Vol. 7, No. 1, 2026, pp. 475-489
DOI: https://doi.org/10.29210/991870

Contents lists available at Elora Center

Lentera Negeri

Journal homepage: https://lentera.eloracenter.org/lentera

Exploring the mechanical performance and durability of recycled concrete for modern civil structures: a literature review

Suharwanto Suharwanto*)
Universitas Wiralodra, Indramayu, Indonesia

Article Info

Article history:

Received May 12th, 2026
Revised Jun 20th, 2026
Accepted Jun 25th, 2026

Keywords:

Recycled aggregate concrete
Mechanical performance
Durability
Sustainable construction
Civil engineering

ABSTRACT

This study investigates the mechanical performance and durability of recycled aggregate concrete (RAC) as an alternative material for modern civil structures. Using a systematic literature review of recent empirical and conceptual studies, the research evaluates how recycled concrete aggregates (RCA) influence compressive, tensile, and flexural strengths, elastic modulus, porosity, and long-term durability under diverse environmental conditions. The findings confirm that although RAC typically demonstrates lower compressive strength, tensile resistance, and stiffness compared to natural aggregate concrete (NAC), these limitations are not intrinsic. They can be effectively mitigated through controlled RCA processing, pre-saturation treatments, supplementary cementitious materials, and fiber reinforcement. Regarding durability, RAC generally exhibits higher water absorption, permeability, and susceptibility to chloride ingress, carbonation, and freeze–thaw damage. Nevertheless, optimized mix designs and appropriate curing regimes can significantly improve its performance, making it suitable for structural applications at low to moderate RCA replacement ratios. Long-term challenges such as creep, shrinkage, fatigue, and fire resistance remain more pronounced in RAC but can be addressed with advanced mix engineering and conservative design practices. This review concludes that RAC is not merely a substitute for NAC but a sustainable material with distinct performance characteristics that require tailored strategies. By integrating technical innovations with quality control and policy support, RAC can contribute to sustainable infrastructure development while maintaining safety and reliability.

Corresponding Author:
Suharwanto Suharwanto,
suharwanto.ft@unwir.ac.id

Introduction

The rapid growth of the construction industry has significantly increased the demand for concrete, which remains the most widely used construction material worldwide. However, this increasing demand has intensified the consumption of natural aggregates and generated large volumes of construction and demolition waste (CDW), creating substantial environmental challenges. The disposal of CDW in landfills requires extensive land resources and contributes to environmental degradation and carbon emissions (OBE et al., 2019). Consequently, the construction sector is increasingly seeking sustainable alternatives that can reduce dependence on virgin materials while supporting effective waste management practices.

Recycled aggregate concrete (RAC), produced by incorporating recycled concrete aggregates (RCA) derived from demolished concrete structures, has emerged as one of the most promising approaches to addressing these challenges. By transforming construction waste into valuable construction materials, RAC supports circular economy principles and promotes more sustainable resource utilization within the construction industry (Li et al., 2022). In addition to its environmental advantages, RAC has attracted growing attention from researchers and practitioners due to its potential application in structural and non-structural civil engineering projects.

Recent studies have demonstrated that RAC can achieve satisfactory engineering performance when appropriate aggregate processing techniques, mix-design strategies, and curing methods are employed (Gholampour & Ozbakkaloglu, 2017; Silva et al., 2018). Several studies have reported measurable sustainability benefits associated with recycled concrete. Life-cycle assessment studies indicate that the use of recycled concrete aggregates can substantially reduce natural aggregate consumption and decrease the amount of construction waste sent to landfills, depending on replacement ratios and local recycling infrastructure (Li et al., 2022; Singh et al., 2023). Furthermore, transportation savings and reduced extraction of virgin aggregates may contribute to lower environmental impacts and improved resource efficiency compared with conventional concrete production.

Despite these advantages, the widespread adoption of RAC remains constrained by concerns regarding its mechanical performance and long-term durability. The characteristics of RCA, particularly the presence of adhered mortar, higher porosity, and variable aggregate quality, can influence the structural behavior of recycled concrete. These factors may affect compressive strength, tensile strength, elastic modulus, permeability, chloride penetration resistance, carbonation resistance, and other durability-related properties that are critical for structural applications (Colman et al., 2021; Guo et al., 2018). As a result, engineers and decision-makers often remain cautious when considering RAC for critical infrastructure such as bridges, high-rise buildings, and transportation facilities.

In addition to technical concerns, practical implementation challenges continue to hinder broader acceptance of recycled concrete. Variations in RCA quality, differences in processing methods, limited standardization, and uncertainty regarding long-term field performance contribute to stakeholder hesitation in adopting RAC on a larger scale (Thomas et al., 2013). Consequently, understanding the factors that govern the performance of recycled concrete is essential for supporting evidence-based implementation in modern civil engineering practice.

Over the last several years, research on recycled concrete has expanded considerably. Recent investigations have examined the effects of RCA replacement ratios, aggregate treatment methods, supplementary cementitious materials (SCMs), and fiber reinforcement on the mechanical and durability performance of RAC (Colman et al., 2021; Ren et al., 2022; Singh et al., 2023; Sun et al., 2022; Zhang et al., 2023). These studies indicate that the performance limitations traditionally associated with RAC can often be mitigated through appropriate material selection and mix optimization strategies. Furthermore, increasing attention has been directed toward long-term durability issues, including chloride ingress, carbonation, freeze–thaw resistance, fatigue behavior, and service-life performance under aggressive environmental conditions.

Nevertheless, the existing literature remains fragmented. Many studies focus on specific aspects of RAC performance, such as compressive strength, durability indicators, environmental benefits, or individual treatment techniques, without providing an integrated evaluation of the relationships among mechanical properties, durability performance, long-term behavior, and practical implementation challenges. Moreover, findings reported in the literature often vary considerably due to differences in aggregate source quality, replacement levels, treatment procedures, curing regimes, and environmental exposure conditions. As a result, a comprehensive synthesis of recent evidence is required to clarify the current state of knowledge and identify the factors that most significantly influence RAC performance in civil engineering applications.

Based on the identified research gap, this review addresses the following research questions: (1) How do recycled concrete aggregates influence the mechanical properties of recycled aggregate concrete compared with conventional concrete? (2) How does RAC perform in terms of durability under various environmental exposure conditions? and (3) What factors most significantly affect the long-term performance and practical implementation of RAC in modern civil structures?

Unlike previous reviews that primarily focused on isolated performance indicators, this study integrates evidence on mechanical properties, durability characteristics, long-term service behavior, and implementation challenges within a single analytical framework.

Therefore, this study employs a systematic literature review approach to critically evaluate the mechanical performance and durability characteristics of recycled aggregate concrete for modern civil structures. A systematic literature review was selected to enable the identification, evaluation, and synthesis of evidence from recent studies in a structured and transparent manner. Specifically, this study aims to: (1) synthesize recent empirical findings concerning the influence of recycled concrete aggregates on compressive strength, tensile strength, flexural strength, and elastic modulus; (2) evaluate the durability performance of RAC in terms of water absorption, permeability, chloride penetration, carbonation resistance, freeze–thaw resistance, and long-term service behavior; and (3) identify the key factors affecting RAC performance, including aggregate quality, replacement ratio, treatment methods, curing conditions, and mix-design strategies. By integrating findings from recent studies, this review seeks to provide a comprehensive understanding of the opportunities and limitations of recycled concrete and to support the development of more sustainable and reliable civil infrastructure systems.

Method

This study employed a qualitative literature review approach to identify, evaluate, and synthesize existing research concerning the mechanical performance and durability of recycled aggregate concrete (RAC) in modern civil structures. A literature review was selected because it enables a comprehensive examination of both conceptual and empirical developments while facilitating the identification of prevailing research trends, knowledge gaps, and future research opportunities (Snyder, 2019). The review was conducted through a structured process of literature searching, screening, classification, and thematic synthesis to enhance transparency and consistency in the selection and interpretation of relevant studies.

Data Sources

The literature reviewed in this study was obtained from several reputable academic databases, including Google Scholar, Scopus, ScienceDirect, and SpringerLink. These databases were selected because they provide extensive coverage of peer-reviewed research in civil engineering, construction materials, and sustainability studies. The review focused primarily on publications addressing recycled aggregate concrete, recycled concrete aggregates, mechanical performance, durability characteristics, and structural applications.

To ensure the relevance and currency of the reviewed literature, priority was given to studies published within the last ten years. However, earlier seminal studies were also considered when they provided important theoretical foundations or were frequently cited in subsequent research. This approach ensured a balanced synthesis between foundational knowledge and recent developments in the field.

Data Collection Techniques

The literature search was conducted using combinations of keywords related to the research topic, including "recycled concrete," "recycled aggregate concrete," "recycled concrete aggregate," "mechanical performance," "compressive strength," "durability," and "civil structures." The identification process involved searching relevant publications within the selected databases and reviewing references from highly relevant studies to identify additional sources.

The selection process was conducted in several stages. First, titles and abstracts were screened to determine their relevance to the objectives of the study. Second, full-text articles were reviewed to evaluate their suitability for inclusion. Studies were included when they specifically discussed the mechanical properties, durability performance, long-term behavior, or practical implementation of recycled concrete in civil engineering applications. Publications with limited relevance to recycled concrete performance or lacking sufficient methodological and analytical information were excluded from further analysis.

The selected literature was subsequently classified into thematic categories according to the primary topics investigated. These categories included compressive strength, tensile and flexural performance, elastic modulus, water absorption, permeability, chloride penetration, carbonation resistance, freeze–thaw performance, long-term behavior, and factors influencing recycled concrete performance. Such classification facilitated a systematic comparison of findings across different studies and research contexts (Tranfield et al., 2003).

Data Analysis Method

The collected literature was analyzed using qualitative content analysis. This analytical approach focused on identifying, comparing, and synthesizing findings from previous studies to develop a comprehensive understanding of the mechanical performance and durability characteristics of recycled aggregate concrete. The analysis involved examining similarities, differences, recurring patterns, and emerging trends reported across the selected studies.

The thematic synthesis process was conducted by grouping research findings according to the predefined categories and evaluating how different factors, such as aggregate quality, replacement ratio, treatment methods, curing conditions, and environmental exposure, influenced the performance of recycled concrete. Particular attention was given to areas where findings were consistent as well as instances where contradictory results were reported. In cases of conflicting findings, interpretation was based on the methodological context, experimental conditions, and scope of the respective studies.

The synthesized evidence was subsequently used to identify current research trends, evaluate the opportunities and limitations of recycled concrete, and formulate conclusions regarding its suitability for modern civil structures. Through this approach, the study provides a structured and comprehensive assessment of recycled concrete while highlighting directions for future research and practical implementation (Bowen, 2009).

Results and Discussions

Mechanical Properties of Recycled Concrete

Recycled concrete's mechanical performance is strongly conditioned by the properties of the recycled concrete aggregate (RCA) used in the mix, making RCA quality a critical factor in determining structural performance. Studies consistently report that the compressive strength of recycled aggregate concrete (RAC) decreases as the replacement ratio of recycled concrete aggregate increases, although the magnitude of reduction varies considerably across studies. Recent investigations indicate that low-to-moderate RCA replacement levels (20–50%) generally result in compressive strength reductions of approximately 5–15% compared with natural aggregate concrete (NAC), whereas replacement ratios exceeding 75% may produce reductions greater than 20%, depending on aggregate quality and mix composition (Bai et al., 2020; Ren et al., 2022; Zhang et al., 2023). Nevertheless, several studies report that the incorporation of supplementary cementitious materials (SCMs), such as silica fume, fly ash, or ground granulated blast-furnace slag, can substantially recover strength losses, enabling RAC mixtures with 30–50% RCA replacement to achieve performance comparable to conventional concrete. These findings suggest that compressive strength should be viewed not as an inherent limitation of RAC but as a parameter strongly influenced by aggregate processing, replacement ratio, and mix-design optimization.

Although increased porosity resulting from adhered mortar is widely recognized as a major factor contributing to strength reduction in RAC, alternative mechanisms have also been proposed in the literature. Some researchers argue that microcracks generated during the crushing and recycling process weaken the aggregate-paste bond and accelerate crack propagation under loading. Others emphasize the role of particle shape and grading characteristics, suggesting that irregular RCA particles may reduce packing density and increase stress concentrations within the concrete matrix. In addition, conflicting findings have been reported regarding the effectiveness of RCA pre-saturation. While several studies indicate that pre-saturation improves interfacial bonding and hydration by reducing water absorption during mixing, other investigations report only limited improvements, particularly when high-quality RCA or low water-to-binder ratios are used. These findings suggest that the mechanical performance of RAC is influenced by multiple interacting factors rather than by adhered mortar content alone (Tam et al., 2018; Ren et al., 2022; Zhang et al., 2023).

The chart on Figure 1 indicates that reductions in mechanical performance become progressively more pronounced as RCA content increases. At replacement levels below 30%, reductions in compressive strength and elastic modulus are generally limited and remain within ranges considered acceptable for many structural applications. However, replacement levels exceeding 50% are frequently associated with noticeable reductions in strength and stiffness, reflecting the increasing influence of adhered mortar, porosity, and weaker interfacial transition zones. The observed trend suggests that partial RCA replacement provides a practical balance between sustainability objectives and structural performance requirements.

Tensile and flexural strengths of recycled concrete generally follow trends similar to compressive strength but are often more sensitive to microstructural defects and interfacial transition zone quality (Ren et al., 2022). Several investigations have documented modest reductions in splitting tensile strength and flexural capacity as RCA content increases, with the reductions being more pronounced under flexural loading where crack propagation across multiple ITZs governs failure (Kisku et al., 2017; Xiao et al., 2005). However, researchers have shown that the use of fiber reinforcement, optimized aggregate gradation, and SCMs such as silica fume or fly ash can mitigate losses in tensile and flexural performance, improving toughness and post-crack behavior to levels suitable for many structural elements. Consequently, where tensile or flexural demands are critical—such as in slender beams or slabs—designers should consider either hybrid mixes (partial RCA replacement plus fibers/SCMs) or limit RCA to noncritical portions of the cross-section.

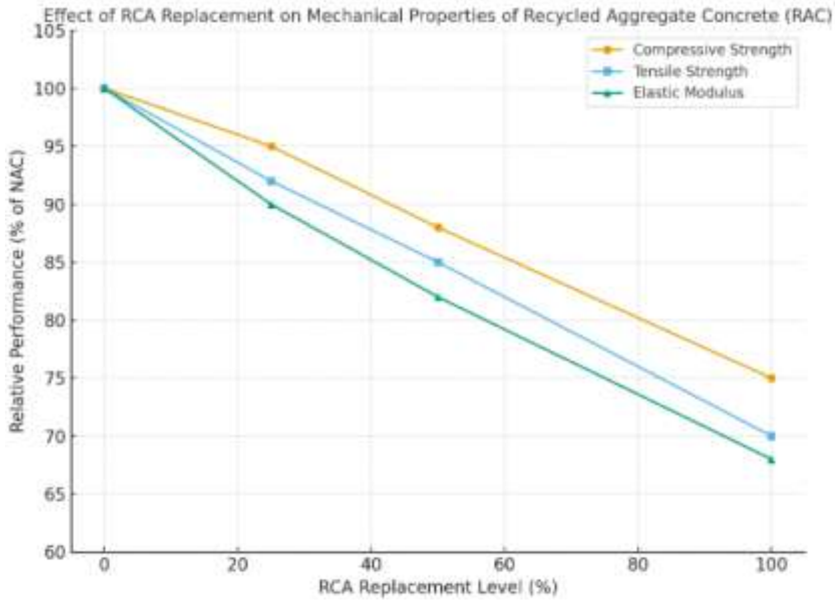

Figure 1 <Impact of RCA Replacement on Mechanical Properties of Concrete>

The elastic modulus and density of recycled concrete are typically lower than those of conventional concrete, reflecting the higher porosity and lower stiffness of RCA compared with natural aggregates (Guo et al., 2018). A reduced modulus has practical implications: deflections, dynamic response, and stress redistribution in structural systems may be affected when RAC is used extensively, so serviceability checks and stiffness-based design criteria must be explicitly evaluated (Thomas et al., 2013). That said, the observed reductions in modulus are often moderate and can be partially compensated by mix design adjustments—such as lowering water-to-cement ratio, using denser SCM blends, or employing better crushed RCA with bonded mortar partially removed—which improve particle packing and stiffen the matrix. Density reductions are usually small in absolute terms but do influence unit weight calculations and may offer advantages in lightweight applications where lower mass is beneficial.

Replacement ratio and aggregate quality emerge as the dominant factors controlling mechanical behavior across studies: low to moderate replacement ratios (commonly cited limits range from 20% to 50% for coarse RCA, depending on desired performance) often yield acceptable mechanical properties without extensive corrective measures, while high replacement ratios exacerbate weaknesses unless accompanied by aggressive RCA treatment and high-performance binders (Bai et al., 2020; Gomes & De Brito, 2009). Aggregate quality variables—such as the strength of the parent concrete, the amount of adhered mortar, particle shape, and contaminant content—explain much of the variability in reported results; for instance, RCA derived from high-quality parent concrete and subject to secondary crushing produces significantly better RAC performance than RCA from low-grade demolition waste. Therefore, effective specification of RCA (including source control, grading, and acceptance criteria) is as crucial as proportioning the mix itself.

Concrete processing and treatment methods influence mechanical outcomes as well. Pre-washing or mechanical abrasion to remove loosely adhered mortar, thermal or chemical treatments to alter surface properties, and pre-saturation to compensate for high RCA absorption are all reported as viable strategies to reduce negative impacts on strength and stiffness (Tam et al., 2018; Xiao et al., 2005). Additionally, the strategic use of SCMs (fly ash, slag, silica fume) and nanoscale additives can densify the new cement matrix and refine pore structure, thereby improving bond at the ITZ and recovering much of the lost mechanical capacity (Kou & Poon, 2015).

From a practical engineering perspective, the acceptability of RAC should be evaluated against established structural performance requirements rather than solely against the performance of natural aggregate concrete. International design standards such as ACI 318, Eurocode 2, and the fib Model Code emphasize performance-based criteria related to strength, serviceability, and durability. The reviewed literature indicates that RAC containing low-to-moderate RCA replacement ratios can generally satisfy these requirements when appropriate quality control, aggregate treatment, and mix-design strategies are implemented. Therefore, the suitability of RAC should be assessed according to project-specific performance demands rather than replacement ratio alone.

A concrete real-world illustration comes from several European infrastructure projects and field trials summarized in recent reviews, where controlled use of RCA in pavements, sub-base layers, and even precast elements demonstrated satisfactory in-service performance when a protocol of source selection, processing, and mix optimization was applied. For example, studies compiled by Tam et al. (2018) report highway and municipal pavement applications in the Netherlands and Japan where RCA-containing mixes met performance targets for compressive strength, rutting resistance, and serviceability over monitored periods. These field cases reinforce laboratory evidence by showing that with appropriate quality control and design—especially conservative limits on coarse RCA replacement or the use of blended binders—RAC can be implemented successfully in modern civil structures.

In summary, the mechanical properties of recycled concrete are not categorically inferior but rather contingent upon RCA quality, replacement level, and mix/treatment strategies. By coupling judicious source control, proven RCA treatment methods, and modern binder technologies, engineers can design RAC with compressive, tensile, flexural, and stiffness properties suitable for many structural applications, while delivering environmental and resource-efficiency benefits.

Durability Performance of Recycled Concrete

Durability of recycled concrete (RC) is a multifaceted issue strongly linked to the physical characteristics of recycled concrete aggregates (RCA), particularly their higher porosity and adhered mortar, which typically increase water absorption and permeability compared with natural aggregates (Silva et al., 2014; Tam et al., 2018). Elevated water absorption in RCA leads to higher capillary porosity in the concrete matrix and a greater network of connected pores, which in turn accelerates ingress of deleterious agents such as chloride ions and carbon dioxide (Guo et al., 2018). Consequently, many laboratory studies report that RC exhibits higher sorptivity and chloride diffusion coefficients than natural aggregate concrete under comparable mix designs, although the magnitude of the effect depends on RCA source quality, replacement ratio, and pre-treatment methods such as pre-saturation or de-bonding of adhered mortar (Dimitriou et al., 2018). Importantly, mitigating strategies—such as lowering the water-to-binder ratio, using supplementary cementitious materials (SCMs) like fly ash or slag, and surface treatment of RCA—have been shown to substantially reduce permeability parameters and improve durability performance to levels approaching conventional concrete.

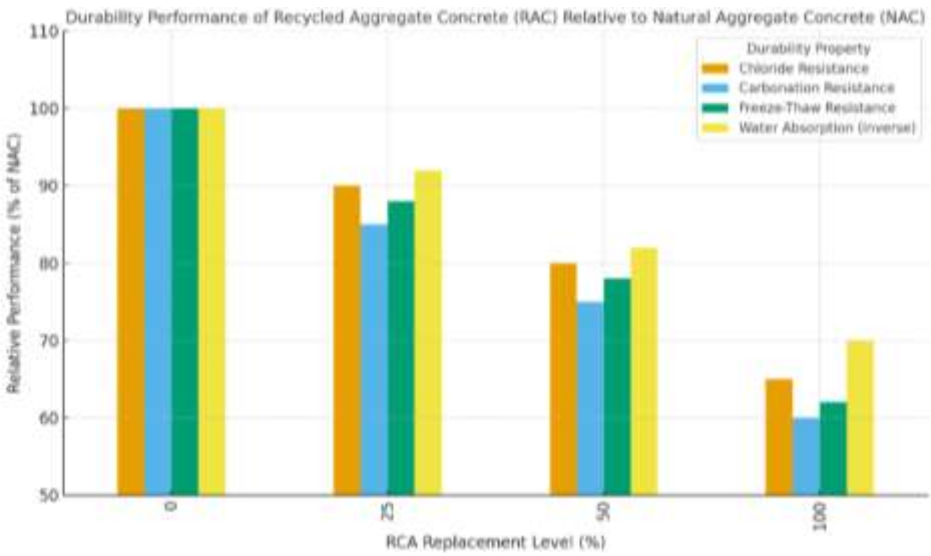

Figure 2 <Durability Performance of RAC vs NAC at Different RCA Levels>

The chart shows that recycled aggregate concrete maintains durability comparable to natural concrete at low replacement levels (≤30%), but durability drops sharply at higher ratios (>50%), emphasizing the need for optimized mix designs and treatments to ensure long-term performance.

Freeze–thaw durability of RC is similarly influenced by pore structure and moisture dynamics, with many studies indicating that RC can suffer greater freeze–thaw damage when RCA increases freezable water content and reduces microstructural resistance to cyclic freezing and thawing (Thomas et al., 2013). Experimental work shows that at moderate RCA replacement ratios and with proper air-entrainment or the use of SCMs, RC can meet freeze–thaw resistance requirements for exposed environments, but performance deteriorates at high replacement levels or when RCA contains weak, highly porous parent material (Evangelista & De Brito, 2014). Field validations and accelerated testing both emphasize the need for specif ic control of entrained air, tighter w/b ratios, and adequate curing when RC is intended for cold climates, since otherwise scaling, strength loss, and surface spalling may occur more rapidly than in natural aggregate concrete.

Chloride penetration and corrosion risk of reinforcement in RC are major practical concerns, because enhanced chloride diffusivity combined with higher permeability may shorten initiation time for steel corrosion in marine or de-icing salt environments (Gomes & De Brito, 2009). Review studies report that chloride diffusion coefficients for RC are commonly higher than for NAC, particularly when RCA replacement exceeds 50% and when RCA is sourced from low-strength parent concrete. Nevertheless, targeted mix designs—such as incorporation of pozzolanic SCMs that refine pore structure and bind chloride chemically, as well as the use of corrosion inhibitors or increased concrete cover—can substantially mitigate corrosion risk and extend service life in practice (OBE et al., 2019). Case studies on pavements and precast elements also demonstrate that with conservative design and rigorous quality control, RCA-containing elements have performed acceptably in chloride-exposed environments when protective measures are applied (Tam et al., 2018).

Carbonation depth and susceptibility to alkali-silica reaction (ASR) in RC are linked to microstructure and the presence of reactive components in the attached mortar of RCA, with several studies indicating increased carbonation rates in RC due to higher porosity and connectivity of pores. However, carbonation-induced corrosion risk depends on multiple factors—cover depth, pH buffering by cementitious phases, and environmental CO_2 exposure—and SCMs can both reduce permeability and alter carbonation kinetics, sometimes counteracting the increased carbonation susceptibility of RC. ASR risk in RC can be complicated by the presence of reactive silica in parent concrete or contaminants, but evidence suggests that careful source control of RCA and the use of low-alkali binders or supplementary materials can limit ASR expansion and associated durability damage (Sun et al., 2022).

A practical illustration comes from monitored field projects and full-scale trials where durability performance was tracked over years: several pavement and precast applications in Europe and Japan using controlled RCA fractions reported service performance comparable to conventional mixes when strict source selection, RCA processing, SCM incorporation, and conservative cover or design measures were enforced. Conversely, case reports on poorly specified RCA use—where demolition waste of mixed composition was crushed without adequate removal of contaminants or adhered mortar—show accelerated deterioration such as increased chloride ingress and surface scaling, underscoring that durability of RC is not an inherent property but an outcome of integrated supply-chain and mix-design practices. Overall, the literature supports a nuanced conclusion: recycled concrete can achieve satisfactory durability for many civil applications provided that RCA quality, replacement level, and mitigating design measures are carefully controlled and validated through both laboratory testing and field monitoring (Ozbakkaloglu et al., 2018).

Long-Term Behavior under Service Conditions

Long-term deformation (creep and shrinkage) in recycled aggregate concrete (RAC) is consistently reported to be higher than in conventional natural-aggregate concrete, primarily because recycled concrete aggregates (RCA) contain adhered mortar and have higher porosity that increases internal moisture movement and reduces stiffness (Silva et al., 2015). Experimental studies show that both autogenous and drying shrinkage tend to increase with higher RCA replacement ratios, and creep coefficients are often larger for RAC—effects that together can produce greater long-term deflections and time-dependent redistribution of stresses in structural members if not accounted for in design (Liu et al., 2024). However, the magnitude of additional deformation is sensitive to RCA pre-treatment, mix design (w/b ratio, use of SCMs), and curing regime; pre-saturation of RCA, removal or abrasion of adhered mortar, and incorporation of pozzolanic materials have been shown to reduce shrinkage strains and creep compliance substantially, bringing long-term deformation closer to that of conventional concrete. Several researchers have proposed modification factors or adjusted prediction models for creep and shrinkage of RAC to inform serviceability checks and long-term design (Rabadia & Aslani, 2023), but broad code acceptance is still developing and practitioners are advised to use conservative assumptions and, where possible, long-term monitoring for critical structures.

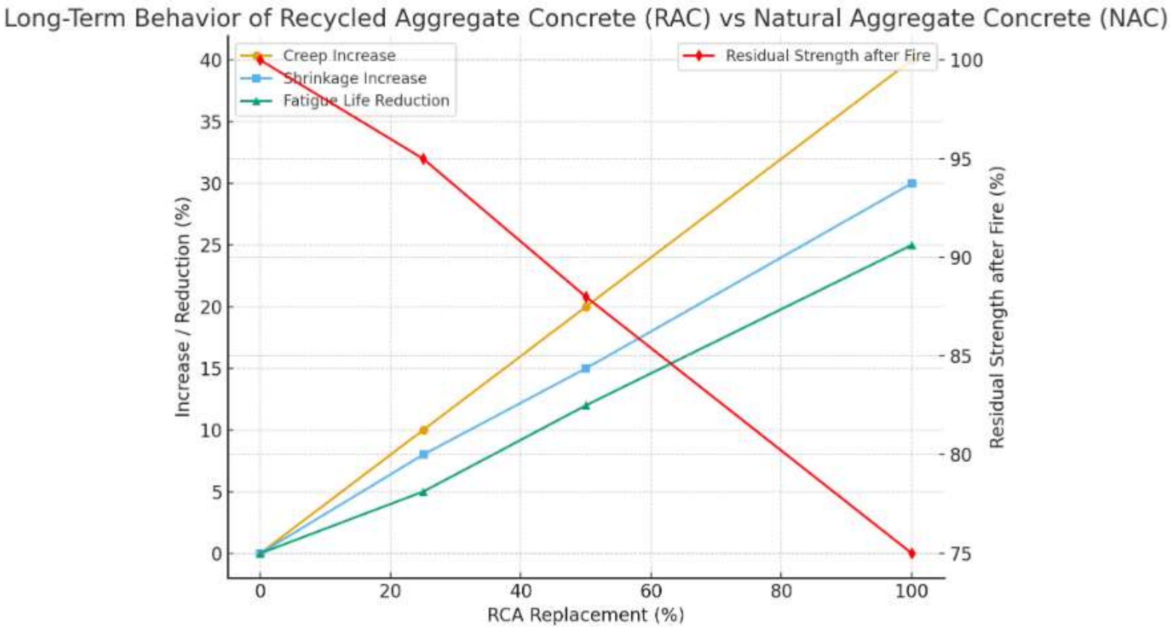

Figure 3 <Long-Term Behavior of RAC vs NAC>

The chart illustrates that increasing the percentage of recycled coarse aggregate (RCA) in concrete generally leads to higher creep, shrinkage, and fatigue life reduction, while simultaneously decreasing residual strength after fire exposure. At 100% RCA replacement, creep and shrinkage increase substantially by around 40% and 30% respectively, and fatigue life is reduced by 25%, indicating a significant compromise in long-term stability. Conversely, residual strength after fire drops to about 75% compared to natural aggregate concrete, highlighting durability concerns in extreme conditions. This suggests that while RAC can be utilized sustainably, higher replacement levels require careful structural considerations and mitigation strategies.

Fatigue resistance under repeated or cyclic loading is another long-term performance dimension where RAC often shows reduced life compared to natural aggregate concrete, especially when high replacement levels or low-quality RCA are used; fatigue strength reductions are attributed to the weaker interfacial transition zones and pre-existing microcracks in RCA particles (You et al., 2021). Laboratory fatigue tests on compressive and flexural loading indicate that endurance limits decrease with increasing RCA content, and fatigue crack growth rates can be higher in RAC unless mitigated by measures such as fiber reinforcement, optimized aggregate grading, or improved binder matrix toughness (Zhong et al., 2025). Notably, recent studies demonstrate that appropriate use of fibers (steel or synthetic), combined with SCMs that enhance matrix ductility, can recover a significant portion of fatigue performance—making RAC feasible for some pavements and bridge deck applications where cyclic loading is dominant (Khan et al., 2025). Field-oriented research remains limited, however, and continued full-scale testing under traffic or operational loads is necessary to validate laboratory predictions.

Fire and thermal resistance of RAC display a mixed picture: on the one hand, RAC often has slightly lower residual mechanical properties after high-temperature exposure than conventional concrete because the adhered mortar and increased porosity promote dehydration and microcracking at elevated temperatures (Hlavička, 2023). On the other hand, some studies report that RAC can exhibit comparable thermal insulation or slower heat transfer due to lower thermal conductivity associated with higher porosity, which in certain composite sections may reduce peak heat flux to internal reinforcement (Chen & Xiao, 2025). Post-fire residual strength, however, typically decreases with exposure temperature for all concretes, and RAC may require more conservative fire-design measures—such as increased cover, use of thermal stabilizers, or incorporation of fibers to control spalling—if used in elements with critical fire-safety requirements.

Emerging strategies such as fiber reinforcement, low-cement binders with controlled thermal decomposition, and protective coatings have shown promise in laboratory studies to improve post-fire integrity of RAC components (Chen & Xiao, 2025).

Practical field cases help illustrate these long-term behaviors and mitigation pathways. Pavement and precast element trials in several European and East Asian projects—where RCA was sourced from well-controlled demolition streams and subjected to careful processing—reported acceptable long-term deformation and fatigue performance when RCA replacement was moderate and when mixes included SCMs or fibers; these projects emphasize that supply-chain quality control, conservative replacement limits, and targeted mix adjustments are decisive for service performance. Conversely, documented failures or accelerated deterioration in poorly specified applications—where mixed demolition waste with contaminants was used without adequate treatment—show increased shrinkage cracking, accelerated chloride ingress and fatigue distress, and worse residual strength after heat exposure, underscoring that RAC durability is an outcome of the entire production and design chain rather than an inherent property.

In sum, long-term behaviour of recycled concrete under service conditions reveals both constraints and opportunities: creep, shrinkage, and fatigue risks are generally higher for RAC but can be managed through RCA quality control, mix engineering (SCMs, fibers), targeted pre-treatments, and conservative design checks; fire performance requires particular attention to spalling and residual strength and benefits from fiber reinforcement and thermal design measures. To mainstream RAC for critical civil applications, the literature recommends integrated strategies—source certification, process control, tailored mix design, performance-based testing, and field monitoring—to ensure that long-term serviceability and safety are maintained while realizing sustainability gains.

Factors Affecting Performance

Quality and treatment of recycled aggregate (RCA).

The intrinsic variability of RCA — influenced by the parent concrete strength, amount of adhered mortar, presence of contaminants (brick, wood, gypsum), and particle shape — is the single most important determinant of recycled concrete performance (OBE et al., 2019). RCA with high adhered-mortar content has higher porosity and water absorption, which weakens the interfacial transition zone (ITZ) and reduces mechanical properties and durability (Tam et al., 2018). Consequently, pretreatment methods such as mechanical abrasion, secondary crushing, thermal treatment, or chemical/acid washing reduce adhered mortar and improve particle interlock, producing RCA with significantly better compressive strength and lower absorption. Empirical studies show that mechanically treated RCA can recover a large fraction of the strength loss otherwise observed at moderate replacement ratios (Forero et al., 2022; Savva et al., 2021). A notable field illustration is documented in Tam et al.'s review where controlled processing and source selection in Japanese and Dutch projects enabled the use of RCA in pavements and precast elements with acceptable in-service performance.

Mix-design optimization and use of additives (SCMs, fibers, admixtures).

Optimizing mix proportions is crucial to compensate for RCA shortcomings: reducing water-to-binder ratio, using optimized grading, and increasing cementitious content typically improve packing density and ITZ quality (Habibi et al., 2021). The systematic incorporation of supplementary cementitious materials (SCMs) fly ash, GGBFS, silica fume — refines pore structure, reduces permeability, and chemically binds deleterious ions, thereby improving both strength and durability of RAC (Colman et al., 2021). Fiber addition (steel, polypropylene) and high-performance admixtures (superplasticizers, shrinkage reducers) enhance toughness, flexural capacity, and fatigue resistance, offsetting tensile/flexural losses associated with RCA. Optimization studies using statistical methods (RSM, DOE) show clear trade-offs: for example, mixes with 25–50% RCA plus SCMs frequently match or exceed the performance of plain NAC mixes, while maximizing sustainability metrics (Golafshani et al., 2024).

Impact of curing methods and exposure conditions.

Curing regime exerts a strong influence on RAC's hydration development, microstructure consolidation, and long-term properties; extended moist curing, internal curing (pre-saturated RCA), and thermal curing accelerate strength gain and reduce long-term shrinkage/creep compared to inadequate curing. Studies show that pre-saturating RCA before mixing mitigates its high absorption (acting as internal curing reservoirs) and reduces autogenous shrinkage and early age cracking (Forero et al., 2022). Conversely, poor curing in field conditions (insufficient moisture, high temperature variability) magnifies the negative effects of RCA, increasing permeability and reducing durability under freeze–thaw or chloride exposure. Practical evidence from monitored projects indicates that elements cast with optimized curing protocols (e.g., moist curing 7–14 days plus SCMs) perform markedly better in long-term durability tests than those cured conventionally.

Concrete case (integrated example).
In several European pavement and precast trials summarized by Tam et al. (2018) and Pedro et al. (2017), projects combined strict source control (demolition from known high-quality parent concrete), mechanical RCA treatment, mix optimization with 30%–50% coarse RCA plus 10% GGBFS or silica fume, and extended moist curing. These projects reported in-service compressive strength and chloride resistance close to NAC benchmarks and acceptable fatigue/deflection behavior over monitoring periods, demonstrating that an integrated approach (quality control + treatment + mix design + curing) is essential to make RCA viable for structural applications.

Table 1 <Challenges and Opportunities of Recycled Aggregate Concrete (RAC)>

Aspect	Challenges	Opportunities
Barriers to Large-Scale Implementation	Variability in recycled aggregate quality and lack of standardized processing.	Advanced treatment methods can improve performance and allow broader structural use.
Sustainability and Environmental Benefits	Limited awareness and weak policy enforcement reduce adoption.	RAC reduces natural aggregate demand, diverts waste, and supports circular economy goals.
Economic Feasibility and Cost Considerations	Higher initial processing costs due to crushing, cleaning, and quality control.	Long-term savings from reduced waste disposal and resource extraction improve cost-effectiveness.
Future Research Directions	Uncertainty about long-term performance in extreme conditions.	Use of SCMs, nanomaterials, and fibers can enhance mechanical and durability properties.

The challenges and opportunities of Recycled Aggregate Concrete (RAC) reflect a balance between limitations in material performance and its significant potential in sustainable construction. On one hand, issues such as variability in aggregate quality, higher processing costs, and uncertainty about long-term durability hinder widespread adoption. On the other hand, technological advances in processing methods, integration of supplementary cementitious materials, and improved design strategies demonstrate RAC's potential to reduce natural resource consumption and construction waste. A practical case can be seen in Japan, where the use of RAC has been standardized for non-structural elements in urban infrastructure, helping to minimize landfill waste while maintaining acceptable quality for secondary construction applications. This example illustrates how institutional support and standardized practices can transform RAC from a niche material into a mainstream sustainable solution.

Table 2 <Comparative Summary of Previous Studies on Recycled Aggregate Concrete (RAC)>

Study	RCA Replacement Level	Main Findings	Key Implications
Xiao et al. (2005)	0–100%	Higher RCA content reduced compressive and tensile strength.	Moderate replacement ratios are preferable for structural applications.
Gomes & De Brito (2009)	Various	Durability and chloride resistance decreased with poor-quality RCA.	RCA quality strongly affects long-term performance.
Thomas et al. (2013)	Various	Increased porosity influenced freeze–thaw resistance and serviceability.	Proper curing and air entrainment are necessary.
Evangelista & De Brito (2014)	20–100%	Mechanical performance declined with increasing RCA replacement.	RCA replacement should be optimized according to design requirements.
Silva et al. (2014)	Various	Higher water absorption and permeability were observed in RAC.	Durability enhancement measures are required.
Kou & Poon (2015)	Various	SCM incorporation improved mechanical properties and durability.	Supplementary cementitious materials effectively mitigate RAC weaknesses.
Silva et al. (2015)	Various	RAC exhibited higher creep and shrinkage than NAC.	Long-term deformation should be considered in design.

Study	RCA Replacement Level	Main Findings	Key Implications
Kisku et al. (2017)	Various	Tensile and flexural strengths decreased with increasing RCA content.	Structural applications require careful RCA proportioning.
Tam et al. (2018)	Various	RCA treatment significantly improved performance and field applicability.	Aggregate processing is essential for successful implementation.
Dimitriou et al. (2018)	Various	RCA increased chloride diffusion and permeability.	Durability-oriented mix design is necessary.
Ozbakkaloglu et al. (2018)	Various	Durability performance depended on aggregate quality and exposure conditions.	Environmental context influences RAC suitability.
OBE et al. (2019)	Various	RAC supports waste reduction and resource conservation objectives.	RAC contributes to sustainable construction practices.
Colman et al. (2021)	25–50%	SCMs improved durability and mechanical performance.	Mix optimization can compensate for RCA-related deficiencies.
Ren et al. (2022)	20–75%	Mechanical properties were strongly influenced by replacement ratio and RCA quality.	Source control and quality assurance are critical.
Sun et al. (2022)	Various	Carbonation and ASR risks can be mitigated through proper material selection.	Durability management is feasible with preventive measures.
Zhang et al. (2023)	25–75%	Strength reductions were minimized through optimized mix design and SCM incorporation.	Moderate RCA replacement can achieve satisfactory structural performance.
Liu et al. (2024)	Various	Higher shrinkage and creep were observed at elevated RCA replacement levels.	Long-term serviceability requires careful evaluation.
Golafshani et al. (2024)	25–50%	Optimized RAC mixes achieved performance comparable to NAC.	Statistical optimization improves sustainability-performance balance.
Khan et al. (2025)	Various	Fiber reinforcement enhanced fatigue resistance.	Hybrid RAC systems improve long-term performance.
Zhong et al. (2025)	Various	Fatigue life decreased with RCA content but improved with fibers and SCMs.	Advanced material combinations can offset performance losses.

Discussion

The findings summarized in Table 2 indicate a consistent trend across more than fifteen empirical studies, showing that the performance of recycled aggregate concrete is strongly governed by RCA quality, replacement ratio, mix-design optimization, and curing practices (Ren et al., 2022; Colman et al., 2021; Zhang et al., 2023).

The findings of this review highlight both the potential and limitations of recycled concrete aggregate (RCA) in modern civil engineering applications. The evidence consistently indicates that mechanical performance, durability, and long-term behavior of recycled aggregate concrete (RAC) are highly dependent on the quality of RCA, mix design strategies, and curing practices. While RAC generally exhibits lower compressive strength, tensile capacity, and stiffness compared to natural aggregate concrete (NAC), such deficiencies are not inherent or insurmountable. Instead, they can be addressed through careful aggregate processing, pre-treatment, and incorporation of supplementary cementitious materials (SCMs) or fibers. These strategies demonstrate that RAC can achieve structural properties comparable to conventional mixes, particularly at low to moderate replacement levels.

From a durability perspective, the higher porosity and water absorption of RCA remain the primary concerns, as they facilitate chloride ingress, carbonation, and freeze–thaw damage. Nonetheless, optimized mix proportions, pozzolanic SCMs, and appropriate curing regimes significantly improve the microstructure of RAC, leading to enhanced resistance against aggressive environments. Field applications in Europe and East Asia confirm that, under rigorous quality control, RAC can perform satisfactorily in pavements, precast elements, and other infrastructure exposed to service loads. Conversely, case studies involving poorly specified RCA illustrate accelerated deterioration, underscoring that durability is not an intrinsic material property but an outcome of holistic supply chain management.

However, not all reported outcomes are positive. Several studies have documented accelerated deterioration of RAC in highly aggressive environments, particularly where poor-quality RCA, inadequate curing, or insufficient durability-oriented mix design strategies were employed. Reports from tropical and high-sulfate exposure conditions indicate that elevated permeability and chloride ingress may compromise long-term durability when quality control measures are not rigorously implemented. These contrasting findings reinforce the importance of evaluating RAC performance within its specific environmental and operational context rather than assuming universally satisfactory behavior (Gomes & De Brito, 2009; Ozbakkaloglu et al., 2018; Sun et al., 2022).

In terms of long-term behavior, RAC tends to experience higher shrinkage, creep, and fatigue-related degradation. These effects can compromise serviceability if not considered during design. However, recent studies demonstrate that advanced treatments of RCA, combined with SCMs and fiber reinforcement, can mitigate such drawbacks. Similarly, the fire performance of RAC—though slightly weaker than NAC due to increased microcracking—can be enhanced through targeted measures such as fiber addition, protective coatings, and conservative cover depths. These findings point to the necessity of integrated design strategies rather than categorical exclusion of RAC from critical structures.

The review also identifies broader challenges in the adoption of RAC, including variability in aggregate quality, lack of standardized specifications, and stakeholder hesitancy. Despite these barriers, the opportunities are significant: RAC reduces dependence on natural aggregates, minimizes construction and demolition waste, and supports the transition toward circular economy practices. Furthermore, its long-term economic feasibility improves when waste management and resource conservation benefits are taken into account. Successful implementation in countries such as Japan demonstrates how standardized practices and institutional support can transform RAC into a mainstream construction material.

Taken together, these findings suggest that RAC should not be regarded merely as an inferior substitute for NAC, but as a sustainable material with distinct performance characteristics requiring tailored approaches. Future research should focus on full-scale structural validations, development of predictive models for long-term performance, and formulation of international standards to guide consistent application. By integrating technical innovations with supportive policies, RAC can play a central role in achieving sustainable construction goals without compromising structural safety and durability.

Unlike previous reviews that focused primarily on individual performance indicators, this review integrates evidence related to mechanical properties, durability characteristics, long-term behavior, and implementation challenges within a unified analytical framework, thereby providing a more comprehensive understanding of RAC performance in modern civil engineering applications.

Limitations of the Reviewed Literature

Although the reviewed studies provide substantial evidence regarding the mechanical performance and durability of recycled aggregate concrete (RAC), several limitations should be acknowledged. First, considerable variability exists in the quality of recycled concrete aggregates (RCA), including differences in parent concrete strength, adhered mortar content, particle grading, and contamination levels. Such variability complicates direct comparison among studies and contributes to inconsistent findings across the literature.

Second, experimental methodologies differ significantly with respect to specimen dimensions, curing conditions, replacement ratios, and testing procedures. These methodological differences may influence reported mechanical and durability properties and limit the generalizability of individual findings. Furthermore, many studies are laboratory-based and evaluate short- to medium-term performance, whereas relatively few investigations provide long-term field monitoring data extending beyond ten years of service.

Third, most available studies focus on specific performance indicators, such as compressive strength or chloride resistance, rather than integrating mechanical behavior, durability performance, and life-cycle considerations within a unified framework. As a result, comprehensive assessments of RAC performance under real service conditions remain limited.

Therefore, future research should prioritize large-scale field validation, standardized testing protocols, long-term monitoring programs, and integrated performance assessment frameworks to improve the reliability and practical applicability of recycled aggregate concrete in modern civil infrastructure.

Conclusions

This literature review demonstrates that the performance of recycled aggregate concrete (RAC) is governed primarily by recycled concrete aggregate (RCA) quality, replacement ratio, mix-design optimization, and curing practices rather than by the use of recycled aggregates alone. Across the reviewed studies, low-to-moderate RCA replacement levels (approximately 20–50%) generally resulted in compressive strength reductions of about 5–15% compared with natural aggregate concrete (NAC), while higher replacement ratios (>75%) were frequently associated with strength losses exceeding 20%. However, the incorporation of supplementary cementitious materials (SCMs), fiber reinforcement, and appropriate aggregate treatment methods was consistently shown to mitigate these reductions and, in many cases, enable RAC to achieve performance comparable to conventional concrete

From a durability perspective, the reviewed literature indicates that RAC is more susceptible to chloride ingress, carbonation, freeze–thaw deterioration, and long-term deformation due to the higher porosity and water absorption characteristics of RCA. Nevertheless, evidence from laboratory investigations and field applications demonstrates that these challenges can be substantially reduced through optimized mix proportions, lower water-to-binder ratios, improved curing regimes, and the use of SCMs. Consequently, RAC containing controlled RCA replacement levels can satisfy structural performance requirements when supported by adequate quality assurance and performance-based design approaches.

The principal contribution of this review lies in its integration of evidence on mechanical properties, durability performance, long-term behavior, and implementation challenges within a single analytical framework. Unlike many previous studies that focused on isolated performance indicators, this review highlights the interconnected influence of aggregate quality, treatment methods, environmental exposure conditions, and mix-design strategies on overall RAC performance. The findings suggest that RAC should not be regarded as an inherently inferior substitute for NAC but rather as a sustainable construction material whose performance depends on appropriate engineering control measures.

Despite significant progress, several unresolved issues remain. Contradictory findings continue to exist regarding the effectiveness of RCA pre-treatment techniques, the long-term durability of RAC in highly aggressive environments, and the performance of high-replacement RAC mixtures under extended service conditions. Furthermore, the limited availability of long-term field monitoring data restricts the ability to fully validate laboratory findings. Future research should therefore prioritize full-scale structural investigations, long-term durability monitoring, development of predictive service-life models, and harmonization of international standards to support the broader implementation of RAC in sustainable civil infrastructure.

Overall, the reviewed evidence indicates that RAC offers a viable pathway toward reducing construction waste and conserving natural resources while maintaining acceptable structural performance. Its successful implementation, however, depends on the integration of material optimization, rigorous quality control, and performance-based design practices to ensure both sustainability and long-term structural reliability.

References

Bai, G., Zhu, C., Liu, C., & Liu, B. (2020). An evaluation of the recycled aggregate characteristics and the recycled aggregate concrete mechanical properties. *Construction and Building Materials*, *240*, 117978.

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, *9*(2), 27–40. https://doi.org/10.3316/QRJ0902027

Chen, Z., & Xiao, J. (2025). Fire-insulation properties of recycled aggregate concrete, its application in composite concrete structures, and concrete-concrete interface effects: a review. *Journal of Building Engineering*, 112681.

Colman, C., Bulteel, D., Thiéry, V., Rémond, S., Michel, F., & Courard, L. (2021). Internal sulfate attack in mortars containing contaminated fine recycled concrete aggregates. *Construction and Building Materials*, *272*, 121851.

Dimitriou, G., Savva, P., & Petrou, M. F. (2018). Enhancing mechanical and durability properties of recycled aggregate concrete. *Construction and Building Materials*, *158*, 228–235.

Evangelista, L., & De Brito, J. (2014). Concrete with fine recycled aggregates: a review. *European Journal of Environmental and Civil Engineering*, *18*(2), 129–172. https://doi.org/10.1080/19648189.2013.851038

Forero, J. A., Brito, J. de, Evangelista, L., & Pereira, C. (2022). Improvement of the quality of recycled concrete aggregate subjected to chemical treatments: a review. *Materials*, *15*(8), 2740.

Gholampour, A., & Ozbakkaloglu, T. (2017). Performance of sustainable concretes containing very high volume Class-F fly ash and ground granulated blast furnace slag. *Journal of Cleaner Production*, *162*, 1407–1417.

Golafshani, E. M., Kim, T., Behnood, A., Ngo, T., & Kashani, A. (2024). Sustainable mix design of recycled aggregate concrete using artificial intelligence. *Journal of Cleaner Production*, *442*, 140994.

Gomes, M., & De Brito, J. (2009). Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. *Materials and Structures*, *42*(5), 663–675.

Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T.-C., Zhang, H., & Wang, Y. (2018). Durability of recycled aggregate concrete–A review. *Cement and Concrete Composites*, *89*, 251–259.

Habibi, A., Ramezanianpour, A. M., & Mahdikhani, M. (2021). RSM-based optimized mix design of recycled aggregate concrete containing supplementary cementitious materials based on waste generation and global warming potential. *Resources, Conservation and Recycling*, *167*, 105420.

Hlavička, Z. Y.-V. (2023). *Fire performance of recycled aggregate concrete: challenges and future prospects*.

Khan, M. S., Khan, M. I., Choudhry, R. M., Khahro, S. H., & Memon, Z. A. (2025). Performance analysis of fiber reinforced recycled aggregate concrete at elevated temperatures using response surface methodology. *Scientific Reports*, *15*(1), 12916.

Kisku, N., Joshi, H., Ansari, M., Panda, S. K., Nayak, S., & Dutta, S. C. (2017). A critical review and assessment for usage of recycled aggregate as sustainable construction material. *Construction and Building Materials*, *131*, 721–740.

Kou, S., & Poon, C. (2015). Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Construction and Building Materials*, *77*, 501–508.

Li, X., Qin, D., Hu, Y., Ahmad, W., Ahmad, A., Aslam, F., & Joyklad, P. (2022). A systematic review of waste materials in cement-based composites for construction applications. *Journal of Building Engineering*, *45*, 103447.

Liu, X., Gong, B., Fu, Y., Jiang, G., & Wang, J. (2024). Investigation of the Time-Dependent Deformation of Recycled Aggregate Concrete in a Water Environment. *Materials*, *17*(18), 4588.

OBE, R. K. D., de Brito, J., Silva, R. V, & Lye, C. Q. (2019). *Sustainable construction materials: recycled aggregates*. Woodhead Publishing.

Ozbakkaloglu, T., Gholampour, A., & Xie, T. (2018). Mechanical and durability properties of recycled aggregate concrete: effect of recycled aggregate properties and content. *Journal of Materials in Civil Engineering*, *30*(2), 4017275.

Rabadia, K., & Aslani, F. (2023). Development of creep and shrinkage prediction models for recycled aggregate concrete. *Structural Concrete*, *24*(5), 6552–6643.

Ren, H., Qian, Z., Lin, B., Huang, Q., Crispino, M., & Ketabdari, M. (2022). Effect of recycled concrete aggregate features on adhesion properties of asphalt mortar-aggregate interface. *Construction and Building Materials*, *353*, 129097.

Savva, P., Ioannou, S., Oikonomopoulou, K., Nicolaides, D., & Petrou, M. F. (2021). A mechanical treatment method for recycled aggregates and its effect on recycled aggregate-based concrete. *Materials*, *14*(9), 2186.

Silva, R. V, de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, *65*, 201–217.

Silva, R. V, De Brito, J., & Dhir, R. K. (2015). Prediction of the shrinkage behavior of recycled aggregate concrete: A review. *Construction and Building Materials*, *77*, 327–339.

Silva, R. V, De Brito, J., & Dhir, R. K. (2018). Fresh-state performance of recycled aggregate concrete: A review. *Construction and Building Materials*, *178*, 19–31.

Singh, A., Miao, X., Zhou, X., Deng, Q., Li, J., Zou, S., & Duan, Z. (2023). Use of recycled fine aggregates and recycled powders in sustainable recycled concrete. *Journal of Building Engineering*, *77*, 107370.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339.

Sun, D., Shen, S., Huang, W., Liu, K., Wang, A., & Chen, J. (2022). A review of quality of recycled aggregate and its effect on durability of recycled aggregate concrete. *Materials Express*, *12*(12), 1415–1426.

Tam, V. W. Y., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, *172*, 272–292.

Thomas, C., Setién, J., Polanco, Ja., Alaejos, P., & De Juan, M. S. (2013). Durability of recycled aggregate concrete. *Construction and Building Materials*, *40*, 1054–1065.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, *14*(3), 207–222.

Xiao, J., Li, J., & Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research*, *35*(6), 1187–1194.

You, F., Luo, S., Zheng, J., & Lin, K. (2021). Analysis of compressive fatigue failure of recycled aggregate concrete. *Materials*, *14*(16), 4620.

Zhang, P., Sun, X., Wang, F., & Wang, J. (2023). Mechanical properties and durability of geopolymer recycled aggregate concrete: A review. *Polymers*, *15*(3), 615.

Zhong, C., Xiao, Q., Fan, Z., Mao, W., Xing, S., Chen, J., Xiao, Y., & Zhou, J. (2025). Experimental investigation on flexural fatigue performance of recycled aggregate concrete hybrid with basalt-polyacrylonitrile fiber. *Scientific Reports*, *15*(1), 5855.