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Recycled Concrete as a Substitute for Natural Aggregate in Transport Infrastructure

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ABSTRACT
The construction sector is both the largest consumer of natural aggregates and a major generator of construction and demolition waste, which accounts for at least 30% of the total solid waste produced worldwide (Ginga et al., 2020). This review evaluates whether recycled concrete aggregate can substitute for natural aggregate in transport infrastructure by examining its concept and production process, its applications in transport structures, and its technical, economic, and environmental performance. The literature shows that RCA, produced by crushing and separating concrete debris, is characterized by adhered old mortar, which lowers density and mechanical strength while increasing water absorption (Berredjem et al., 2020). However, these reductions, compressive strengths roughly 14–32% and elastic moduli 25–40% lower than natural aggregate at high replacement levels, can be offset through blend optimization, with replacement ratios of about 50% repeatedly emerging as the preferred balance between stiffness, permanent deformation, and bearing capacity (Kakizaki et al., 2023; Toka & Olgun, 2021). In pavement applications, RCA delivers ultimate bearing capacities of 186–480 kPa, comparable to natural aggregates (Zargar et al., 2024). Economically, production costs are approximately 40% lower per tonne for recycled aggregate than for natural aggregate (Ohemeng & Ekolu, 2020), and recycling operations can yield positive net benefits where conventional disposal is costly (Tam, 2008). Environmentally, life-cycle assessments show that recycled aggregate concrete roughly halves the environmental impact of natural-aggregate concrete across key indicators (Pavlů et al., 2019), with carbon emission reductions of up to nearly 50% when high-quality recycled aggregate fully replaces natural aggregate (Pavlů et al., 2025). The review concludes that RCA is a technically serviceable, economically competitive, and environmentally advantageous substitute for natural aggregate in transport infrastructure, provided that processing, mix design, and quality control are properly managed; wider adoption depends on unified standards and further long-term field performance data.

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I. INTRODUCTION

The construction sector consumes natural aggregates at a rate that is difficult to sustain, while simultaneously generating enormous volumes of construction and demolition waste. Construction and demolition waste alone accounts for at least 30% of the total solid waste produced worldwide, amounting to roughly 924 million tonnes in the European Union in 2016 and 2.36 billion tonnes in China in 2018 (Ginga et al., 2020). The traditional response to this waste, dumping in sanitary landfills, is becoming increasingly unviable, and the extraction of virgin aggregate continues to cause environmental degradation (Ginga et al., 2020; Surya et al., 2013).

Recycled concrete aggregate, produced by crushing concrete debris, is recognized as a viable substitute for natural aggregate in infrastructure applications, including pavement layers, and embodies circular-economy strategies for sustainable construction (Elmasri et al., 2025; Fanijo et al., 2023). Implementing RCA in new pavements can minimize carbon footprint, conserve natural resources, reduce harmful emissions, and lower life-cycle costs (Fanijo et al., 2023). Laboratory-based studies confirm that recycled aggregate concrete may be usefully applied in transportation infrastructure such as pavements and bridges, although long-term field performance still requires further investigation (Surya et al., 2013). This document reviews the concept and production of RCA, its application in transport structures, the technical and economic aspects of its use, and its environmental significance.

1.2 Problem Statement

The problem that motivates this review has two interconnected faces: the depletion of natural resources and the accumulation of construction waste. Construction aggregates — sand, gravel, and crushed stone — are among the most heavily consumed materials on Earth. Recent estimates place global demand for construction aggregates at 40–50 billion tonnes per year (Přikryl, 2021), a figure consistent with other assessments of world consumption exceeding 40 billion tonnes annually (Pascal, 2014) and ranging between 32 and 50 billion tonnes per year (Bendixen et al., 2021). Roughly half of this demand originates in China, the world's largest aggregate market at some 15–20 billion tonnes per year, followed by India with about 5.5 billion tonnes per year (Přikryl, 2021). The global construction aggregate market was valued at over €75 billion in 2012 and was projected to grow from 48.3 billion tonnes in 2015 toward 66.3 billion tonnes by 2022 (Brito & Silva, 2016).

Transport infrastructure is the dominant driver of this demand: aggregates contribute about 90% of asphalt pavements and 80% of concrete roads (Pascal, 2014). The resulting extraction is not environmentally neutral — aggregate mining affects biodiversity, water turbidity, water-table levels, and landscape, and adds carbon dioxide emissions through transportation (Pascal, 2014). Looking ahead, the OECD projects that global use of natural raw materials will rise from about 90 gigatons today to roughly 167 gigatons by 2060, underscoring the need for resource-conserving alternatives in construction (Bamigboye et al., 2020). Set against this are the vast waste streams described above (Ginga et al., 2020): the same activity that depletes virgin aggregate deposits simultaneously generates millions of tonnes of demolished concrete, most of which is landfilled. Recycling concrete into aggregate addresses both sides of this problem at once, which is why it has emerged as a central strategy for sustainable road construction (Elmasri et al., 2025; Fanijo et al., 2023).

1.3 Aims and Objectives

The aim of this review is to evaluate whether recycled concrete aggregate can serve as a substitute for natural aggregate in transport infrastructure, with reference to its production, technical performance, economic viability, and environmental benefits.
The specific objectives are:

- To introduce the concept of recycled concrete aggregate and describe its production process;
- To review the applications of RCA in transport structures, particularly pavement layers;
- To analyse the technical and economic aspects of substituting RCA for natural aggregate;
- To assess the environmental significance of RCA use, including life-cycle impacts; and
- To synthesize quantitative evidence from the literature and identify the main barriers and research needs for wider adoption.

1.4 Scope and Organization of the Document

This document is a literature-based review drawing on peer-reviewed experimental studies, case reports, and life-cycle assessments of recycled concrete aggregate in transport applications. Its scope covers the production of RCA from construction and demolition waste, its use in pavement base, subbase, and surface layers, and its comparative technical, economic, and environmental performance against natural aggregate.

The document is organized as follows. Section 2 defines recycled concrete and describes its production process. Section 3 reviews the application of recycled concrete in transport structures. Section 4 analyses the technical and economic aspects of its application. Section 5 addresses the environmental significance of using recycled concrete. The succeeding sections then present the results and discussion of the reviewed evidence and the main conclusions of the study.

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II. Background and methods

Recycled aggregates are derived by crushing inert construction and demolition waste. The material is classified as recycled concrete aggregate when it consists primarily of crushed concrete, whereas the broader term "recycled aggregate" applies when it contains substantial quantities of other materials (Kryeziu et al., 2023). The fundamental difference between recycled and natural aggregates is the presence of old, adhered mortar attached to the aggregate surface, which governs most of the differences in physical and mechanical behaviour (Kryeziu et al., 2023). Because of this adhered mortar and possible foreign substances, recycled aggregates exhibit larger quality deviations than natural aggregates, making quality control a central concern in production (Kim, 2021).

The production process typically involves several stages. Concretes debris is first crushed to a maximum size of about 1200 mm in fixed plants (or 400–700 mm in mobile plants), then subjected to secondary grinding using impact, hammer, or conical crushers, after which contaminating elements, mainly steel remains, are removed and the aggregate is stored by size fractions, with coarse aggregate typically representing 65–80% of the output (Merino et al., 2009). A modern recycling plant generally consists of crushers, screeners, magnetic separators, wind-sifting devices, and manual separation stations (Wang et al., 2017). Survey data from the recycling industry indicate that jaw crushers are the most common choice for primary crushing, followed by cone crushers, with jaw, cone, and impact crushers used for secondary crushing (Kim, 2021). Processing can take place on-site with mobile crushers, which reduces initial investment and production costs, or at stationary recycling plants, which involve higher investment but produce higher-quality aggregates with better impurity removal (Kim, 2021). Recycled aggregates must satisfy specification requirements for properties such as particle density, water absorption, and fine-particle content set out in national and international standards (Wang et al., 2017); in Europe, for example, Annex E of BS EN 206 recommends the use of coarse recycled aggregates with diameter $d \geq 4$ mm for new concrete construction (Kryeziu et al., 2023).

Emerging technologies are further improving the quality of recycled products. For instance, Advanced Dry Recovery and Heating Air Classification are industrial-scale, mobile technologies that separate end-of-life concrete into coarse, fine, and ultrafine particles, yielding recycled coarse and fine aggregates whose mechanical properties are comparable to those of the reference natural-aggregate concrete (Gebremariam et al., 2020).

2.1 Application of Recycled Concrete in Transport Structures

RCA has found its widest application in road and transport infrastructure, where large volumes of aggregate are consumed. Reviews of pavement construction identify three principal applications, pavement sublayers, rigid layers, and flexible layers, each with its own evaluation techniques (Fanijo et al., 2023). RCA can be applied effectively to a variety of pavement layers, including base and surface layers (Dhemaied et al., 2024).

For flexible pavements, RCA performs well as an unbound granular material in subbase and base layers. Experimental studies show a steady gain in stiffness of RCA specimens with increasing load cycles at low moisture contents, high confining pressures, and high vertical axial pressure, supporting its use in granular pavement layers (Jayakody et al., 2019). Research based on materials from urban renewal projects found that RCA base and subbase samples complied with AASHTO specification requirements and retained adequate stiffness after 1 to 20 freeze–thaw cycles, indicating high performance potential in flexible pavement construction under varying environmental conditions (Akbaş et al., 2023). Studies of unbound subbase construction using RCA from two different sources (with original compressive strengths of 20–30 MPa and 31–40 MPa) characterized optimum moisture content, density, California Bearing Ratio, and resilient modulus, using the results in nonlinear pavement analysis to assess critical tensile and compressive strains under traffic loading (Al-Mosawe et al., 2022).

RCA has also been validated as a subbase material in terms of bearing capacity. Cyclic plate load tests report ultimate bearing capacities of different RCA configurations ranging from 186 to 480 kPa, comparable to values for natural and recycled aggregates in previous studies, with geocell-reinforced sections reaching the upper end of this range (Zargar et al., 2024). In highway applications, blends of recycled materials have been assessed against British Standards, Highway Agency specifications, and AASHTO requirements; a 50% reclaimed asphalt pavement + 50% RCA mix was demonstrated suitable for unbound subbase application, with the presence of RAP improving drainage properties (Ayan, 2011).

The use of RCA extends beyond heavy-traffic pavements. In Central Europe, recycled aggregates from an airport, a road overpass, and building demolition were tested according to European standards and used to produce concrete for cycle-path substructural layers, achieving 28-day compressive strengths of 5.9–17.3 MPa and frost resistance ratios close to 1.0 (Konca et al., 2024). These values met the requirements of EN 12390-3 for class C8/10 when using CEM II B/V 32.5 cement with a water–cement ratio of 1, demonstrating that RCA concrete can serve lower-traffic transport applications with appropriate mix design (Konca et al., 2024). Overall, the evidence supports RCA as a practical substitute for natural aggregates in transport structures, from cycle paths to highway base and subbase layers (Konca et al., 2024; Surya et al., 2013).

2.2 Technical and Economic Aspects of Application

2.2.1 Technical Aspects

The technical behaviour of RCA is governed by its porous, adhered-mortar structure. RCAs are characterized by lower densities, higher water absorption capacities, and lower mechanical strength than NAs, with the high porosity of RCA being the main cause; these factors directly affect workability, mechanical resistance, and durability of the resulting concrete (Berredjem et al., 2020). The durability of RAC is largely determined by transport properties such as permeability and hydric diffusivity, which depend strongly on the porous network and its connectivity (Berredjem et al., 2020). Studies on 14 batches of RAC confirm that compressive strength is not the only decisive factor — mechanical and durability-related properties are also affected by the size and content of the coarse recycled aggregates (Ozbakkaloglu et al., 2017).

Nevertheless, carefully designed RAC can achieve performance close to conventional concrete. In concrete with recycled fine aggregate, compressive strengths were similar to those of the conventional concrete, with a maximum decrease of 5% at 28 days, and all concretes showed compressive strengths 16% higher at 84 days than at 28 days (Zega & Maio, 2011). A comparative study of RAC with 50%, 75%, and 100% recycled aggregate observed no significant variation in compressive, split tensile, or flexural strength, although modulus of elasticity and resistivity decreased and water absorption increased with the proportion of recycled aggregate (Surya et al., 2013). Concrete produced with 100% recycled aggregate can satisfy strength and durability requirements if high packing density is achieved (Yehia et al., 2015). Long-term properties have also been explored in self-compacting concrete produced with recycled fractions (0–4 mm, 4–8 mm, and 8–16 mm), where careful grading and mixing enable adequate performance (Manzi et al., 2017). In practice, the variability of RCA properties requires testing to guarantee quality, and the replacement of NA by RCA may require adjustments to the water–cement ratio to overcome flow difficulties in fresh concrete (Berredjem et al., 2020; Konca et al., 2024).

2.2.2 Economic Aspects

From an economic perspective, RCA production is generally less expensive than natural aggregate production. A South African case study found that the long-term cost of producing one tonne of coarse recycled concrete aggregate was about 40% less than that for coarse natural aggregate, while the environmental benefit of producing one tonne of RCA was approximately 97% higher; notably, the net benefit of producing either aggregate type was found to be negative, though less so for RCA (Ohemeng & Ekolu, 2020). Early economic analysis reached similar conclusions, with the production cost of recycled concrete aggregate estimated at about 38% lower than natural aggregate. However, because concrete members containing RCA must be roughly 20% larger in volume to achieve equal performance, conventional concrete remained economically more attractive at equal delivery distances. This relationship reversed only when natural aggregate was in short supply or when recycled aggregate enjoyed a transportation-distance advantage of at least 15 miles (Frondistou-Yannas & Itoh, 1977).

A case-study comparison of concrete recycling found a positive net benefit of about $30,916,000 per year for the recycling method, versus a negative net benefit of about −$44,076,000 per year for the conventional method, demonstrating that aggregate produced by recycling is more economical in the long term (Tam, 2008). A critical factor affecting the viability of aggregate recyclers, however, is the availability of feed materials; fluctuating or seasonal debris supply, as well as pricing controlled by outside factors, can reduce operational profitability (Tam, 2008). Recycled aggregates can also remain competitive even when transport distances from the plant to the work site exceed those of natural aggregates—a conclusion that holds without considering landfill taxes, which range from about €3 per tonne in Italy to €63 per tonne in Denmark and would further enhance the profitability of recycling (Linares et al., 2024). Cost-benefit assessments of ready-mixed high-performance concrete made with RCA in Thailand likewise support the commercial attractiveness of recycled aggregate production (Makul, 2020).

Table 1. Economic Factors Influencing the Viability of Recycled Concrete Aggregate

Economic factor	Evidence from the reviewed studies	Practical implication
Aggregate production cost	RCA production was approximately 38–40% less expensive than natural aggregate production (Frondistou-Yannas & Itoh, 1977; Ohemeng & Ekolu, 2020).	RCA can reduce material-production costs when processing and quality-control expenses remain manageable.
Structural or mix-design requirements	Concrete members containing RCA may need to be approximately 20% larger to provide performance equivalent to that of conventional concrete (Frondistou-Yannas & Itoh, 1977).	Aggregate savings may be partly offset by additional concrete or structural-material requirements.

Transport distance	RCA becomes more economically favourable when natural aggregate is scarce or when RCA has a transport-distance advantage of at least 15 miles (Frondistou-Yannas & Itoh, 1977).	Local availability and plant location are decisive factors in project-level cost comparisons.
Recycling benefit	One case study reported an annual net benefit of approximately \$30,916,000 for recycling, compared with a negative net benefit of approximately −\$44,076,000 for the conventional method (Tam, 2008).	Large-scale recycling can generate substantial long-term economic benefits.
Feed-material availability	Seasonal or fluctuating supplies of demolition debris and externally controlled pricing can reduce recycler profitability (Tam, 2008).	Stable C&D waste streams and predictable market conditions are needed for reliable operation.
Landfill taxation	Landfill taxes ranging from approximately €3 to €63 per tonne can further improve the relative profitability of recycling (Linares et al., 2024).	Disposal charges strengthen the economic case for diverting C&D waste into RCA production.
High-performance concrete	Cost-benefit analysis of ready-mixed high-performance concrete made with RCA supported its commercial attractiveness in Thailand (Makul, 2020).	RCA may be economically viable beyond low-grade applications when mix design and quality requirements are properly managed.

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Taken together, the evidence indicates that RCA offers lower production costs and measurable environmental co-benefits, provided that feed supply, transport distance, quality control, and mix-design requirements are managed. The economic advantage is therefore not universal: it depends on the distance between demolition sites, recycling plants, and construction projects, as well as on the performance-related costs associated with using RCA. Project-specific cost-benefit analysis remains necessary because lower aggregate-production costs may be offset by processing, testing, transport, or structural-design requirements.

2.3 Environmental Significance of Using Recycled Concrete

The environmental rationale for RCA rests on three pillars: waste diversion, resource conservation, and emissions reduction. Life-cycle assessment comparisons of natural-aggregate and recycled-aggregate concrete report environmental savings from reduced use of primary resources, lower embodied energy, lower embodied emissions, and reduced pressure on landfill sites (Pavlů et al., 2019). A comparative environmental evaluation of RCA versus NA pavements concluded that RCA inclusion contributes to sustainability by minimizing health-hazard effects, waste generation, and the pressure on landfill sites relative to conventional pavement construction (Fanijo et al., 2023).

Quantitative carbon assessments reinforce this picture. For conventional concrete with natural aggregates, carbon emissions ranged between 323 and 332 kg CO_2e per cubic metre of concrete; replacing 25% of the cement with fly ash reduced emissions by up to 17%, and concrete mixes with 100% recycled aggregates and 25% fly ash achieved lower carbon emissions than concrete made with natural aggregates only (Sabău et al., 2021). Earlier studies cited in the LCA literature found that the carbon emission of recycled concretes was reduced by about 30% compared with conventional concretes, and that LCA of recycled aggregates in highway applications yields substantial economic and environmental benefits through reduced landfill requirements and carbon emissions (Zhang et al., 2022). More recent work reports that fully replacing natural aggregate with high-quality recycled aggregate reduces the environmental impact of concrete by nearly 50%, primarily through lower resource depletion and transport emissions (Pavlů et al., 2025). The global warming potential of concrete per unit volume has been shown to vary widely, between 278.35 and 524.44 kg CO_2 equivalent depending on mix design, demonstrating that the environmental performance of concrete is strongly influenced by material choices, and that recycled aggregate combined with supplementary cementitious materials amplifies ecological advantages (Chaitanya et al., 2026).

Beyond emissions, RCA supports circular-economy principles by reducing dependence on quarrying and diverting C&D waste from landfill. The complete utilization of waste concrete offers unique opportunities for supply-chain security and reduced consumption of natural resources, harmonizing current treatment practices as a first step toward policy and standards development (Zaccardi et al., 2021). RCA is consequently recognized as a key driver of sustainable road construction and a multi-layered solution that protects natural resources, minimizes road construction costs, and limits harmful emissions (Dhemaied et al., 2024). Recommendations on replacement rates in asphalt mixtures still vary widely, underscoring the need for unified standards and specifications to realize RCA's full environmental potential (Dhemaied et al., 2024).

III. Results and Discussion

3.1 Mechanical and Physical Properties

The reviewed experimental results consistently confirm that recycled aggregate concrete exhibits somewhat lower mechanical performance than natural-aggregate concrete, although the magnitude of the difference varies markedly between studies. In controlled comparisons between RAC and normal-weight concrete produced with a jaw crusher, compressive strength was found to be lower by 14 to 32% and elastic modulus lower by 25 to 40% (Kakizaki et al., 2023). Similar trends are reported in reviews of the broader literature: compressive strength, splitting tensile strength, and modulus of elasticity all decrease as the replacement ratio of recycled aggregate increases, an effect attributed to the cement mortar adhering to the recycled coarse aggregate, yet no significant reduction in ultimate load capacity was observed (Alkhteeb & Dawood, 2025). Static and dynamic elastic modulus both decline with increasing replacement ratio (Wardeh et al., 2014).

Other studies, however, report near-parity. Differences between recycled and natural aggregate concrete were found to be negligible, not exceeding 5%, except for the initial tangent elastic modulus, where the difference was about 10%. Concrete containing recycled fine aggregate achieved compressive strengths within 5% of the conventional concrete at 28 days, and all mixes gained roughly 16% strength between 28 and 84 days (Zega & Maio, 2011). Concrete produced with 100% recycled aggregate can satisfy strength and durability requirements when a high packing density is achieved (Yehia et al., 2015).

The scatter in these results is itself a finding: it reflects the decisive influence of the adhered old mortar and the porous structure of RCA, which determine workability, mechanical resistance, and durability (Berredjem et al., 2020), as well as the dependence of RCA properties on crushing methods, the extent of crushing, and the amount of residual paste (Fanijo et al., 2023). This variability explains why quality control is central to recycled-aggregate production (Kim, 2021) and motivates the development of analytical models that predict elastic modulus as a function of the mortar, natural and recycled aggregate phases (Li et al., 2024). Accordingly, comparisons between RAC and conventional concrete should consider not only the nominal replacement ratio but also RCA source quality, particle grading, moisture condition, adhered-mortar content, and mix-design strategy. These variables help explain why moderate replacement levels may produce limited performance losses in some applications, whereas poorly processed or highly porous RCA can result in more pronounced reductions in stiffness and strength.

3.2 Performance in Pavement Layers

Results from granular pavement testing indicate that RCA performs at levels comparable to natural aggregate when properly blended and processed. In a systematic study of mixes containing RCA from concretes of three different compressive strengths at replacement ratios of 25, 50, and 75%, the highest resilient modulus among pure RCAs was observed for one source at an average of about 200 MPa, while the highest values for blended mixtures averaged about 250 MPa; the minimum permanent deformation was obtained at a 50% RCA content, and the highest California Bearing Ratio values were recorded for the pure RCAs (Toka & Olgun, 2021). The same study reported average permeability coefficients of 9.973×10^{-6} m/s for RCAs and concluded that blending with natural material, generally at around 50%, is preferable to pure use, with blends up to 75% acceptable when the source concrete is strong (Toka & Olgun, 2021). Correlations developed from 52 remoulded granular samples containing natural aggregates, RCA, and reclaimed asphalt pavement showed that resilient modulus increases with RAP content while CBR follows the opposite trend, and that residual accumulative strain rises substantially with RAP addition, a potential disadvantage for pavement service life that must be weighed in design.

The principal pavement-related indicators reported in the granular-layer studies are summarized below.

Table 2. Summary of Reported Performance Indicators for Granular Pavement Layers Containing RCA and RAP

Indicator	**Reported result**	**Engineering implication**
RCA replacement ratios	25, 50, and 75%	Performance depends on the selected blend ratio and RCA source
Highest resilient modulus for pure RCA	Approximately 200 MPa	Properly processed RCA can provide substantial stiffness
Highest resilient modulus for blended mixtures	Approximately 250 MPa	Blending RCA with natural aggregate can improve stiffness

Preferred RCA content	Approximately 50%	Provides a favourable balance between stiffness and permanent deformation
Maximum acceptable blend in some cases	Up to 75%	Feasible when the source concrete has adequate strength
Average permeability coefficient	9.973×10^{-6} m/s	Indicates the drainage potential of granular RCA layers
RAP effect on resilient modulus	Increases with RAP content	May improve stiffness
RAP effect on CBR	Decreases with RAP content	May reduce bearing performance
RAP effect on accumulated strain	Increases substantially with RAP content	May increase deformation-related service-life risks

Structural test results reinforce these findings. Load-bearing tests on various RCA configurations delivered ultimate bearing capacities of 186 to 480 kPa, comparable to previously reported values for natural and recycled aggregates (Zargar et al., 2024). RCA from urban renewal projects in Istanbul complied with AASHTO specification requirements for base and subbase gradations and retained adequate stiffness after 1 to 20 freeze–thaw cycles (Akbaş et al., 2023). In Central Europe, RCA concrete for cycle-path substructural layers achieved 28-day compressive strengths of 5.9–17.3 MPa and frost resistance ratios close to 1.0, satisfying EN 12390-3 class C8/10 requirements (Konca et al., 2024). Nonlinear pavement analysis using measured resilient-modulus models has enabled the computation of critical tensile strains at the bottom of the asphalt layer and compressive strains at the top of the subgrade for subbases containing different RCA percentages and sources. Taken together, the results support the conclusion that RCA offers equivalent or better performance than virgin aggregate for almost any unbound application given proper process control, while full-scale testing is still recommended before field deployment (Aytekin & Mardani, 2021).

Table 3. Structural Performance of RCA in Pavement Layers

Application or test condition	**Reported performance**	**Interpretation**
RCA subbase configurations	Ultimate bearing capacity of 186–480 kPa	Comparable to reported natural- and recycled-aggregate values
Urban-renewal RCA	Complied with AASHTO base and subbase gradation requirements	Suitable for specification-controlled pavement layers
Freeze–thaw exposure	Adequate stiffness after 1–20 cycles	Demonstrates resistance under repeated environmental exposure
Cycle-path substructural concrete	28-day compressive strength of 5.9–17.3 MPa	Satisfied the specified C8/10 strength classification
Frost resistance	Ratio close to 1.0	Indicates limited deterioration under the reported test conditions
Nonlinear pavement analysis	Critical tensile and compressive strains calculated for different RCA contents and sources	Supports layer-specific structural design

These findings indicate that the suitability of RCA cannot be assessed solely by comparing its nominal replacement percentage with that of natural aggregate. Resilient modulus, CBR, permanent deformation, permeability, gradation, and freeze–thaw resistance must be considered together. A blend that maximizes stiffness may not minimize accumulated strain, while a highly permeable material may provide drainage benefits but require additional attention to moisture-sensitive subgrade conditions. Accordingly, RCA selection should be linked to the function of the pavement layer: materials with adequate stiffness and low deformation should be prioritized for heavily loaded base and subbase courses, whereas less uniform materials may be more appropriate for lower-risk or lightly trafficked applications. Field validation remains necessary because laboratory results do not fully capture construction variability, seasonal moisture changes, traffic loading, and long-term particle breakdown (Aytekin & Mardani, 2021).

3.3 Economic Performance

Economic results consistently favour recycled aggregate production over natural aggregate production, although the magnitude of the advantage depends on case-specific conditions. A South African case study found the long-term cost of producing one tonne of coarse RCA to be about 40% less than for coarse natural aggregate, with an approximately 97% higher environmental benefit per tonne; however, the net benefit of producing either aggregate type was negative, although RCA was less disadvantageous (Ohemeng & Ekolu, 2020). Early studies estimated RCA production costs at roughly 38% below those of natural aggregate, but noted that mixtures containing RCA must be about 20% larger in volume for equal performance, making conventional concrete more attractive at equal delivery distances unless recycled aggregate enjoyed a transport-distance advantage of at least 15 miles (Frondistou-Yannas & Itoh, 1977). A case-study comparison of concrete recycling reported a positive net benefit of about $30,916,000 per year for recycling versus a negative net benefit of about −$44,076,000 per year for the conventional disposal method (Tam, 2008).

Table 4. Economic burden of conventional disposal compared with recycling

Economic factor	**Reported result**	**Effect on RCA competitiveness**
Long-term coarse RCA production cost	Approximately 40% lower than natural aggregate	Favourable to RCA
Environmental benefit of coarse RCA	Approximately 97% higher per tonne	Strengthens the broader value proposition
Early RCA production-cost estimate	Approximately 38% below natural aggregate	Favourable under suitable operating conditions
Required volume for equal performance in an early study	Approximately 20% greater	Can reduce or eliminate cost savings
Required transport advantage in the early comparison	At least 15 miles	Demonstrates strong sensitivity to haulage distance
Annual net benefit of recycling case study	Approximately $30,916,000	Indicates substantial potential benefit
Annual net benefit of conventional disposal	Approximately −$44,076,000	Shows the economic burden of disposal

The competitiveness of RCA is further strengthened when waste-disposal costs are internalized: landfill taxes range from about €3 per tonne in Italy to €63 per tonne in Denmark, and including them would substantially enhance the profitability of recycling even when transport distances from plant to site exceed those of natural aggregates (Linares et al., 2024). Cost-benefit analysis of ready-mixed high-performance concrete with RCA in Thailand similarly supported the commercial attractiveness of recycled aggregate production (Makul, 2020). Two caveats emerge from the results: recycler viability depends heavily on the availability of feed materials, since fluctuating or seasonal debris supply and externally controlled pricing can erode profitability, and the distance sensitivity of aggregate transport means plant location is a decisive economic variable.

The economic evidence therefore supports a conditional rather than universal advantage for RCA. Production savings may be offset by additional processing, sorting, quality testing, moisture management, storage, and transportation requirements. Conversely, recycling becomes more attractive when demolition waste is generated near the processing facility, disposal charges are high, and a dependable local market exists for the recovered aggregate. The economic assessment should consequently include both direct production costs and avoided disposal costs. It should also account for the value of reduced quarrying, potential savings in raw-material procurement, and the cost of meeting project-specific quality requirements. These boundary conditions explain why RCA may be highly competitive in urban areas with limited landfill capacity but less advantageous in regions where natural aggregate is abundant and transport distances are short.

3.4 Environmental Performance

Life-cycle assessment results show consistent environmental advantages for recycled aggregates across impact categories. In an assessment covering two use cycles of concrete, the recycled aggregate values were roughly half those of natural aggregate for every reported indicator—ADP fossil 0.0314 versus 0.0160 MJ, global warming potential 0.0024 versus 0.0012 kg CO_2-eq, acidification potential 1.53×10^{-5} versus 8.91×10^{-6} kg SO_2-eq, eutrophication potential 5.32×10^{-6} versus 2.04×10^{-6} kg phosphate-eq, and photochemical ozone creation potential 2.82×10^{-10} versus 5.56×10^{-15} kg ethene-eq per functional unit (Pavlů et al., 2019). Carbon-oriented studies report that conventional concrete with natural aggregates emits 323 to 332 kg CO_2e per cubic metre, that replacing 25% of cement with fly ash reduces emissions by up to 17%, and that mixes with 100% recycled aggregates and 25% fly ash achieve lower emissions than natural-aggregate concrete (Sabău et al., 2021). Earlier LCA work found carbon-emission reductions of about 30% for recycled concretes (Zhang et al., 2022), and more recent assessments report reductions of nearly 50% when high-quality recycled aggregate fully replaces natural aggregate (Pavlů et al., 2025). Global warming potential per unit volume of concrete varies widely, between 278.35 and 524.44 kg CO_2 equivalent, depending on mix design, confirming that material selection governs environmental outcomes (Chaitanya et al., 2026).

Table 5. Comparative Environmental Performance of Natural and Recycled Aggregates

Environmental indicator	Natural aggregate value	Recycled aggregate value	Relative tendency
ADP fossil	0.0314 MJ	0.0160 MJ	Recycled aggregate approximately halves the value
Global warming potential	0.0024 kg CO_2-eq	0.0012 kg CO_2-eq	Recycled aggregate approximately halves the value
Acidification potential	1.53×10^{-5} kg SO_2-eq	8.91×10^{-6} kg SO_2-eq	Lower for recycled aggregate
Eutrophication potential	5.32×10^{-6} kg phosphate-eq	2.04×10^{-6} kg phosphate-eq	Lower for recycled aggregate
Photochemical ozone creation potential	2.82×10^{-10} kg ethene-eq	5.56×10^{-15} kg ethene-eq	Substantially lower for recycled aggregate
Carbon emissions of conventional concrete	323–332 kg CO_2e/m^3	Lower with recycled aggregate and fly ash	Depends on cement and aggregate composition
Carbon reduction reported in earlier LCA work	—	Approximately 30%	Favourable to recycled concrete
Carbon reduction with full replacement by high-quality RCA	—	Nearly 50%	Strongly dependent on source and mix design

Recent work that explicitly accounts for carbon uptake during production found that the net GHG emissions of recycled concrete are lower than those of virgin concrete, with higher RCA replacement rates yielding further reductions; carbonation during the production phase contributes significantly to carbon capture, and recycled concrete requires less green area for carbon absorption (Huang et al., 2025). Studies of reclaimed asphalt further show substantial decreases in energy use and GHG emissions at RAP contents of up to 50%, and recycled concrete pavements reduce the environmental burdens of pavement construction relative to conventional materials (Bamigboye et al., 2020). One counterexample deserves note: a Colombian case study found that using warm-mix asphalt with RCA as a replacement for coarse natural aggregate deteriorated the environmental profile of the pavement structure (Vega-Araujo et al., 2020). This result is framework-dependent, arising from SimaPro modelling with the TRACI impact-assessment method, and illustrates that LCA outcomes can vary with the functional unit, allocation rules, transport distances, energy sources, and local conditions. The balance of evidence, however, supports RCA as a means of minimizing health-hazard effects, waste generation, and landfill pressure relative to conventional construction (Fanijo et al., 2023).

The environmental advantage of RCA is thus primarily associated with avoided extraction and disposal. Replacing virgin aggregate reduces demand for quarrying, while processing construction and demolition waste can reduce the volume of material sent to landfill. Nevertheless, recycling is not impact-free. Crushing, screening, washing, stockpiling, and transporting RCA consume energy and may generate dust and additional emissions. The environmental benefit is therefore greatest when RCA is processed efficiently, used near its source, and incorporated into mixtures that do not require disproportionately higher cement contents. LCA comparisons should also distinguish between aggregate-level benefits and whole-pavement outcomes, since a lower-impact aggregate may not produce a lower-impact pavement if its use increases binder demand, haulage distances, or maintenance requirements.

3.5 Discussion of Overall Findings

The results taken together reveal a recurring trade-off between performance and sustainability. At high replacement levels, RAC may exhibit mechanical reductions of roughly 14–32% in compressive strength and 25–40% in elastic modulus (Kakizaki et al., 2023). These reductions, however, are offset by documented environmental gains of approximately 30–50% in carbon terms (Pavlů et al., 2025; Zhang et al., 2022) and by reductions approaching one-half across several life-cycle impact categories (Pavlů et al., 2019). The evidence therefore does not support a simple comparison in which RCA is judged solely by its performance relative to natural aggregate. Rather, its suitability depends on whether the material is matched to an appropriate application, processed to a consistent quality, and incorporated into a mixture designed to compensate for its inherent variability.

Engineering practice resolves this tension through three complementary strategies. First, blend optimization is used to limit the performance penalty associated with high RCA contents. A replacement level of approximately 50% repeatedly emerges as a practical ratio for balancing stiffness, permanent deformation, and bearing capacity (Toka & Olgun, 2021). Second, high-packing-density mix design can reduce voids and improve particle interlock, thereby permitting the use of 100% recycled aggregate while maintaining the required strength and durability (Yehia et al., 2015). Third, RCA can be assigned according to the demands of each pavement layer. Unbound granular layers generally tolerate RCA more readily than applications requiring high structural strength or stringent durability performance (Aytekin & Mardani, 2021). This layer-specific approach allows the environmental benefits of recycling to be obtained without requiring identical RCA contents throughout an entire pavement structure.

Table 6. Summary of Key Findings and Practical Implications for RCA Use

Finding	**Evidence from the reviewed literature**	**Practical implication**
Mechanical performance	Compressive strength may decrease by approximately 14–32%, while elastic modulus may decrease by 25–40% at high replacement levels (Kakizaki et al., 2023)	High RCA contents require mix optimization and performance verification
Optimum blending	A replacement ratio near 50% repeatedly balances stiffness, deformation resistance, and bearing capacity (Toka & Olgun, 2021)	Partial replacement may provide the most reliable compromise for general applications
High RCA replacement	High-packing-density design can permit 100% recycled aggregate use while satisfying strength and durability requirements (Yehia et al., 2015)	Full replacement is feasible when material quality and mixture design are carefully controlled
Layer suitability	Unbound granular layers generally accommodate RCA more readily than more demanding structural applications (Aytekin & Mardani, 2021)	RCA content should be selected according to the function of each pavement layer
Environmental performance	Carbon reductions of approximately 30–50% and near-halving of several life-cycle indicators have been reported (Pavlů et al., 2019, 2025; Zhang et al., 2022)	Environmental performance should be included alongside mechanical criteria in material selection
Principal limitation	RCA properties depend on crushing method, adhered-paste content, and source-concrete quality (Fanijo et al., 2023)	Standardized testing, source characterization, and quality control are essential

The principal barrier to wider adoption is therefore not technical feasibility but variability. Recycled aggregate is not a uniform material: its performance depends on the original concrete, the presence and condition of adhered mortar or paste, contaminant content, particle grading, crushing method, and storage conditions (Fanijo et al., 2023). These factors influence water absorption, density, stiffness, strength development, and durability. Consequently, a single universal replacement ratio cannot be expected to provide the same results in all regions or pavement systems. Unified standards should establish minimum quality requirements, but project-specific testing remains necessary to confirm that the available RCA satisfies the intended application.

The findings also indicate that RCA should be evaluated as part of a complete pavement system rather than as an isolated aggregate product. A material may have a lower production-stage impact but produce limited whole-life benefits if it requires additional cement, longer transport, more intensive processing, or more frequent maintenance. Conversely, RCA sourced close to a project and used in a layer suited to its properties may provide simultaneous reductions in raw-material extraction, landfill demand, and construction-related emissions. The most effective implementation strategy is therefore one that integrates material quality, structural design, logistics, environmental assessment, and anticipated service life.

IV. Conclusion

Before turning to the specific findings, the overall picture can be stated plainly. This review set out to establish whether recycled concrete aggregate can substitute for natural aggregate in transport infrastructure. Across the technical, economic, and environmental dimensions examined, the evidence converges on a positive answer: RCA is a feasible, competitive, and beneficial alternative, provided its use is managed through appropriate processing, mix design, and quality control (Elmasri et al., 2025; Fanijo et al., 2023). Its adoption should not be understood as a universal one-for-one replacement strategy. Instead, RCA is most effective when its content and application are selected according to source quality, pavement-layer requirements, transport conditions, and the environmental objectives of the project.

Table 7. Overall Assessment of Recycled Concrete Aggregate for Transport Infrastructu

Assessment dimension	**Overall finding**	**Conditions for successful application**
Technical feasibility	RCA can provide adequate strength, stiffness, bearing capacity, and freeze–thaw performance for several pavement applications	Use source characterization, optimized blends, and standardized quality-control testing
Economic feasibility	RCA can reduce production and disposal-related costs compared with natural aggregate (Ohemeng & Ekolu, 2020; Tam, 2008)	Maintain a reliable feedstock supply and minimize transport distances

Environmental performance	RCA generally reduces resource extraction, landfill pressure, and life-cycle emissions (Pavlů et al., 2019, 2025; Zhang et al., 2022)	Process and use the material efficiently, preferably near its source
Structural application	RCA is particularly suitable for unbound subbase and other granular layers (Ayan, 2011; Aytekin & Mardani, 2021)	Match RCA quality and replacement level to the demands of the pavement layer
Risk management	Performance and environmental outcomes vary among sources and assessment frameworks (Fanijo et al., 2023; Vega-Araujo et al., 2020)	Use project-specific testing, transparent LCA assumptions, and long-term monitoring

Use project-specific testing, transparent LCA assumptions, and long-term monitoring

4.1 Technical Findings

Technically, the results confirm that RCA introduces measurable reductions in mechanical performance relative to natural aggregate. At high replacement levels, compressive strengths are roughly 14–32% lower and elastic moduli are 25–40% lower than those of comparable natural-aggregate mixtures (Kakizaki et al., 2023). These differences are primarily associated with the lower density and higher porosity of recycled particles and with the presence of adhered mortar or paste. Nevertheless, the reductions are not prohibitive for transport infrastructure. The literature consistently demonstrates that the losses can be reduced or offset through blend optimization, appropriate compaction, and mixture designs that improve particle packing.

A replacement ratio of about 50% repeatedly emerges as a preferred balance between stiffness, permanent deformation, and bearing capacity (Toka & Olgun, 2021). This proportion can limit the adverse effects of weaker or more porous particles while retaining a substantial share of the environmental benefits of recycling. At the same time, high-packing-density mix design can permit the use of 100% recycled aggregate while still satisfying strength and durability requirements (Yehia et al., 2015). These findings indicate that replacement percentage should be treated as a design variable rather than a fixed limitation.

In pavement applications specifically, RCA delivers ultimate bearing capacities of 186–480 kPa, comparable to natural aggregates (Zargar et al., 2024). It also maintains adequate stiffness through 1–20 freeze–thaw cycles (Akbaş et al., 2023), and a 50% reclaimed-asphalt-pavement blend has been demonstrated to be suitable for unbound subbase application (Ayan, 2011). The following summary highlights the relationship between material content and application suitability.

Table 8. Technical Performance and Application Suitability of RCA in Pavement Applications

Technical application or property	Reported result	Interpretation
Compressive strength at high RCA contents	Approximately 14–32% lower than natural-aggregate concrete (Kakizaki et al., 2023)	The reduction is measurable but can be managed through mixture design
Elastic modulus at high RCA contents	Approximately 25–40% lower (Kakizaki et al., 2023)	Stiffness-sensitive applications require verification and possible blend adjustment
Preferred general replacement level	Approximately 50% RCA (Toka & Olgun, 2021)	Provides a practical balance among stiffness, deformation, and bearing performance
Full recycled-aggregate replacement	Feasible with high-packing-density mix design (Yehia et al., 2015)	Requires high-quality input material and rigorous quality control
Ultimate bearing capacity	186–480 kPa (Zargar et al., 2024)	Indicates suitability for several pavement subbase applications
Freeze–thaw performance	Adequate stiffness maintained through 1–20 cycles (Akbaş et al., 2023)	Supports use in climates where freeze–thaw resistance is required
RAP/RCA granular blend	50% blend suitable for unbound subbase (Ayan, 2011)	Demonstrates the potential for combining recycled material streams

Demonstrates the potential for combining recycled material streams

The principal technical constraint is variability. Because RCA properties depend on crushing method, adhered-mortar content, and source-concrete quality, quality control and standardized testing are indispensable (Kim, 2021). Testing should address grading, density, water absorption, contaminant content, compaction behavior, bearing capacity, and durability under the environmental conditions expected at the project site. Long-term monitoring is also needed because laboratory performance does not always capture the effects of seasonal moisture changes, traffic loading, freeze–thaw exposure, and construction variability.

4.2 Economic Findings

Economically, RCA production compares favourably with natural aggregate production in many settings. Case studies report long-term production costs roughly 40% lower per tonne for coarse recycled aggregate than for natural aggregate, together with substantially higher environmental benefits per tonne (Ohemeng & Ekolu, 2020). Recycling operations have also been shown to deliver positive net benefits where conventional disposal is costly (Tam, 2008). These findings suggest that RCA can create value through two simultaneous mechanisms: it can replace purchased virgin aggregate, and it can reduce the costs associated with transporting and disposing of construction and demolition waste.

The economic advantage becomes stronger when landfill taxes and disposal charges are internalized. Reported landfill taxes range from approximately €3 per tonne in Italy to €63 per tonne in Denmark (Linares et al., 2024). Such charges alter the relative attractiveness of recycling by making disposal less competitive and by assigning a monetary value to the avoidance of landfill use. However, the economic outcome remains highly location-specific. Plant economics depend on a reliable supply of feed material, suitable processing infrastructure, local demand, and the quality of the recovered aggregate.

Table 9. Economic Factors Affecting RCA Competitiveness

Economic factor	**Effect on RCA competitiveness**	**Boundary condition**
Production cost	Coarse RCA has been reported to cost roughly 40% less per tonne than natural aggregate in some case studies (Ohemeng & Ekolu, 2020)	Results depend on plant scale, feedstock quality, and processing requirements
Disposal avoidance	Recycling can produce positive net benefits when conventional disposal is expensive (Tam, 2008)	Benefits increase with landfill charges and limited disposal capacity
Landfill taxation	Reported taxes range from approximately €3/t in Italy to €63/t in Denmark (Linares et al., 2024)	The effect depends on local regulations and whether disposal costs are fully internalized
Transport distance	Short haulage distances improve RCA competitiveness	Long-distance transport can offset production and environmental advantages
Feedstock supply	A stable stream of suitable demolition material supports continuous operation	Irregular or contaminated feedstock increases sorting and processing costs
Market demand	Nearby pavement and construction projects create a dependable outlet for RCA	Limited demand may increase stockpiling and handling costs

Limited demand may increase stockpiling and handling costs

At equal delivery distances, conventional concrete can remain competitive unless recycled aggregate enjoys a haulage advantage (Frondistou-Yannas & Itoh, 1977). This finding is particularly important because the economic and environmental performance of RCA is often strongest when it is used near the demolition site or processing plant. A regional supply-chain strategy—linking demolition, processing, and pavement construction within a relatively short transport radius—can therefore be more important than the nominal price of the aggregate at the plant gate.

4.3 Environmental Findings

Environmentally, the case for RCA is strongest, although it is not unconditional. Life-cycle assessments show that recycled aggregate concrete can roughly halve the environmental impact of natural-aggregate concrete across key indicators, including global warming, acidification, and eutrophication potentials (Pavlů et al., 2019). Carbon-oriented studies report emission reductions on the order of 30% (Zhang et al., 2022) and up to nearly 50% when high-quality recycled aggregate fully replaces natural aggregate (Pavlů et al., 2025). Further gains may be obtained when carbon uptake during the production phase is credited (Huang et al., 2025).

Concrete made with natural aggregates emits approximately 323–332 kg CO_2e per cubic metre, whereas mixes containing 100% recycled aggregates and 25% fly ash achieve lower emissions than natural-aggregate concrete (Sabău et al., 2021). These results emphasize that the environmental performance of RCA depends not only on aggregate replacement but also on cement content and supplementary cementitious materials. The aggregate-level benefit can be weakened if the use of RCA requires a disproportionate increase in binder content.

Table 10. Environmental Considerations and Sustainability Implications

Environmental consideration	**Finding**	**Significance**
Resource conservation	RCA reduces demand for newly quarried aggregate	Helps conserve primary mineral resources
Landfill diversion	Processing construction and demolition waste reduces disposal volumes	Relieves landfill pressure and extends disposal capacity
Global warming impact	Recycled aggregate concrete can produce reductions of approximately 30–50% in reported studies (Pavlů et al., 2025; Zhang et al., 2022)	Supports lower-carbon construction when system conditions are favourable
Multiple life-cycle indicators	Several indicators are approximately halved relative to natural aggregate (Pavlů et al., 2019)	Benefits extend beyond carbon emissions
Carbon uptake	Carbonation during production can contribute to carbon capture (Huang et al., 2025)	Net emissions may be lower when uptake is included in the assessment
Cement content	Environmental benefits depend on avoiding disproportionately higher cement demand (Sabău et al., 2021)	Mixture design must be optimized at the whole-concrete level
Processing and transport	Crushing, screening, washing, stockpiling, and haulage consume energy and generate emissions	Local sourcing and efficient processing are essential

Local sourcing and efficient processing are essential

Beyond emissions, the use of RCA conserves primary resources, reduces pressure on landfills, and supports the transition to circular-economy principles in construction. Nevertheless, recycling is not impact-free. Crushing, screening, washing, stockpiling, and transporting RCA consume energy and may generate dust and additional emissions. The environmental benefit is therefore greatest when RCA is processed efficiently, used near its source, and incorporated into mixtures that do not require disproportionately higher cement contents.

Environmental comparisons must also distinguish between aggregate-level benefits and whole-pavement outcomes. A lower-impact aggregate may not produce a lower-impact pavement if its use increases binder demand, haulage distances, construction energy, or maintenance requirements. In addition, life-cycle outcomes are framework-dependent. The Colombian case study demonstrates that using RCA as a replacement for coarse natural aggregate in warm-mix asphalt can worsen the environmental profile of a pavement structure under particular modelling assumptions (Vega-Araujo et al., 2020). This counterexample does not negate the broader environmental advantages reported for RCA; instead, it shows that the functional unit, allocation rules, transport distances, energy sources, maintenance assumptions, and local conditions must be stated clearly.

4.4 Barriers to Wider Adoption

Wider adoption nonetheless faces three principal barriers. First, mechanical variability across sources and processing routes must be managed through unified standards and specifications, which currently vary widely across jurisdictions (Aytekin & Mardani, 2021). Standards should define minimum requirements for grading, density, absorption, contaminant content, durability, and mechanical performance while allowing testing procedures to reflect the intended application.

Second, long-term field-performance data remain scarce relative to laboratory evidence. Full-scale trials are still recommended before deployment, particularly for heavily trafficked pavements, regions exposed to severe freeze–thaw conditions, and projects using high RCA replacement levels. Field data should document construction quality, moisture response, rutting, bearing capacity, cracking, maintenance requirements, and end-of-life recovery potential.

Third, environmental comparisons are framework-dependent. As the Colombian case study demonstrates, replacing natural aggregate with RCA can worsen—rather than improve—the environmental profile of a pavement structure when assessed under particular life-cycle assumptions (Vega-Araujo et al., 2020). This issue reinforces the need for transparent and consistent LCA procedures. Assessments should report the functional unit, system boundary, allocation method, transport distance, electricity mix, cement content, maintenance schedule, and assumptions concerning carbon uptake.

Table 11. Barriers to Wider Adoption of RCA and Recommended Responses

Barrier	**Consequence**	**Recommended response**
Variability in source and processing quality	Results from one RCA source may not apply to another (Fanijo et al., 2023)	Require source characterization and batch-level quality control
Inconsistent standards	Different jurisdictions may impose different acceptance criteria (Aytekin & Mardani, 2021)	Harmonize specifications and testing procedures
Limited long-term field evidence	Laboratory results may not predict full-service pavement behavior	Conduct monitored full-scale trials and long-term performance studies
Transport dependence	Long haulage distances can reduce economic and environmental advantages (Frondistou-Yannas & Itoh, 1977)	Prioritize regional processing and local use
Increased binder demand	Aggregate-level benefits may be offset at the concrete or pavement-system level (Sabău et al., 2021)	Optimize the complete mixture rather than the aggregate fraction alone
LCA framework dependence	Results can change with assumptions and impact-assessment methods (Vega-Araujo et al., 2020)	Report assumptions transparently and use consistent system boundaries
Market and supply uncertainty	Irregular demolition flows may increase stockpiling and operating costs	Develop stable regional recycling networks and procurement policies

4.5 Final Remarks

In summary, recycled concrete aggregate constitutes a technically serviceable, economically competitive, and environmentally advantageous substitute for natural aggregate in transport infrastructure. With controlled processing, blend design, and quality assurance, RCA can deliver pavement-layer performance comparable to virgin-aggregate systems while generating substantial sustainability gains. Its suitability, however, is not universal or independent of context. Performance depends on the quality and composition of the source concrete, the processing route, the intended pavement layer, the replacement ratio, moisture conditions, traffic loading, and the quality of construction and compaction. RCA should therefore be treated as an engineered construction material whose properties must be verified for each application rather than as a uniform commodity.

The evidence reviewed indicates that RCA is particularly promising for unbound subbase and subgrade-related applications, although appropriately processed material can also be incorporated into bound mixtures and higher-performance pavement systems. Successful implementation requires source characterization, control of grading and contamination, management of absorption and moisture sensitivity, and mixture designs that account for the material's residual mortar and variable density. Economic and environmental benefits are likewise greatest when demolition, processing, transport, batching, placement, and future recovery are considered as an integrated system. Excessive haulage distances, inefficient processing, increased cement or binder demand, and premature maintenance can reduce or even reverse the anticipated benefits.

Accordingly, the wider adoption of RCA should proceed through a risk-based and application-specific framework. Specifications should establish clear minimum requirements while permitting technically justified adjustments for local materials and climatic conditions. Demonstration projects and monitored full-scale trials are needed to supplement laboratory findings, particularly for heavily trafficked pavements, severe freeze–thaw environments, and high replacement levels. Performance monitoring should include construction quality, moisture response, deformation, cracking, bearing capacity, maintenance needs, and end-of-life recovery.

Future research should therefore prioritize the harmonization of standards, the generation of long-term field performance data, and the refinement of life-cycle assessment frameworks to fully realize RCA's potential. Further work should also address reliable methods for predicting source variability, optimizing processing energy, integrating carbon uptake into environmental assessments, and evaluating the economic effects of regional supply networks. Taken together, these measures can support more consistent procurement decisions and reduce uncertainty for designers, contractors, regulators, and infrastructure owners. RCA is unlikely to replace natural aggregate in every application, but under properly defined technical, economic, and environmental conditions, it can become a dependable component of more resource-efficient and circular transport infrastructure.

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