clinker), and a concrete filler after grinding. The selection of these three options should be based on an economic study tailored to each context.[36]

The incorporation of CRCA and FRCA in new concrete has been proposed as a possible resolution to this problem.[44] Using 100% CRCA and FRCA to make entirely recycled aggregate concrete, Xiao *et al.*[69] investigated the material's fracture behavior. The original aggregate peeling off old mortar and the attached old mortar cracking were the main causes of failure at several sites, brought on by the old mortar's initial damage and weak old ITZ. In practical scenarios, incorporating 30% of CRCA and FRCA in concrete mixtures can provide adequate performance at high temperatures, rendering it equivalent to concrete made with natural aggregates. The compressive strength of concrete comprising natural aggregate is 16% higher than that of RCA concrete at room temperature. Following exposure to 150, 300, and 450 °C, there were gradually declining compressive strengths of approximately 29.7%, 40.9%, and 57%, respectively.[58] Additionally, Gales *et al.*[72] proposed that properly designed sustainable concretes containing RCA have the potential to meet specific fire design requirements up to a temperature of 500 °C. With proper material selection and proportioning, recycled coarse and fine aggregates can be used to produce concrete with appropriate properties.[44] Combining CRCA and FRCA in concrete production may be a viable strategy.

2.3 Advantages and disadvantages of using RCA in precast concrete

The utilization of RCA in precast concrete presents both advantages and disadvantages, outlined in Fig. 6. Integrating RCA offers numerous benefits, such as preserving natural aggregate sources, reducing construction waste production, conserving landfill land, promoting a sustainable environment, and potentially mitigating the carbon footprint of the construction industry.[9,11,22,73] However, a notable drawback of RCA is that it may possess higher porosity and water absorption than conventional aggregates, which compromises the final product's quality.[11,74] Other factors such as labor, worker expertise, and quality control measures (during mix design, curing, and transportation) must be carefully managed to ensure high-quality precast concrete.[75]

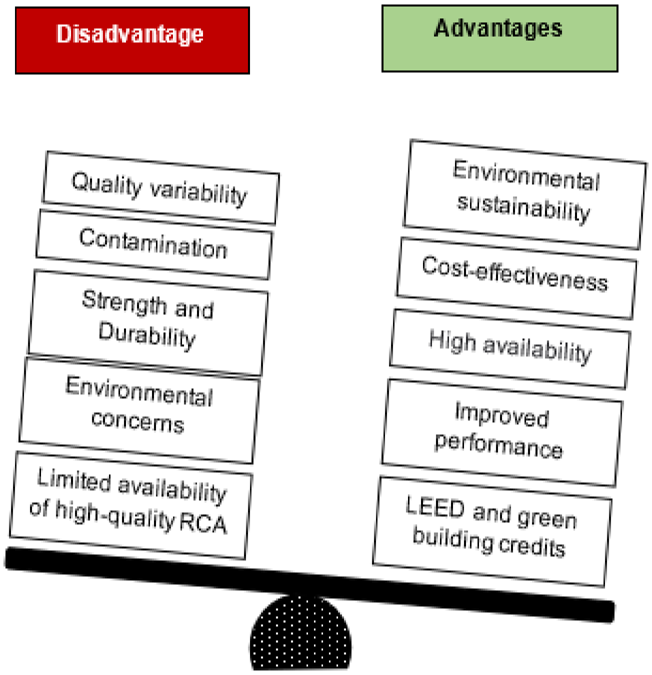

Fig. 6 Advantages and disadvantages of using RCA.

Incorporating RCA in precast concrete offers several benefits, including the following:

- Environmental sustainability: Using RCA in precast concrete production promotes environmental sustainability in the construction industry, aligning with circular economy principles.[8,27] By reducing the need for virgin aggregates,[39,76] RCA helps conserve natural resources[5] and minimizes the environmental impact of aggregate mining.[4,6,50] This practice also diverts construction and demolition waste from landfills, reducing the strain on waste disposal facilities[77,78] and lowering associated carbon emissions.[67,74] Further, precast concrete manufacturing inherently offers environmental advantages vis-a-vis on-site production,[7,79,80] reducing energy consumption, water usage, and air pollution.[81]
- Cost-effectiveness: Incorporating RCA in precast concrete proves cost-effective, especially with a nearby source. It reduces the cost of sourcing and processing, compared to virgin aggregates.[44,74] Local RCA sourcing minimizes transportation costs[28,52] contributing to overall project savings by diverting concrete waste from landfills.[22] Concrete with RCA offers a 9.19% cost reduction due to lower prices.[3] Shin and Kim[82] observed cost savings of $122,057 (a 10% reduction) in apartments when RCA was employed as nonstructural material, compared to the original material. The associated cost savings in embodied CO_2 (eCO_2) emissions amounted to -$2,958 (a 5% reduction). These results demonstrate the optimal scenario, with a 0.158% decrease in the overall construction cost. RCA-manufacturing setups support large-scale recycled concrete production, ensuring

cost-effectiveness and material conservation.[74] However, regular maintenance, cleanliness, and adherence to safety are crucial for consistent quality and efficient production.[43] This approach replaces natural aggregates with RCA, reducing CO_2 emissions and production expenses of precast concrete components. However, RCA usage leads to increased water consumption,[4] as illustrated in Fig. 7.

- High availability: CDW, generating over 3.57 billion metric tons of concrete waste globally,[18] presents a significant source of RCA production.[25,76] This constitutes about 36% of global waste and is highly recyclable.[83] The European Union contributes approximately 900 million tons annually, which is around 30% of total global waste,[31,32, 83] while China generates 1.5 billion tons per year.[83] In the United States, an estimated 123 tons of demolition debris are generated annually.[31] The widespread global establishment of RCA manufacturing facilities has significantly increased the availability of this resource.[77] This abundance of RCA aligns with sustainability principles,[30] offering a reliable alternative to traditional aggregate sources.[84] With measurable figures, such as the annual CDW production in the EU and China, the precast concrete industry benefits from a dependable and readily available supply of RCA, ensuring greater flexibility and adaptability in manufacturing processes.
- Improved performance: Incorporating RCA in precast concrete offers more consistent material properties than natural aggregates, thus enhancing quality control. The controlled production process and single-source origin contribute to predictability, providing confidence in RCA's performance.[41,68] Studies show superior performance compared to RCA from returned ready-mix concrete,[73] with comparable workability and air content in high-performance structural concrete.[85] RCA does not significantly impact the compression strength gain over time.[73] and established sources exhibit low levels of harmful substances, constituting less than 1% in all RCA categories. This property provides an advantage over alternative forms of RCA. Laboratory experiments demonstrate RCA's viability in precast concrete, especially in situations involving extensive prestressing.[86] Moreover, the controlled processing and quality assurance measures employed during RCA production lead to improved material uniformity.[68] However, the water absorption rate of RCA may reduce the workability of concrete.[74]
- Leadership in Energy and Environmental Design (LEED) and green building credits: Using RCA in precast concrete aligns with global green construction trends, earning LEED and green building credits.[8,77] The majority of green rating systems encourage the reuse and recycling of waste materials in construction and infrastructure projects to lessen the environmental effects of material consumption.[87] Green rating systems award points for using recycled materials, with one point for over 10% and another for over 20% of the material cost.[88,89] Recycling construction debris during renovation or construction can earn LEED points.[83] RCA, as an environmentally responsible building material,[72] reduces the ecological footprint and minimizes the demand for virgin aggregates. This aligns with sustainable construction practices,[89,90] earning credits in LEED categories such as Materials and Resources, Sustainable Sites, and Innovation in Design.[87] Incorporating RCA in precast projects supports green building credits by reducing waste, conserving resources, and lessening environmental impact.[87,88]

The disadvantages of using RCA in precast concrete are as follows:

- Quality variability: The use of RCA in precast concrete presents a notable disadvantage-variability in quality. This stems from diverse sources and processing methods,[45] unlike virgin aggregates sourced from consistent geological formations. RCA, often from different demolition sites, varies in concrete composition, age, and potential contaminants.[4]

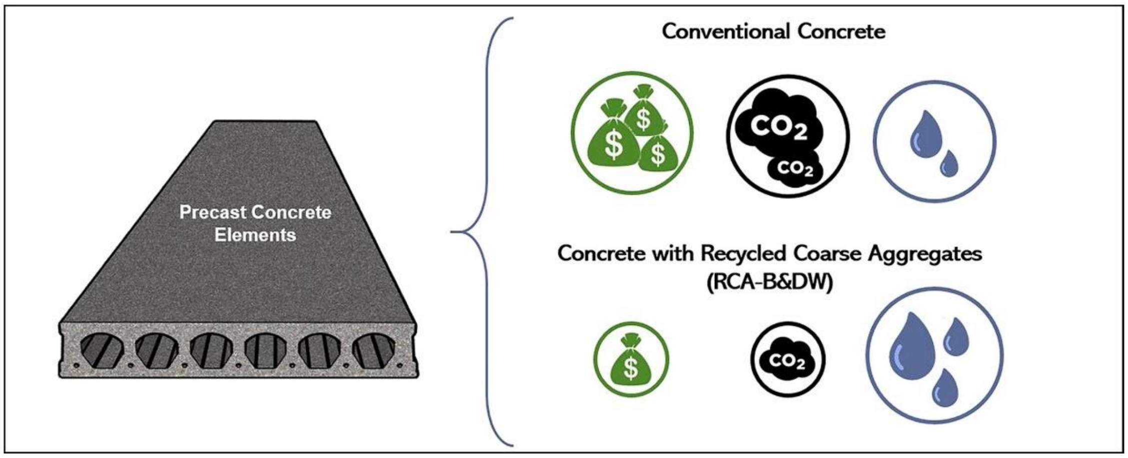

Fig. 7 Environmental and economic advantages of using RCA for precast concrete. Reproduced with the permission from [4], Copyright 2018 Elsevier Ltd.

RCA from precast panels may be unsuitable for structural use due to poor material quality,[45], leading to increased porosity and water absorption, impacting overall concrete quality.[6,39,74] Factors such as materials used and aggregate source cause variability in precast concrete quality.[91,92] Research shows that RCA quality affects the consistency and reliability of concrete mix designs, influencing compressive strength.[73] This variability challenges uniformity and predictability, requiring additional testing, quality control, and adjustments to compensate for RCA differences. It complicates production and increases the risk of substandard elements, impacting structural integrity and durability.[1,93]

- Contamination concerns: Contamination is a known issue with RCA, originating from various sources such as the original concrete, the environment, and the recycling process.[94] The level and type of contamination are crucial determinants of RCA quality.[40,81] Old mortar and contaminants in RCA weaken concrete, reducing its lifespan.[37] Adhered mortar increases water absorption and contamination risk.[32,54] Contaminants such as clay or organic matter compromise concrete performance and lifespan.[6,15] The presence of wood, plastic, or metal in recycled aggregate adversely affects concrete properties [Fig. 8]. Deicing salts can contaminate RCA with chlorides and sulfates, impairing the mechanical and transport properties of new concrete.[95] Balancing environmental advantages and the need for reliable and durable construction materials is crucial due to the contamination risks associated with RCA.

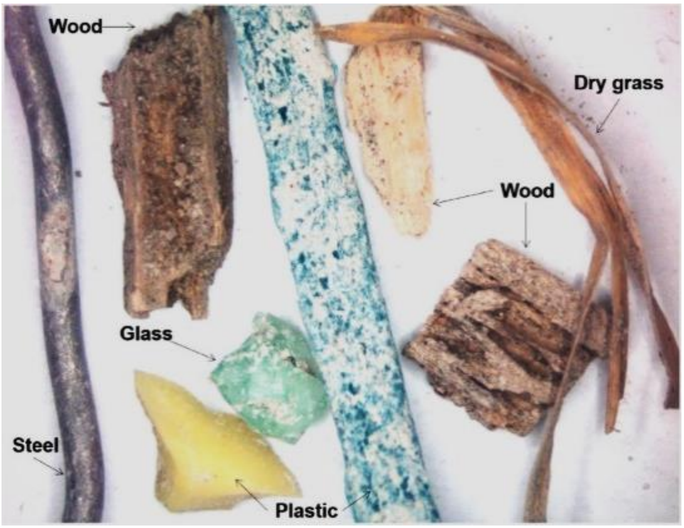

Fig. 8 Contaminants in FRCA. Reproduced with the permission from [95], Copyright 2021 The Author(s).

- Strength and durability: Lower strength and durability in RCA, compared to high-quality natural aggregates, pose a significant disadvantage in precast concrete applications. Factors contributing to this reduction include contamination[32,55,81] difficulties in mortar adhesion, and the inherent physical properties of RCA.[55,90] Contamination, with impurities weakening the cementitious matrix and hindering aggregate-mortar bonding, is a primary factor.[15,28] Contaminants interfere with cement particle hydration, reducing the overall strength and integrity of concrete.[35] Physical properties such as porous particles and variations in size distribution contribute to reduced compressive strength and structural performance.[35,54] The irregular shape and surface texture of some RCA particles leads to incomplete bonding with mortar, diminishing the overall structural efficiency.[6]

- Environmental considerations: The use of RCA may increase air pollution and dust during processing, generating particulate matter.[8,10,23,31,96] RCA processing may demand extra energy, resulting in a high carbon footprint for the precast concrete sector.[41,48] Additionally, using RCA might require more transportation, leading to higher greenhouse gas emissions.[2,41,50,97] Dust is produced in large amounts during recycling, but precautions such as dust collection systems help minimize air pollution.[98] Recycled concrete powder can be added to concrete as a supplement, addressing environmental considerations.[96,99]

- Limited availability of high-quality RCA: Limited availability of high-quality RCA poses challenges to precast concrete manufacturers, often necessitating reliance on natural aggregates. Ensuring consistent RCA quality is difficult due to its high porosity and material inconsistencies.[74] Studying the quality of RCA derived from laboratory-produced parent concrete can reveal its potential.[95] Brandes and Kurama[86,100] show that high-quality RCA from precast concrete outperforms returned ready-mix concrete and increases prestressed beam service load deflections without affecting the bond strength of steel prestressing strands. The limited availability of RCA obtained from precast concrete poses significant concerns regarding its longevity and sustainability.[31] The high demand for aggregates further raises concerns about depleting natural resources and the need to explore alternatives.

3. Precast concrete

3.1 Historical background

Precast concrete is a building material produced in a controlled factory setting and then transported to the construction site. It is made by pouring concrete into molds, where it cures under regulated conditions. This material can be prestressed for added strength.[101,102] Manufacturing precast concrete involves producing most structural components according to standardized specifications.[103] While most of the production occurs in specialized facilities, elements are sometimes cast at or near the site due to economic or logistical factors. Precast concrete construction offers advantages such as better quality control, faster construction, and reduced labor costs.[104] The historical origin of precast concrete dates back to ancient Rome when a basic form of concrete was cast in wooden molds for greater precision and longevity. Its development continued through the 20th century, with the establishment of organizations like the Precast Institute.[105] The evolution of precast concrete can be divided into developing years, mass production and standardization, lightweight and long-span construction, and the current emphasis on sustainability and energy efficiency.[106] Precast concrete provides various benefits, including enhanced safety and cost-effectiveness. In contrast, traditional cast-in-place concrete allows for more design flexibility and surface textures.[107] Table 3 presents a comparison of precast concrete and traditional concrete. The primary purpose of precast concrete is to enable efficient production in a controlled environment, reducing on-site construction time and costs while maintaining quality and consistency. Its durability and versatility make it a vital component in modern construction, having various applications in large structures to architectural details such as facades, walls, and bridges.[101]

3.2 Types of precast concrete

Precast concrete can be classified into the following varieties:

- Architectural precast concrete: This is used for decorative and architectural purposes, serving both functional and aesthetic roles.[108] Modern fabrication techniques have expanded the range of possibilities in terms of color, shape, and texture. This type is versatile and can be used in architectural design, either as standalone architectural elements or in combination with other materials,[108,109] as shown in Fig. 9. The moldability of concrete allows for a wide range of architectural styles, but it demands meticulous quality control, indoor production facilities, and clear communication.[110]
- Structural precast concrete: In the mid-1980s, structural precast concrete started gaining popularity for its load-bearing purposes, including for beams, columns, frames, and walls,[111] as shown in Fig. 10. It offers advantages in terms of construction speed, durability, and quality, making it suitable for various applications such as building parking garages, bridges, and office buildings. Most structural components are manufactured off-site in specialized plants before being transported to the construction site.[112]
- Prestressed precast concrete: Manufacturing this type involves pre-tensioning or post-tensioning techniques, using steel cables or rods incorporated into the concrete. The cables are tensioned and then released, resulting in high-strength concrete capable of resisting tensile forces.[114] Prestressed

Fig. 9 Interior of Bahá’i House of Worship, Wilmette, Illinois. Reproduced with the permission from [109].

Table 3. Comparison of precast concrete and traditional concrete.[101]

Factor	Precast concrete	Traditional concrete
Preparatory work	Excavate land as necessary.	Excavation necessitates the creation and placement of on-site forms.
Weather	A controlled environment is not affected by weather when forming.	Unforeseen weather conditions may impede progress. Low temperatures can increase the duration required for the substance to fully cure.
Strength	Stringent strength criteria must be met before departure from the facility. Uniformity in precast materials	Variables impact the outcome. Environmental factors such as temperature, wind, and humidity can affect the ultimate strength of the material.
Quality control	The controlled environment precludes external factors. Concrete must undergo rigorous testing. Optimal conditions are maintained.	Concrete is susceptible to external factors and variable circumstances. On-site testing is mandatory.

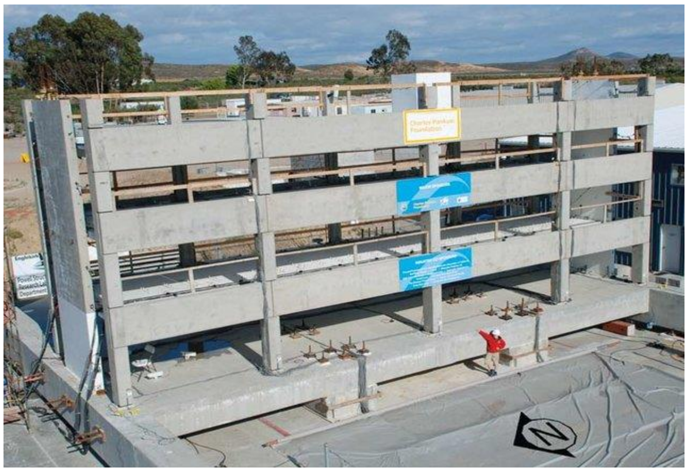

Fig. 10 Three story was erected by precast concrete structure. Reproduced with the permission from [113].

precast concrete offers benefits like lighter members, longer span, and economic viability.[115] It is commonly used in infrastructure projects globally due to its reliability and durability (Fig. 11).[116,117]

Fig. 11 Prestressed precast concrete truss. Reproduced with the permission from [117].

3.3 Advantages and disadvantages of precast concrete

3.3.1 Advantages: Precast concrete offers numerous benefits such as follows

- Accelerated construction: Precast concrete allows for off-site manufacturing while site preparation is ongoing, leading to quicker construction and reduced project delays.[118] This construction approach is faster than traditional on-site construction methods. Precast items can be transported and set up efficiently, minimizing traffic disruptions and expediting project completion.[119]
- Enhanced quality control: The controlled factory environment ensures consistent quality and precision in precast concrete components. Quality assurance technicians oversee various production stages, resulting in high-level quality control and construction quality.[120] Additionally, precast concrete is more easily controlled, leading to superior quality and durability compared with cast-in-place concrete.[27,110]
- Durability and strength: Precast concrete is known for its reliability, durability, and high compressive and tensile strength.[27,101] It offers superior bonding capabilities[121] and can even incorporate innovative additives for enhanced early strength and production capacity. The selection of connections between precast elements is crucial for the precast system's structural performance and long-term durability.[122]
- Cost savings: Precast concrete can reduce costs in specific scenarios by minimizing material waste and clutter at the construction site.[27] Studies have shown cost savings in terms of material usage,[110] life-cycle costs,[107] and overall project expenses,[123] making it a cost-effective choice. Overall, precast concrete's durability, low maintenance, and ease of installation contribute to cost savings in construction projects.
- Versatility: Precast concrete is highly versatile and can be used in a wide range of applications. Due to its factory-made nature, precast concrete is more flexible than site-cast concrete as it can be shipped to diverse customers with different requirements. It allows for various design options, motifs, colors, and finishes, making it suitable for buildings, bridges, and various other structures.[101] Precast elements, such as lattice-reinforced joist slabs, provide benefits like reduced material consumption, labor cost savings, and adaptability to different market demands.[124]

In summary, precast concrete provides increased speed, quality control, durability, strength, cost savings, and versatility advantages. Investors consider precast concrete elements highly beneficial, as depicted in Fig. 12. These advantages add to the popularity of precast concrete in a wide range of construction projects.

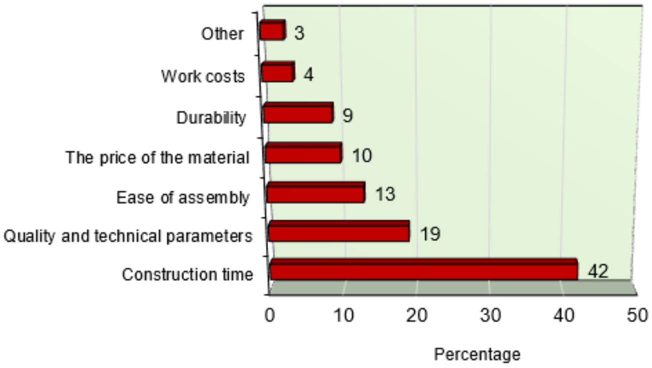

Fig. 12 Advantages of precast concrete elements. Reproduced with the permission from [110].

3.3.2 Disadvantages: Precast concrete has several disadvantages including the following

- Transportation and handling: Transporting precast elements to the construction site can be challenging and costly.[125] Issues that arise during transportation, especially in urban areas with heavy traffic and infrastructure constraints, can limit design possibilities. Load weight and size are restricted by infrastructure capacities, such as those of bridges, pavements, tunnels, and underpasses.[126] Heavy precast components require specialized equipment for installation, leading to increased transportation and handling costs.[127] Glass and Pepper[125] reported that cost-effective precast concrete often involves large panels, necessitating high-capacity cranes for lifting. Handling precast concrete can be challenging, particularly on congested construction sites where only a few panels can be delivered per load.

- Limited flexibility: Already manufactured precast concrete elements are challenging to modify on-site, limiting design flexibility.[125] The standardized nature of precast components constrains design possibilities, and specific considerations, such as connections, differ significantly from cast-in-place concrete.[128] Precast concrete element design must consider multiple production and construction stages, which do not apply to cast-in-place concrete.[118] However, flexible formwork can help mitigate this issue by allowing for more diverse components that meet structural requirements while retaining flexibility in other areas.[129]
- High initial cost: Precast concrete can be more expensive than cast-in-place concrete due to production and transportation costs. Prefabricated systems typically have an initial construction cost that is 50% more than regular superstructures.[130] Specialized equipment, facilities, and machinery are necessary, resulting in a higher initial investment.[105,129] Additionally, cranes and heavy equipment are required for transportation and installation.
- Long lead times: Precast concrete often requires extended lead times, involving various stages from order placement to delivery to the project site. Made-to-order products, fabrication in specialized shops, and the need for pre-booking production slots can lead to project delays and inflexibility in design decisions.[125] Additionally, precast concrete members must be stacked during the lead time, making the yard area a critical factor influencing the overall timeline. Securing the lead time is crucial because precast concrete members' production period is longer than their erection period.[131]

In summary, precast concrete offers some disadvantages regarding transportation and handling, limited flexibility, high initial cost, and long lead times; the disadvantages of / barriers to precast concrete elements are depicted in Fig. 13.

3.4 Precast concrete process

The precast concrete method utilizes premanufactured elements in construction. The quality of components is crucial as it impacts the overall structure's quality. The process typically involves the following steps (Fig. 14):

1) Design and engineering: The design phase focuses on meeting project-specific requirements, considering factors like joints, nodes, and structural prerequisites.[132] Detailed drawings are prepared, emphasizing quality, accuracy, finishes, and manufacturing organization. Design engineers play a pivotal role in setting structural requirements and optimizing designs.[133]

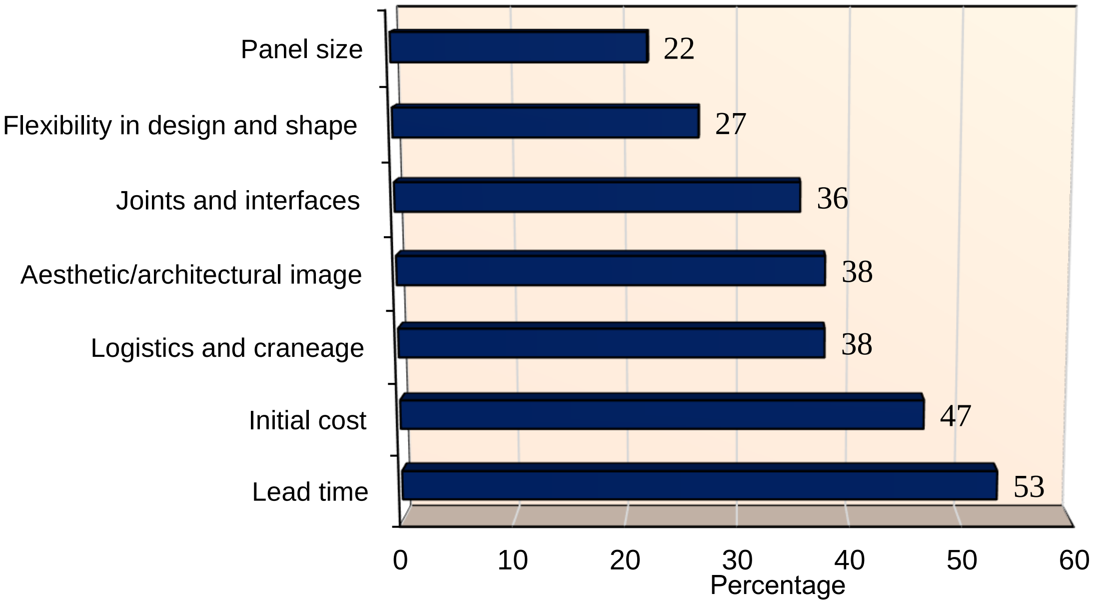

Fig. 13 Disadvantages of / barriers to precast concrete elements. Reproduced with the permission from [125], Copyright 2011 Taylor and Francis.

2) Mold preparation: Molds are prepared for casting precast elements. Traditional methods are labor-intensive and expensive, while newer methods like additive manufacturing can reduce costs and production times.[134] Proper mold preparation improves precision and appearance.[133]

3) Reinforcement placement: Steel bars, wire mesh, or fibers are placed within the mold to enhance the strength and durability of the precast element.[135] Placing drawings guide reinforcement placement, specifying details like bar counts, lengths, and positions.

4) Concrete pouring: Pouring concrete is a crucial step in precast concrete production. The concrete is mixed according to design requirements and carefully poured into the mold. Accurate weight control during pouring is critical. Research has focused on enhancing control and precision during the pouring process.[136]

5) Consolidation and finishing: Vibration or concrete is used to ensure optimal strength, durability, and quality appearance. However, SCC offers benefits like lower labor and equipment expenses, reduced risk of defects, improved production rates, and better surface finishes.[137]

6) Curing: Curing promotes hydration and strength gain before application. Steam curing is a conventional method, but alternative approaches like direct electric curing, microwave curing, and room temperature curing have been explored.[138] The benefits of carbon dioxide use in curing have also been studied.[139]

7) Stripping and storage: Stripping involves removing formwork after casting and curing. This step allows inspection, followed by the preparation of concrete elements for storage or transportation.[108,140] Proper storage conditions and inspections are essential to maintain the elements' condition and integrity.[141] Additionally, the concrete elements should be stacked to ensure even weight distribution and prevent cracking or deformation.[142]

3.5 Processing time

The processing time in precast concrete production is influenced by several factors, including the size, complexity, and design of the precast element, production methods, and curing processes. Generally, the precast method is known for relatively quick processing times, particularly for elements like beams, plates, and stairs.[143] However, the entire process typically takes several weeks to complete. Mold preparation and reinforcement placement usually require a few days, while concrete pouring, consolidation, and finishing can range from several hours to days, depending on the product's size and design complexity. Curing times vary based on design and environmental conditions but typically last several days. Achieving 28-day strength can occur within 16 hours or less after stripping, depending on the concrete type.[144] The choice of curing method can significantly impact curing time, with steam curing yielding faster results.[137-139] Additionally, curing complex precast elements, especially those with complex, curved shapes, can be time-consuming and costly.[145] Bridge construction specifications and certain project requirements may necessitate specific curing conditions, further influencing processing time.[146] As a result, the processing time in precast concrete production varies depending on project needs and production methods. Innovative production processes are continuously being developed to improve quality and shorten processing times, which would reduce construction duration. These processes often involve standardized design, mass production, automation, and consistent quality assurance.[147]

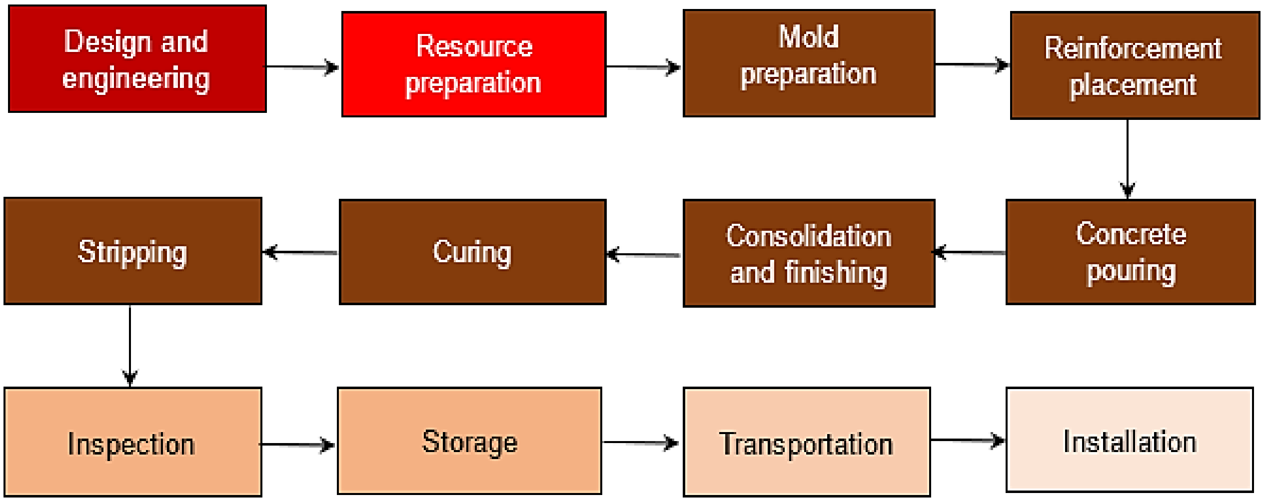

Fig. 14 Precast concrete for in-situ production process. Reproduced with the permission from [140], Copyright 2014 Elsevier B.V.

Fig. 15 (a) In-situ house and (b) Prefab bridge constructed using 3D-printed concrete. Reproduced with the permission from [148], Copyright 2020 The Authors.

3.6 Technology

The precast concrete industry is evolving with the adoption of various new technologies and innovations. Some of these technologies and trends include the following:

- 3D printing: 3D printing with concrete is gaining traction in the construction industry, enabling the creation of complex shapes and designs,[148] as shown in Fig. 15. It offers advantages such as material optimization and functional component integration within structural elements.[149] Research has shown that implementing 3D concrete printing technology in mass production can enhance the efficiency and quality of precast concrete manufacturing.[150] However, factors like printing accuracy, material availability, costs, and printing time need to be carefully considered for practical construction applications.[151]
- Digital twin technology: Digital twin technology is transforming precast concrete construction by enabling simulation-based planning and optimization. It enhances quality, sustainability, efficiency, and safety risk prediction models,[152] as shown in Fig. 16. The integration of building information modeling (BIM) with Industry 4.0 technologies facilitates the creation of digital twins for precast concrete elements, optimizing design, production, maintenance, and repair processes.[153]
- Smart concrete: Smart concrete, with electrical conductivity and electromagnetic shielding properties, has been used for applications such as ice and snow removal, structural health monitoring, and corrosion detection.[154] Its manufacturing involves embedding sensors or electronic components within concrete to enable real-time monitoring of performance, damage, and deterioration, thus enhancing the durability of precast structures,[155] as shown in Fig. 17. In addition, this

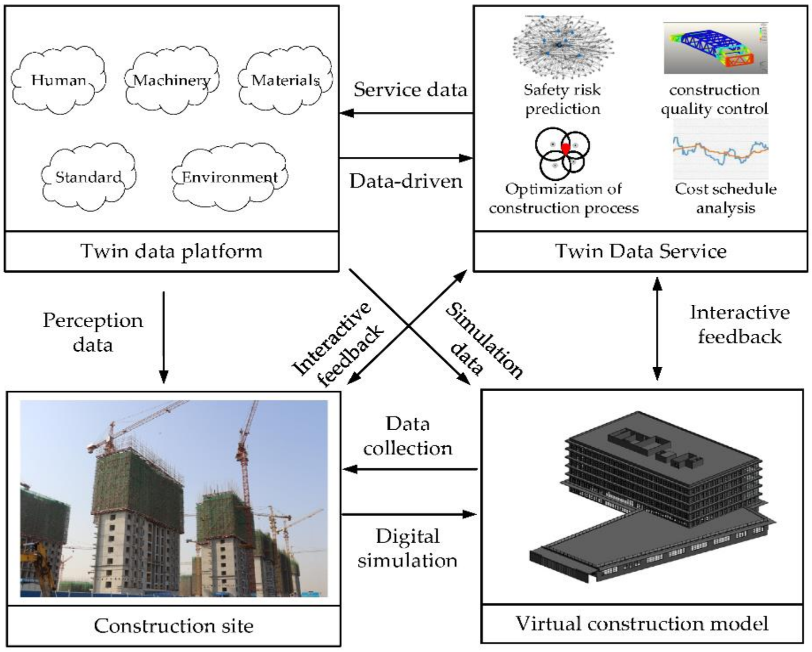

Fig. 16 Digital twin frame in the construction field. Reproduced with the permission from [152].

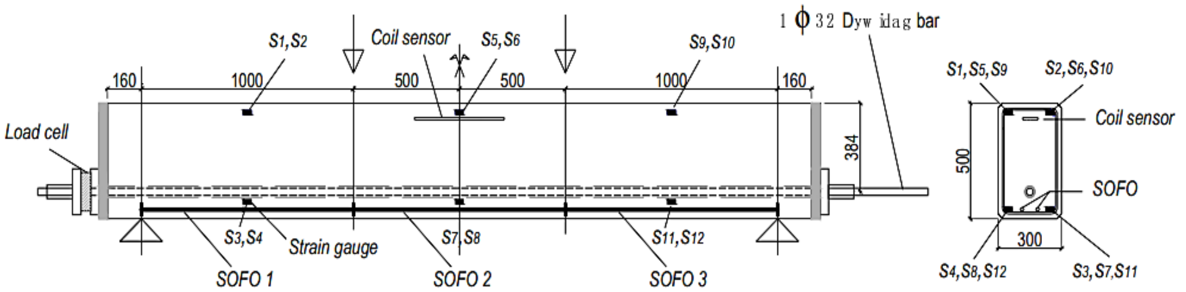

Fig. 17 Prototype of smart precast concrete element. Reproduced with the permission from [155], Copyright 2009 Trans Tech Publications Ltd.

this technology encompasses various types of smart additives, significantly enhancing the durability and longevity of precast structures while reducing the need for high-cost repairs and maintenance.[156]

- Automation and robotics: Automation and robotics have been increasingly applied in precast concrete production to improve speed, efficiency, and quality control.[157,158] Robotics is an increasingly sophisticated type of automation in the precast concrete industry, while automation in general refers to a broad spectrum of mechanical systems.[157] Robotics, in particular, has proven cost-effective in formwork and other precast processes, given the high labor costs and the rapidly growing market,[158,159] as shown in Fig. 18. Challenges remain in achieving high dimensional accuracy, formwork flexibility, and shuttering stability.[159]
- Sustainable materials: The precast concrete industry is increasingly concerned with sustainability, leading to the use of environmentally friendly materials. This involves using recycled materials and by-products such as wood ash, palm oil ash, rice husk ash, fly ash, and crushed slag to lessen the environmental effect of precast concrete.[160-163] However, as the precast industry continues to embrace sustainable development and utilizes a diverse range of local materials, the availability of materials for concrete recycling may need improvement.[163] The use of sustainable materials contributes to a more ecologically responsible construction approach.

3.7 Modeling

Modeling plays a vital role in the precast concrete industry, aiding in design, production, and analysis. Several modeling techniques are commonly used, such as follows:

- Computer-aided design (CAD): CAD software can be employed to create 2D and 3D models, allowing for accurate design visualization, issue identification, and process optimization. It replaces manual drafting, reduces costs, and enhances design alternatives.[164] An example of a 3D software tool, StructureWorks® Precast Office 2006, has been developed to expedite the development of building projects by enabling data sharing throughout the design and production process. This tool reduces the data input required for drawing and industry-specific calculations.[165]
- Building information modeling (BIM): BIM technology integrates data from multiple sources to create a digital representation of precast structures. It facilitates efficient design, cost savings, and enhanced productivity by allowing the transition from 2D drawings to a shared 3D model,[166] as shown in Fig. 19. BIM technology is extensively utilized in the entire life-cycle of prefabricated buildings due to its benefits of visualization, parameterization, and integration.[167]
- Finite element analysis (FEA): FEA is used to analyze the structural behavior of precast elements under varying loads. It aids in understanding connections' behavior,[168] optimizing designs, reducing material usage, and improving structural

Fig. 18 Robotic formwork system with a shuttering robot. Reproduced with the permission from [158], Copyright 2021 The Author(s).

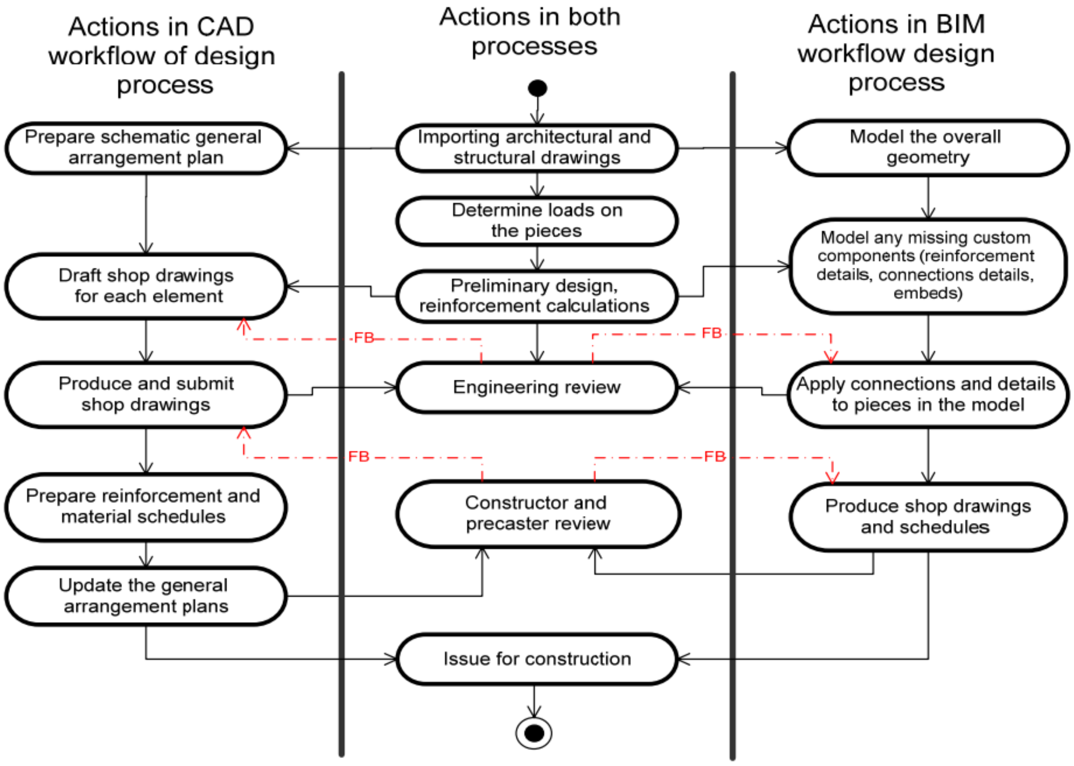

Fig. 19 Detailed comparison of CAD and BIM workflows. Reproduced with the permission from [166].

performance.[169] Additionally, FEA can be employed to model entire precast concrete structures while considering the local behavior of joints. This approach enables efficient and rigorous analysis and design through mathematical optimization.[170]

- Computational fluid dynamics (CFD): CFD simulates fluid flow and heat transfer in precast structures. Based on mathematical models and computational software that adhere to conservation laws,[171] CFD is a component of multiphysics system analysis that facilitates design optimization, material usage reduction, improved performance, and potential applications in areas such as vehicle fire analysis.[172]
- Physical modeling: Physical models, either scale or life-size, provide a visual representation of real-world objects and systems. Scale models are smaller versions of the actual object or system, while life-size models are the same size as the real. Yu *et al*.[173] investigated using solar thermal energy in precast concrete steam curing to reduce fossil fuel use and CO_2 emissions. Physical modeling by Zarrabi and Eslami[174] examined how construction affects pile performance. They cut pile size and quantity, lowering building costs and time. Topbas *et al*.[175] modeled and designed an ultra-high-performance concrete precast shell bridge. A 1:5 scale model was used to inspect this 25-meter pedestrian crossing with a 2.5-meter deck width in a factory. The use of physical models in precast concrete construction proved valuable for testing, performance, and various aspects of construction processes.

3.8 Sustainability

The precast concrete industry has made significant strides toward sustainability in recent years due to several contributory factors, as shown in Fig. 20.

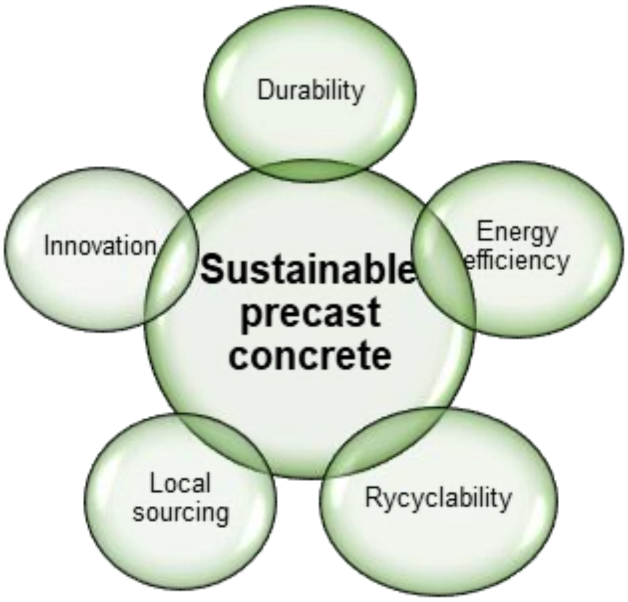

Fig. 20 Sustainable precast concrete.

- Durability: Precast concrete is known for its durability, with products designed to last 50 to 100 years. Precast concrete producers' use of high-strength concrete significantly bolsters its durability.[27,110,119] Moreover, the use of pozzolan material, polymer coating, and acrylic-based or CO_2 surface treatment enhances durability and strength and reduces the carbon footprint during construction.[176–180] Precast concrete's durability and longevity minimize the need for frequent repairs and replacements, thus reducing the overall environmental impact of buildings.[145]

- Energy efficiency: Precast concrete can be designed with insulation and thermal mass, reducing the energy required for heating and cooling by up to 25%.[181] Precast concrete sandwich panels and energy-efficient production processes contribute to improved energy efficiency with a thermal resistance (R value) of 2.48 m^2K/W.[182–183]
- Recyclability: Precast concrete is recyclable, and manufacturers often incorporate recycled materials into their products.[184] To promote sustainability in the precast concrete sector, measures such as recycling scrap steel for reinforcement and reducing and reusing product packaging in facilities must be adopted.[185] This practice minimizes waste, reduces the demand for new resources, and diverts waste from landfills. Using recycled materials and supplementary cementitious materials enhances recyclability.[176]
- Local sourcing: Producing precast concrete locally reduces transportation emissions and supports local economies. About 4-14% of concrete's environmental impact is from transportation. Natural aggregates travel an average of 0.3–280 km, while RCA travels 0–40 km.[2] According to Sabău *et al.*,[186] the global warming potential of 50% RCA was found to be 306 kg CO_2e, without considering transportation distances. However, when transportation distances of 47.5 km were considered, the global warming potential increased to 324 kg CO_2e, with the difference of 18 kg CO_2e being attributed to transportation. Local sourcing thus plays a crucial role in sustainable precast concrete production. Implementing lean manufacturing techniques in precast concrete factories can eliminate waste and enhance supply chain efficiency.[187] This may involve adopting just-in-time sourcing practices with suppliers; lean production techniques can reduce waste and the need for extensive storage areas and large supplies.[188]
- Innovation: The precast concrete industry focuses on innovation, research, and development to create high-quality prefabricated elements.[110] Automation in precast concrete production enhances output by educating people to run efficient machinery, improving plant safety.[189] Prefabrication relies on robotics,[174] and advanced formwork system improvements[159] are vital for the precast production line to enhance productivity, quality, and competitiveness.

4. Use of RCA in precast concrete

4.1 Ways to use RCA in concrete

The increasing use of RCA in concrete is attributed to its environmental and economic advantages. RCA is produced by crushing and reusing old concrete, which would otherwise be sent to a landfill. Fig. 21 depicts some of the ways to use RCA in concrete.

- Aggregate replacement: RCA can be used in concrete to substitute natural coarse aggregates up to 100%,[69] reducing the ecological footprint and promoting sustainability. However, the quality and proportion of RCA used in place of natural aggregates can affect concrete's overall quality and consistency.[190] The attachment of old cement paste to the surface of recycled concrete aggregates can also cause inadequate properties in concrete. Several mechanical treatment techniques have been developed to enhance RCA characteristics by eliminating attached mortar.[191,192] Using RCA in concrete production can reduce CO_2 emissions, costs, and energy consumption. Proper process control measures must be implemented to ensure consistent and high-quality concrete output[31,96]
- Road construction: RCA is suitable for producing unbound road base and subbase materials for road construction. Its favorable particle size distribution, durability, and strength make it a cost-effective choice, reducing the need for additional landfill space and minimizing the demand for virgin natural resources.[193,194] RCA can be employed in producing cement-treated subbases for roads with the implementation of mixed recycled aggregates.[195] Integrating RCA as a base layer for low-traffic roads with a cement content of 250 kg/m^3

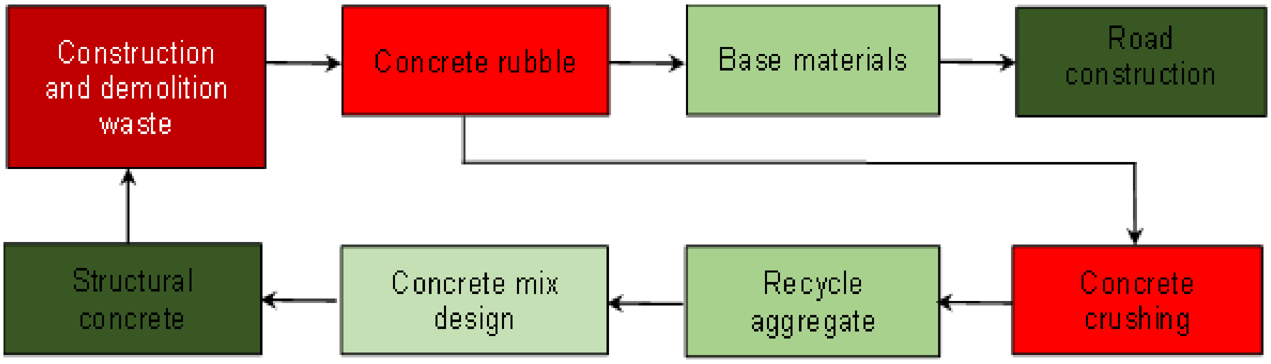

Fig. 21 Ways to use RCA in concrete. Reproduced with the permission from [31].

resulted in compressive and splitting tensile strength values exceeding 20 and 2.5 MPa, respectively, after 28 days,[196] characterizing the features of RCA for unbound road base and subbase materials.[197]

4.2 Current status of RCA use in precast concrete

The construction sector's adoption of RCA in precast concrete is rising since RCA is eco-friendly and cost-effective. Its use is restricted by the absence of standardized production procedures and apprehensions regarding concrete's performance. The current trends and developments in using RCA in precast concrete are summarized in Fig. 22.

- Research expansion: Extensive research has explored recycled precast concrete aggregate created by crushing rejected components.[4,28,45,56,60-62,64,204] Bahera *et al.*[6] recommended further research due to a limited understanding of RCA in precast concrete. To accelerate adoption, collaborative research initiatives between academia, industry, and governmental bodies need to be fostered. These partnerships can address knowledge gaps, develop guidelines, and facilitate technology transfer, apart from implementing incentive programs or policies offering financial benefits or tax breaks for incorporating a percentage of RCA in precast projects. Current research focuses on RCA properties and their impact on precast concrete.[205] A 2022 study on chloride penetration found comparable permeability with 30% RCA replacement but a significant rise at 60% or 100%.[206] In 2016, RC flexural members with strengthening inclusion showed higher stiffness and strength than standard RCA beams.[207] The impact of rapid carbonation on vibro-compacted porous concrete, using RCA and natural aggregate, achieved a significant CO_2 capture ratio of 52.52 kg/t. Compared to atmospheric curing, a 525% increase in carbon capture was achieved under accelerated carbonation conditions.[208] These findings need to be disseminated through targeted workshops, webinars, and training programs for architects, engineers, and construction professionals to build confidence in RCA use.
- Standards and guidelines: Addressing the absence of standardized production procedures and performance concerns surrounding concrete with RCA, discussions about standards and guidelines have gained prominence.[209–210] While universal standards are lacking, regional research and regulations demonstrate that RCA can meet the necessary performance criteria. For instance, RCA from CDW can be employed in precast non-structural concrete that adheres to Spanish norms, allowing up to 100% CRCA; indications are that adding 20% coarse aggregate will not degrade properties.[211] To accelerate RCA adoption, active participation in international efforts to establish standardized procedures for RCA production and usage in precast concrete is crucial. Engaging with relevant bodies to contribute to the formulation of comprehensive standards is essential. The European standard EN 12620 addresses natural and artificial/recycled aggregates in concrete. Concrete-derived CRCA can reach 100%.[212]

The proposed amendments to EN 12620 include new requirements for recycled aggregates, emphasizing aspects such as drying shrinkage, acid-soluble chloride content, water-

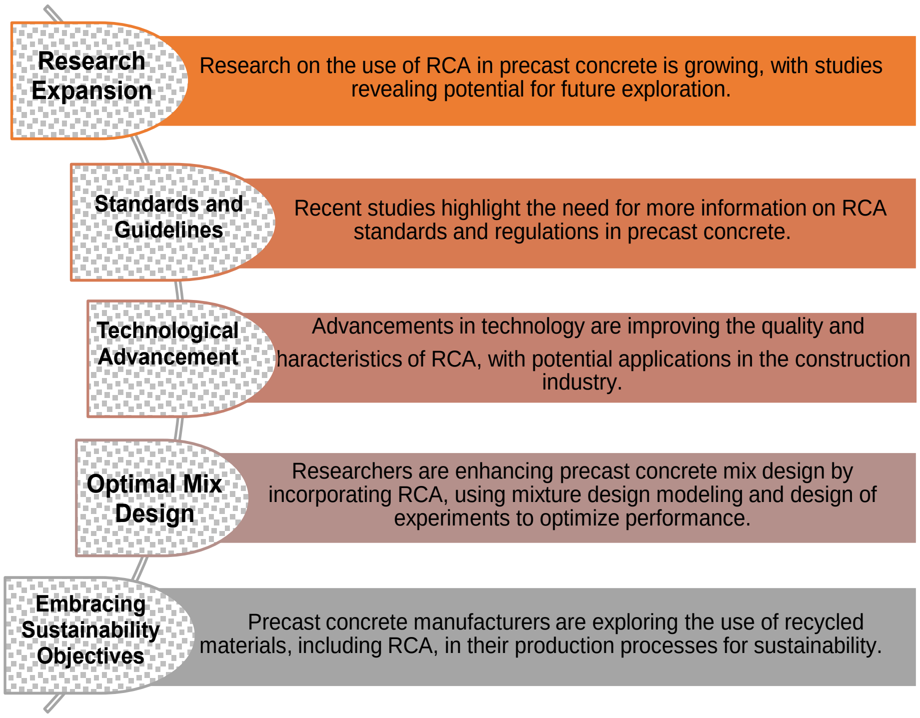

Fig. 22 Current status of RCA use in precast concrete.

soluble sulfate, and constituents affecting concrete setting and hardening.[213] Besides these efforts, a robust system should be developed for monitoring the performance of precast concrete incorporating RCA. Long-term studies tracking structural integrity, durability, and environmental impact can provide empirical data to support broader adoption. This educational aspect is vital for the continued growth and acceptance of RCA in the construction industry.

- Technological advancements: Ongoing technological advancements, including innovative mechanical and thermos-mechanical treatment techniques, aim to improve RCA quality by minimizing impurities.[1] Several techniques are adopted for removing attached mortar from aggregate surfaces or strengthening weak adherent mortar to improve RCA characteristics, including surface coating, CO_2 treatment, bio-deposition, acid solution, chemical pretreatment, presoaking, freeze-thaw, thermal expansion, microwave heating, ultrasonic treatment, and mechanical grinding.[3,6,9,33,36,43,46, 50–51] Research has also focused on multi-recycled concrete aggregates to improve technical understanding and quality.[214–216] The structural performance of the new concrete remains satisfactory, even when using 100% RCA as a substitute. By incorporating recycled and multi-recycled coarse aggregate from the precast concrete industry, compressive strength can be increased by up to 5%.[214] In a recent study, three RCA cycles were created and studied from well-structured parent concretes for understanding multi-recycled concrete aggregates. The study recommends using these aggregates in structural concrete, depending on water absorption and aggregate replacement.[209] Polymerization and alkaline activation were carried out to recycle CDW's coarse and fine fractions, as well as powder. FRCA and CRCA are used in fiber-reinforced materials, concretes, mortars, and precast structures. The physical-mechanical properties of these CDW-based composites enable their usage in the construction industry.[217]
- Optimal mix design: Researchers are exploring the optimal mix design by evaluating different ratios of RCA and natural aggregates to achieve the desired properties. Mix design modeling and experimental methods have been used to predict fresh and hardened concrete performance with varying levels of RCA substitution. With 75% RCA, compressive strength reaches a maximum of 83.48 MPa.[218] Response surface methodology has been employed to assess the impact of recycled aggregates on concrete performance.[219] Additionally, the use of innovative materials and techniques can contribute to producing structural concrete that is both efficient and sustainable and made completely of CDW-recycled aggregate.[220]
- Embracing sustainability objectives: Precast concrete manufacturers are aligning with sustainability goals, leading to empirical studies on the technical viability of incorporating RCA. Researchers are particularly interested in the mechanical and longevity characteristics of concrete products. Studies have shown that RCA derived from precast components can be used effectively, especially in developing high-performance SCC.[221] Moreover, substituting cement or sand in non-structural precast concrete products with locally available materials presents a more environmentally friendly option for recycling industrial waste.[222]

4.3 Case studies on the application of RCA in precast concrete

The incorporation of RCA into precast concrete offers increased sustainability benefits for the next generation of the precast concrete industry, though accompanied by engineering performance challenges. The origin of these challenges lies in the repurposing of concrete to create RCA. The objective of this integration is to carry out its implementation to uncover the difficulties, advantages, and overall sustainability of this integration. Numerous case studies include this integration, providing insightful perspectives on various aspects. A study, based on water absorption and substitution levels, demonstrated that high-quality RCA can effectively integrate into structural concrete for building applications.[209] Data on the properties of these materials were collected during this study, and the researchers independently arrived at this conclusion as a result of their investigation. RCA obtained from discarded precast concrete was found to outperform returned ready-mix concrete. This suggests that RCA is a more ecologically sustainable material. Thus, it can potentially function as an acceptable substitute for natural coarse aggregates in both precast and prestressed concrete.[73]

The emergence of economic problems has reinforced the importance of carefully considering the growing demand for cement required to attain the desired level of strength.[223] However, the durability performance has substantially decreased by 20%.[28] The large-scale production of SCC was evident to observers. An analysis revealed that employing 100% CRCA led to a 5% decrease in expenses. Nevertheless, there was a notable decline in durability and performance. Research showed that using RCA significantly impacts the strength, stiffness gain, and bond strength of steel prestressing strands in concrete beams, suggesting that it works well for building components.[86,224] Therefore, further research should examine the impact of precast concrete made from RCA on structural elements due to its superior quality.

The ratio of replaced aggregate is a crucial factor in assessing the preservation of concrete properties, as indicated by the findings of feasibility studies. The studies have also highlighted the importance of considering practical factors in precast applications.[225] Besides, these studies have revealed a significant issue. For example, high-performance SCC with a type of RCA possessing a higher compressive strength of 65 MPa was observed for precast structural uses and did not result in significant changes in its mechanical and long-lasting properties. Compared to other mixtures, the mixture with 25% RCA demonstrated superior mechanical performance, incurring property losses below 10%. In contrast, the mixture consisting entirely of RCA exhibited significantly higher losses, with compressive strength and elastic modulus decreasing by as much as 26%.[221,226]

From a company-oriented perspective regarding the viability of RCA in a precast concrete facility, it was determined that there is a possibility for the efficient large-scale production of SCC, exhibiting sufficient fluidity and compressive strength. Employing a multi-criteria approach, we assessed and identified the feasibility of RCA. Implementing RCA in a precast concrete manufacturing facility acknowledges this as a consequence. Using 100% CRCA resulted in a 20% decrease in durability performance (Fig. 23).[28] Researchers revealed this specific trade-off as a compromise, and the prevailing circumstances deemed the situation detrimental. In additional case studies, researchers used RCA to manufacture precast concrete products such as architectural panels[227] and concrete blocks.[210,223,228] A study explored the possibility of using mixed recycled aggregate instead of natural coarse aggregate in precast SCC for architectural sandwich wall panels. The results showed that mixed recycled material can comprise up to 10% of the total aggregate weight. The study aimed to ascertain the level of difficulty associated with achieving this outcome. After investigating the possibility of substituting some of the natural coarse aggregates with a combination of recycled aggregate, the study concluded that, on the contrary, the increase in demand for cement led to the onset of economic hardships.[223] Moreover, increasing the amount of RCA in precast concrete block mixes by up to 50% above the standard level did not noticeably affect the compressive strength of the blocks. Furthermore, the addition of RCA to precast concrete blocks was observed to lead to a decrease in both compressive strength and durability while maintaining compliance with regulations.[210] This situation occurred when production was conducted on a large scale. Blocks containing RCA demonstrated satisfactory mechanical properties, even when the absorption rate was maintained within the standard limit of 6%[228] despite the lower aggregate substitution level. Additionally, the quantities of aggregate substitution decreased in this situation. The researchers studying the suitability of RCA in vibropressed precast concrete blocks reached this conclusion after conducting individual investigations.

This compilation of case studies showcases the successful implementation of RCA in a diverse range of precast concrete scenarios. It also showcases the feasibility of the method, along with the possible advantages it can provide in terms of cost reduction and sustainability assurance. Moreover, it illustrates the viability of the technique. The recognized challenges include concerns regarding durability, variations in compressive strength, and economic considerations. Addressing the variations in compressive strength is another challenge worth noting. These challenges emphasize the

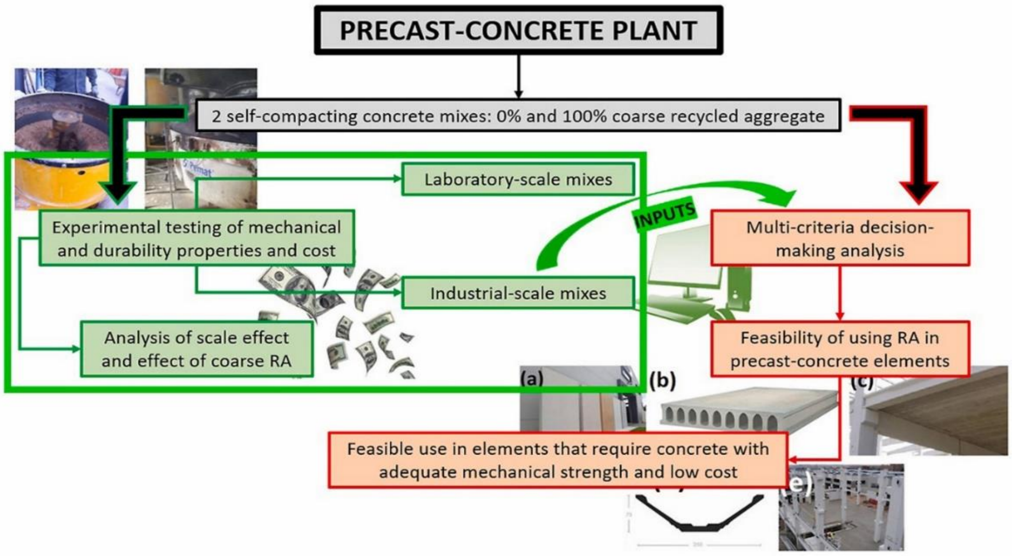

Fig. 23 A multi-criteria approach to using RCA in a precast concrete factory. Reproduced with the permission from [28], Copyright 2022 The Authors.

importance of thorough evaluation and consideration in precast concrete applications. Thus, further investigation is required to acquire an in-depth understanding of the attributes and conduct of RCA in relation to precast concrete uses, which remain inadequately explored.

5. Sustainable energy and cleaner production

5.1 Role of RCA in sustainable energy and cleaner production

Using natural aggregates in concrete demands substantial energy and causes carbon dioxide emissions. Incorporating RCA into precast concrete aligns with sustainable energy and cleaner production practices in several significant ways, as depicted in Fig. 24.

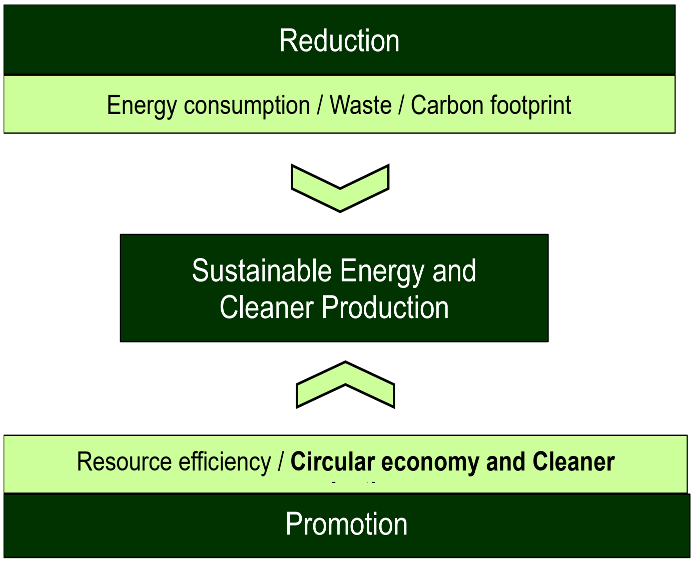

Fig. 24 Role of RCA in sustainable energy and cleaner production.

- Energy conservation: RCA reduces energy consumption in concrete production by decreasing the need for energy-intensive quarrying, crushing, and transportation of virgin aggregates.[7,17,81] The inclusion of RCA in precast concrete significantly reduces primary energy consumption. For instance, Attri *et al*.[229] observed that pure silica dust with 45% CRCA cuts global warming potential by 4.8% and primary energy consumption by 11.8%. Further, 100% stone crusher dust with 45% CRCA reduces global warming potential by 5% and primary energy use by 12%. According to Tang *et al*.,[7] the energy demand decreased by approximately 28.3% when the RCA replacement ratio increased from 0% to 50%, with values changing from 1.66 x 10^6 MJ to 1.19 x 10^6 MJ. Previous studies have demonstrated that the production of RCA consumes less energy than that of natural aggregate. Specifically, energy savings of 20%,[33] 30%,[64] 30.5%,[230] and even up to 58%[41] have been reported.
- Waste reduction: Reducing building waste to zero is a challenge, given the global requirement for zero waste as a breakthrough solution to the environmental catastrophe.[9] Using RCA in concrete production reduces waste generation, promotes resource preservation, and lowers greenhouse gas emissions. Yuan and Chen[14] summarized waste reduction by comparing the quantity of concrete waste generated to that of recycled aggregate produced, which amounted to 26.4%. Rachid *et al*.[64] observed a 35% reduction in waste when RCA was used in the production of recycled aggregate concrete. Developed countries have achieved recycling and reuse rates ranging from 70% to 95%.[23] Recycling concrete waste into RCA effectively reduces landfill waste and energy consumption,[231] aligning with the principles of circular economy and sustainable production.[232] Additionally, this policy can effectively minimize waste generation and promote the reclamation of CDW.[11]
- Carbon footprint reduction: By lowering the need for natural aggregates and preserving natural resources, RCA incorporation lowers the carbon footprint of concrete production.[28,50,233] This aids in the worldwide endeavor to mitigate greenhouse gas emissions and address climate change. Cement and concrete production are major contributors to global warming[76] and using RCA minimizes the embodied carbon of concrete, aiding in carbon capture efforts. RCA substantially contributes to carbon capture during its secondary life, absorbing as much as 41% of the CO_2 released during the production of a binder made entirely of Portland cement.[234] The global warming potential of 30% RCA (282.64 kg CO2/kg) is significantly lower than that of 0% RCA, with a reduction of 33.82%. According to Tang *et al*.,[7] the global warming potential decreased by approximately 26.3% when the RCA replacement ratio increased from 0% to 50%, with values changing from 2.65x10^5 kg to 1.95x10^5 kg. The carbon footprint of certain projects can be reduced substantially through the substitution of natural aggregate concrete with RCA as the structural material. This approach offers environmental benefits, especially considering the impact of recycling methods and transportation routes on energy use and embodied carbon, as highlighted by Xiao *et al*..[235]
- **Resource efficiency:** RCA repurposes materials that would otherwise be treated as waste, enhancing resource efficiency, promoting recycling, and conserving landfill space and natural resources.[236] One of the most commonly used secondary aggregates, RCA not only supports economic and social progress but also minimizes waste generation and conserves valuable resources.[4,237-238] Shooshtarian *et al*.[30] identified challenges and proposed solutions across various stages of the construction materials' lifecycle, providing valuable insights

for researchers and policymakers interested in improving resource efficiency.

- **Circular economy and cleaner production:** RCA serves a crucial role in advancing circular economy principles and cleaner production practices within the precast concrete industry. Using RCA is a sustainable solution whereby waste materials are repurposed, promoting circularity and reducing environmental impact.[1,36] Precast concrete operations benefit from RCA's ability to recycle concrete waste into valuable construction components, reducing the reliance on virgin aggregates and decreasing waste sent to landfills.[10,39,45,77] This approach enhances resource efficiency, conserves natural resources, and lessens the environmental consequences of waste disposal, aligning perfectly with the circular economy concept.[9,23,30,69] Simultaneously, the incorporation of RCA lowers the carbon footprint associated with precast concrete production, resulting in cleaner and more environmentally friendly practices.[10,26] In the precast concrete sector, using RCA is a practical solution that significantly contributes to waste reduction, resource conservation, and the advancement of sustainable construction practices.

5.2 Environmental and economic benefits of RCA use in precast concrete

RCA incorporation in precast concrete has various environmental advantages (see Fig. 25), including the following:

- **Reduced landfill waste:** The use of RCA in precast concrete yields significant environmental benefits, particularly in reducing landfill waste. The repurposing of recycled concrete aggregates substantially diminishes the volume of concrete waste ending up in landfills. This not only conserves valuable space but also mitigates greenhouse gas emissions associated with traditional landfill disposal methods.[4,60] Recycling construction and demolition waste, including precast concrete components, offers a practical solution to reducing pollution and alleviating the strain on landfill capacity. Through its transformation from waste into a valuable resource, RCA effectively addresses the pressing issue of construction waste disposal while promoting sustainable waste management practices.[239]
- **Reduced environmental impact:** The use of RCA in precast concrete plays a crucial role in reducing the overall environmental impact of construction practices. Through the recycling of concrete waste into valuable aggregates, RCA reduces the demand for natural resources, such as sand and gravel, consequently reducing the environmental harm caused by mining and quarrying operations.[31] Additionally, incorporating RCA into concrete production minimizes waste generation, conserves landfill space,[60,286] decreases greenhouse gas emissions by about 65%, and saves energy by as much as 58%.[64] RCA aids in achieving cleaner production practices, promoting a circular economy, and addressing sustainability objectives in the construction industry.[9,30,69,78] This environmentally conscious approach not only conserves vital resources but also lessens the industry's carbon footprint, ultimately contributing to more eco-friendly construction processes.[233,235,237,240]
- **Conservation of natural resources:** The incorporation of RCA in precast concrete plays a key role in conserving valuable natural resources such as sand and gravel. These resources, essential for concrete production, are non-renewable and in high demand.[6] RCA is derived by crushing various concrete waste materials, including demolition debris and discarded precast components.[4,6,62,64] By integrating RCA into construction applications, the strain on natural aggregates, typically extracted through mining and quarrying, is significantly reduced.[64,241] This approach not only conserves natural habitats and existing water resources but also curtails the negative environmental impacts linked to acquiring traditional aggregates.[35,242] Using RCA, which transforms construction waste into a valuable resource, presents a sustainable option that supports natural resource preservation (50% resource conservation when RCA is used) while reducing the environmental effects of construction operations.[62,64,243] By adopting RCA, the construction industry contributes to the responsible management of precious natural resources, fostering environmental protection and long-term sustainability.
- **Improved air quality:** The incorporation of RCA into precast concrete significantly contributes to enhancing air quality throughout the construction process. Firstly, this is achieved by reducing the need to transport virgin aggregates over long distances.[244,245] This reduction in transportation-related pollution is particularly vital in mitigating air quality concerns, especially near quarry sites where dust particles from conventional aggregate extraction pose environmental and health risks to local communities.[246] The type and distance of aggregate transportation also influence these environmental impacts.[247] Moreover, the production of RCA itself plays a role; the deliberate crushing of existing concrete eliminates the need to extract new natural resources through energy-intensive processes involving fossil fuels. This not only curbs emissions but also mitigates environmental hazards linked to traditional concrete manufacturing.[95,245] The sustainability of society is supported when new materials, such as RCA, are produced without depleting existing resources. It minimizes the quantity of CO_2, NOx, particulate matter, and

other air pollutants released in aggregate production while also saving a substantial amount of energy.[95]

- **Sustainable construction goals and materials:** In the pursuit of sustainable construction, the incorporation of RCA in precast concrete represents a substantial leap toward achieving environmental goals.[10,19] By recycling concrete waste into construction materials, this practice aligns with the overarching objectives of sustainability, including waste reduction, resource conservation, and lower carbon emissions.[19,27,39] RCA addresses the construction industry's need for more eco-friendly materials, promoting a cleaner production process and minimizing environmental impact. It offers a tangible solution for reducing landfill waste, conserving natural resources, and advancing sustainable construction practices. This shift toward sustainable materials, driven by the use of RCA, contributes to a more responsible and eco-conscious construction industry.[3,9,32,33]
- Economic aspects: The integration of RCA in precast concrete offers notable economic benefits and resource efficiency, reducing waste and costs.[6,43] Locally sourcing RCA from construction sites minimizes the need for extensive quarrying and transportation, enhancing economic feasibility.[1,7–9,25,41,59] Lower transportation and crushing costs associated with RCA contribute to an overall cost reduction compared to natural aggregates.[4,31] The cost-effectiveness of RCA from CDW provides a sustainable alternative to traditional aggregates.[11,14] saving natural resources and reducing water (11%), energy (20%), life cycle costs (21%), and carbon dioxide emissions (16%) in road construction.[33] Studies show that 100% RCA can reduce the total cost per m^3 of concrete by 19.38%,[35] with a 5% cost reduction in SCC using 100% CRCA.[28] Increased RCA content correlates with decreased concrete costs, with 100% RCA-based concrete being 6.69–8.73% cheaper than conventional mixes.[64] Onsite recycling of out-of-service concrete further optimizes economic benefits, potentially saving 9.19% of concrete costs with a 60% RCA.[3] RCA usage may cut construction costs significantly, with a potential 60% savings when replacing natural aggregates.[41] A 45% RCA replacement in RCA proves to be the most cost-efficient, ensuring a 15.67% cost reduction, compared to a 0% RCA.[57] Embracing RCA in precast concrete aligns with environmental goals while promoting economic viability and resource efficiency in the expanding construction industry.[9,50]

5.3 Life cycle assessment (LCA) of precast concrete comprising RCA

LCA is a systematic methodology for assessing the environmental effect of a product or process over its full life cycle. In the context of precast concrete, LCA plays a pivotal role in understanding the ecological consequences of using RCA instead of natural aggregates.[39,248] The LCA process includes several stages, such as raw material extraction, transportation, manufacturing, use, and disposal.[249–251] Comparing the environmental performance of these two aggregate types, LCA studies have consistently underscored the favorable environmental benefits of incorporating RCAs in precast concrete production. When conducting an LCA to evaluate the environmental impact of RCA, a comprehensive description of the mixture design methods employed for RCA must be provided. A critical difference was observed when comparing the impact of RCA with that of natural aggregates.[2]

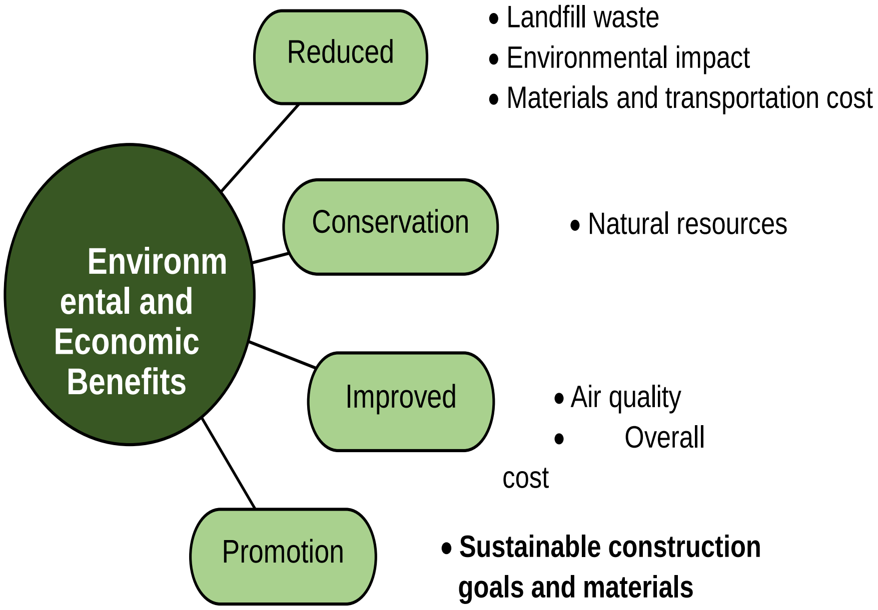

Fig. 25 Environmental benefits of RCA use in precast concrete.

A noteworthy dimension of LCA analyzes in the concrete industry is the consideration of operational and embodied energy. These factors are essential to understanding the overall environmental impact. Operational energy involves the assessment of energy consumed during the operational use of precast concrete products, while embodied energy is that expended in the manufacturing and transportation of precast concrete products. It encompasses the energy used in raw material extraction, processing, and production, as well as in transportation to construction sites.[252–253] Environmental impacts can be mitigated by using RCA, which is 30% less embodied energy and emits 60% less CO_2 than natural aggregate incorporation.[64] Further, according to Wijayasundara *et al.*,[253] when RCA is received at a construction site and its "cradle-to-gate" embodied energy is compared to natural aggregates, RCA differs from natural aggregates by just +2.1 to −1.1%. Xiao *et al.*[254] found that using RCA instead of natural aggregate in high-rise concrete structures can reduce the carbon footprint by up to 2.175×10^5 $kgC_{e.}$

The Precast/Prestressed Concrete Institute initiated a comparative study in 2009 to enhance the understanding of precast products and construction stages in LCAs and found that precast concrete has no additional environmental impact.[255] Various LCA studies, though some of them are not specific to precast concrete production with RCA, offer insights into the environmental benefits of incorporating RCA in construction materials. Notably, Xing *et al.*[256] used RCA and other cementitious materials to investigate sustainable concrete and related factors such as water content, compressive strength, and RCA and supplementary cementitious material ratios. Findings from research[257] highlight the importance of proper RCA treatment, as it can impact the overall environmental footprint, particularly concerning the consumption of chemical agents. LCA studies comparing CDW-based geopolymer mortars to traditional Portland cement-based mortars demonstrate substantial reductions of around 60% in CO_2 emissions and energy consumption.[258] Studies have reinforced the favorable environmental effects of using RCA, emphasizing financial and material savings.[259,260] Large-scale LCAs also contribute to the understanding of emissions from RCA concrete production, shedding light on potential alternatives such as RCA as fill material. When considering a durable functional unit, the CO_2 emission factor can be reduced from 348 to 164 kg $CO_{2\text{-eq}}/m^3$.[261-263]

6. Conclusions

This systematic review delved extensively into RCA use in precast concrete production. The review provides valuable insights into the current applications of RCA in precast concrete, highlighting its benefits, limitations, and environmental impact. It also reveals several pivotal facets that collectively define the future direction of sustainable precast concrete production. The main findings and novel conclusions derived from the analysis are as follows:

- The advantages and challenges of the integration of RCA into precast concrete have been critically and significantly reviewed. The findings strongly resonate with environmental benefits, the foremost among them being waste reduction, diminished reliance on virgin aggregates, and a substantial reduction in the construction industry's carbon footprint. Challenges, including the variability in RCA properties and the necessity for stringent quality control, were discussed. Our recommendation echoes the industry's clarion call for consistent quality standards and procedures to maximize the extraordinary potential of RCA.
- Comparative analyzes indicate that RCA-based precast concrete structures exhibit lower compressive strengths than high-quality RCA through various treatment methods but indicate higher performance than traditional concrete structures. The environmental advantages, including reduced carbon emissions and waste diversion, enhance the overall sustainability of RCA-based structures. Despite potential variations in RCA quality, meticulous testing and quality control can mitigate concerns. Overall, RCA-based precast concrete structures present a promising and sustainable alternative, with performance on par with traditional concrete structures.
- RCA has a transformative role in advancing sustainable energy practices and heralding a cleaner production era within the construction sector. The finding that RCA significantly curtails energy consumption during production is a powerful testament to its sustainable capability. Localized sourcing of waste materials leads to not only resource efficiency but also a marked reduction in transportation emissions, thereby enhancing air quality and championing sustainable energy practices.
- Research and standardization are important. Although the environmental advantages of using RCA in precast concrete are apparent, additional research is necessary to evaluate its extended durability and economic viability. In addition, it is imperative to establish guidelines and industry standards for the integration of RCA in precast concrete. This is essential to guarantee a uniform level of quality and performance.
- This review strongly advocates for the widespread incorporation of RCA into precast concrete as a pivotal step toward advancing sustainability in the construction sector. By

actively promoting and adopting RCA, the industry can significantly reduce its environmental impact, thus contributing to a more sustainable future. Additionally, a comprehensive analysis of the life cycle assessment (LCA) for precast concrete integrated with RCA, spanning from raw material extraction to end-of-life disposal, underscores its position as a beacon of sustainability, firmly aligned with the overarching objectives of green construction.

- Recognizing the environmental benefits of RCA in precast concrete, stakeholders should implement clear policies and regulations, such as tax incentives and minimum RCA content requirements, in public projects. Industry collaboration, knowledge sharing, and best practice development are crucial. Strategic investments in research and certification of RCA-derived concrete are needed for industry confidence. Education programs for professionals and public awareness campaigns should emphasize the technical aspects and advantages of RCA. This comprehensive approach will facilitate the seamless adoption of RCA in precast concrete, aligning construction practices with sustainability goals.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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